R. & M. No. 3512

MINISTRY OF TECHNOLOGY

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

Bibliography of Heat-transfer Instrumentation

By F. J. Bayley and A. B. Turner

LONDON: HER MAJESTY'S STATIONERY OFFICE
1968
PRICE £1 6*s*. 6*d*. NET

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Reports and Memoranda No. 3512*
November, 1966

PREFACE

The preparation of this bibliography of Heat Transfer Instrumentation was undertaken by the authors at the request of the Heat and Mass Transfer Sub-Committee of the Aeronautical Research Council. It is based upon an initial survey of references in this field carried out by Mr. A. J. Cruttenden, Secretary, and members of the Committee. In this bibliography we have followed the classification adopted by Mr. Cruttenden which sub-divides the whole field into seven sections which are listed below. No further sub-division has been attempted and there is no special significance in the order in which the references under each heading are dealt with although papers on a common subject have, where possible, been grouped together.

In Section I headed 'General and Miscellaneous' we deal principally with techniques of measurement not dealt with in the subsequent specialist chapters, and particularly refer to heat-flux meters and their application in various specialist fields. The second Section deals entirely with thermocouples, lists the types available, their calibration and thermocouples for special purposes. The particular difficulties of measuring surface temperatures are dealt with in Section III and a variety of means of dealing with this very important experimental problem is surveyed. Chapter IV on kinetic heating is concerned with the special problems of measurement in aircraft structures and missiles. The last three chapters deal successively with the special techniques required for measurement of radiation, the application of phase change methods and lastly the uses of resistance thermometers. About one hundred references are dealt with in these seven sections. The list of contents which follows gives the titles of the papers in the main text, and an alphabetical author index appears at the end.

A number of the references are books or edited proceedings of symposia. In the case of one or two particularly important sections in this type of reference we have treated separate chapters as if they were independent papers in the appropriate section of the bibliography. Usually however, we have merely indicated the general objective of the text concerned and where appropriate, listed separate paper or chapter titles. In all other references we give a brief synopsis of the contents of the paper and wherever possible have outlined the important conclusions drawn by the authors.

We hope that this bibliography will be of assistance to those working in the general field of heat transfer and that its contents will enable the reader to determine which of the references dealt with are relevant to any particular problem with which he is concerned. Our thanks are due to the Aeronautical Research Council for their support of this work from the One Thousand Pound Fund, and to members of its Committees who have helped by supplying references. Our thanks are also due to the Librarians of the Aeronautical Research Council and of many other organisations for their invaluable help in obtaining many of the references surveyed.

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1. *General and Miscellaneous.*

I.1. *Temperature, its Measurement and Control in Science and Industry.*

General Editor, Herzfield, C. M.
Volume III Part 1, Basic concepts, standards and methods, Editor, Brickwedde, F. G.
Part 2, Applied methods and instruments, Editor, Dahl, A. I.
Publishers: Reinhold, New York; Chapman & Hall Ltd., London.

Volume III, Part 1: contains papers by various authors divided into the following sections: 1. Basic concepts of temperature, 2. Basic scales of thermometry, 3. Establishment of the thermodynamic scale, 4. Thermometric fixed points, 5. Liquid in glass and thermoelectric thermometry, 6. Platinum resistance thermometry above −183°C, 7. Platinum resistance thermometer scale, 10° to 90°K, 8. Practical low temperature thermometry, 9. Optical pyrometry, 10. Spectroscopic methods of measuring temperatures, 11. Temperature measurements in plasmas over 100,000°K, 12. Temperature measurements in astrophysics, 13. Temperature measurements in geophysics.

Volume III, Part 2: contains papers divided into eight sections and although Volume III of this series has here been treated as one reference, many of the papers in Part 2, as indeed in Part 1, are worthy of summaries in their own right. In this respect, it has been thought helpful to include a list of the papers contained in Part 2.

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11. The use of refractory metals for ultra high-temperature thermocouples, Lachman, J. C. and McGurty, J. A.
12. High-temperature thermocouples using nonmetallic members, Franks, E.
13. Platinel: a noble metal thermocouple, Accino, D. J. and Schneider, J. F.

C. *Performance Characteristics of Thermocouples.*

14. Thermoelectric stability of platinum *vs.* platinum-rhodium thermocouples, Freeman, R. J.
15. Some experiences with Noble-metal metal-sheathed thermocouples, Bostwick, W. E.
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19. The effects of cold working, heat treatment, and oxidation on the thermal e.m.f. of nickel-base thermocouples, Potts, J. F., Jr., and McElroy, D. L.
20. The effects of nuclear radiation on thermocouples, Kelly, M. J., Johnston, W. W. and Baumann, C. D.

21. Calculated radiation induced changes in thermocouple composition. Browning, W. E., Jr., and Miller, C. E., Jr.
22. Operation of thermocouples under conditions of high temperature and nuclear radiation, Levy, G. F., Fouse, R. R. and Sherwin, R.
23. Limitations in the use of thermocouples for temperature measurements in magnetic fields, Loscoe, C. and Mette, H.
24. Drift studies on Chromel-P-Alumel thermocouples in helium atmospheres, Bennett, R. L. and Rainey, W. T., Jr.

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31. Suitability of carbon resistors for field measurement of temperatures in the range of 35 to 100°R, Herr, A. C., Terbeek, H. G. and Tiefermann, M. W.
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35. Application of radiation pyrometry to glass-forming processes, McGraw, D. A. and Mathias, R. G.
36. The place of photovoltaic detectors in industrial pyrometry, Barber, R. and Land, T.

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C. *Radiation from Gases, Plasmas and Incandescent Solids.*

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43. Monochromatic radiation pyrometry of hot gases, plasmas, and detonations, Tourin, R. H.
44. Spectroscopic diagnostics of a Gerdien-type plasma stream using argon, McGregor, W. K. and Dooley, M. T.
45. Gas-temperature measurements in internal-combustion engines, Ghandi, B. K., Myers, P. S. and Uyehara, O. A.
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61. Heat-flux probe for dynamic measurements in high-temperature gases, Fingerson, L. M. and Blackshear, P. L., Jr.
62. A rocket engine heat-flux transducer, Vrolyk, J. J.
63. Thermocouple probes for evaluating local heat-transfer coefficients in rocket motors, Sellers, J. P., Jr.
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66. Thermocouples for measurement of the surface temperature of nuclear fuel elements, Browning, W. E., Jr., and Hemphill, H. L.
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70. The control systems approach to process design: Analytical tools required for temperature control, Lefkowitz, I.
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72. An electric temperature controller with proportional and reset action, Rolfson, F. B.
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86. Temperature measurement by Infra-red thermal images, Astheimer, R. W.
87. Thin film thermometry in detonation research, Laderman, A. J., Hecht, G. J. and Oppenheim, A. K.
88. The accuracy and reliability of bimetallic temperature measuring elements, Huston, W. D.
89. Ultrasonic temperature determinations in a plasma, Carnevale, E. H., Poss, H. L. and Yos, J. M.
90. Plasma jet diagnosis utilizing the ablating probe, Freeman, M. P.
91. Measurement of the temperature distribution in the workpiece during metal-cutting, Hollander, M. G.
92. Determination of gas temperatures using beta-ray gauges or electron beam probes, Schumacher, B. W.
93. Absolute measurement of temperatures of microwave noise sources, Estin, A. J., Trembath, C. L., Wells, J. S. and Daywitt, W. C.
94. Recent developments in fusible temperature indicators, Kasanof, D. R. and Kimmel, E.
95. Temperature measurement by infra-red thermal images, Astheimer, R. W.
96. Use of pyroelectric devices for measuring small temperature changes, Lang, S. B.

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98. Measurement of surface temperature in an arc-image furnace, West, W. E. and Maccalous, J. W.
99. A self-calibrating high-temperature radiation standard, Blau, H. H., Martin, W. S. and Chaffee, E.
100. High-temperature generation and control by thermal imaging techniques, Glaser, P. E. and Ploetz, G. P.
101. A scanning radiation sampler for imaging furnaces, Cook, J. C.
102. Method for temperature and reflectance determination in an arc-imaging furnace, Comstock, D. F., Jr.
103. Method of calibrating and controlling the radiant energy output of imaging furnaces, Carter, J. A.

I.2. *Temperature Measurement in Engineering, Volumes I and II.*

Baker, H. D., Ryder, E. A. and Baker, N. H., Wiley New York and London, 1961.

Volume I deals primarily with thermocouple technique. The first four chapters are introductory, with respect to the two-volume sequence.

Volume I contains chapters on: 1. Temperature, 2. Methods for measuring temperature, 3. Precision requirements, 4. Conditions affecting temperature measurement, 5. The thermocouple thermometer circuits, 6. Indicating instruments, 7. Design calculation techniques, 8. Installation design types, 9. Drilling technique, 10. Special materials: Protective coatings, heat- and corrosion-resistant metals, plastics, refractories and cements, 11. Cemented installation designs, 12. Temperature gradient installation designs.

Volume II is divided into two parts. Part I deals with technique. Chapters on (1) Resistance thermometers, (2) Resistance-thermometer design calculations, (3) Radiation detectors and (4) Radiation pyrometry-design calculation techniques are included.

Part II deals with the application of the above to: (1) Surface temperatures, (2) Rapidly changing temperatures, (3) Moving bodies, (4) Transparent bodies, (5) Liquids, (6) Gases, (7) High-temperature gases, (8) Low temperatures, (9) Flame temperatures and (10) Arc, plasma, upper air, stellar and nuclear-reactor temperatures.

I.3. *Measurement of Temperature*: *Advanced-state-of-the-art Bibliography.*

Pearlstein, J., *Diamond Ordnance*, August, 1961.

This is a bibliography of selected papers on temperature measurement and control given at 'The Fourth Symposium on Temperature, its Measurement and Control in Science and Industry', held in Columbus, Ohio, March 27th to 31st, 1961. The bibliography lists *only* the titles of the papers, the authors and the organizations that have conducted or sponsored the work. It was published as a rapid guide for surveying the current state-of-the-art on temperature, measurement and control.

The work is grouped under the headings:

1. Basic concepts of temperature, 2. The temperature scales, 3. Thermocouples, 4. Spectroscopic methods and pyrometry, 5. Temperature instrumentation in biophysics and medicine, 6. Gas thermometers, 7. Resistance thermometers, 8. Temperature measurement in moving systems, in cryogemics, automatic methods and problems, special sources, arcs, image furnaces, and temperatures in plasmas over 100 000°K.

All the papers listed in this report have been summarised and copies of the 115 page programme containing these summaries can be obtained from The American Institute of Physics, 335E.45 Street, New York 17, New York.

I.4. *Some Developments in Techniques for Temperature Measurements.*

Thermodynamics and Fluid Mechanics Group, *I. Mech. E.*, *Symposium*, 26th April, 1962.

This publication is a collection of eight papers on temperature measurement together with a general discussion on other techniques.

The papers are:

1. Suction pyrometers.
2. Thermocouples for gas temperatures up to 2 000°C.
3. Theory and practice of methods for measurement of temperatures for industrialized flames.
4. Spectrum line reversal techniques of temperature measurement.
5. The gas bridge thermometer.
6. The use of thermocouples for the measurement of surface and internal temperatures.
7. Thin-film resistance thermometers and calorimeters.
8. Radiation techniques for surface-temperature measurement.

I.5. *Significance of Errors in High-temperature Measurement.*

Moen, W. K., *S.A.E.* Prep. (750 F), September, 1963.

The significance of the errors in temperature measurement is taken with regard to the design of fabricated heat shields for spacecraft. The paper discusses the magnitude and sources of error in measurement by thermocouples. The range of measurement errors can be greatly reduced by considerations of thermocouple placement, ratios of specimen material and thermocouple conductivity, specific heat, wire diameter and welding and cementing techniques.

Based on results of steady state and transient experiments the effects of temperature measurement errors on the design weight of spacecraft heat shields at the 1600°F range show that structural weight could be increased by 16% owing to a 50°F measurement error.

The report concludes that in installation of a thermocouple in a low conductivity material the most important factors are:

1. Placing the thermocouple (minimum length $\frac{3}{8}$ inch) accurately and parallel to the surface being heated.

2. Using a maximum of 36 gauge (5 ml.) wire.

3. Sealing the thermocouple with a cement having a thermal conductivity as close as possible to the material being tested.

Brief recommendations are also made for the installation of a thermocouple on a space-vehicle skin material.

I.6. *Response Characteristics of Temperature-sensing Elements for Use in the Control of Jet Engines.* By Dahl, A. I. and Fiock, E. F., *Journal of Research of the National Bureau of Standards*, 45 N° 4, p. 292, October 1950.

This paper is concerned particularly with the rates of response of temperature-sensing elements normally immersed in flowing gas. The factors which determine rates of response and characteristic times (τ) are discussed in relation to: 1. Heat transfer by convection, forced and natural and, 2. By radiation.

It is shown that in forced convection, τ of an element is essentially independent of the temperature and of the temperature difference to which it is subjected but very dependent on the mass rate of flow. Since τ of any object varies directly as its mass and inversely as its surface area any method of increasing the surface area proportionately greater than the mass will reduce τ. In natural convection, however, the response depends upon the particular temperature conditions encountered. In radiative heat transfer, the rate of response depends markedly on (a) whether the junction is being heated or cooled, (b) the temperature level, (c) the temperature interval.

In jet engines the rate of change in temperature of the sensing element is determined almost entirely by the rate of heat transfer by forced convection, the effects of radiation and conduction being insignificant.

The laboratory apparatus for simulating engine conditions, for measuring τ is described. Two systems are mentioned, one for temperatures to 1600°F and one for temperatures to 2000°F, at mass flow rates of up to 15 lb/sec.ft^2.

Instantaneous exposure to the hot gas is achieved by surrounding the sensing element with an Inconel tube through which cool air is blown. The tube is removed suddenly by a spring and the cool air supply cut off automatically. Some typical results, obtained for bare, untwisted Chromel-Alumel thermocouples are presented showing that the variation of τ with mass-flow rate is independent of the operating temperature.

The paper concludes that the overall rate of response of the control system must be sufficiently high so that adequate protection is provided at the lowest mass-flow rates which occur during static starts and at the flight ceiling. If this is accomplished then the protection provided at all other altitudes and engine speeds should be more than adequate.

I.7. *On a Thermometer with Recovery Factor* $r > 1$.

Rietdijk, J. A., and Valstar, A., *Applied Sciences Res.* Section A. pp. 251–6, Vol. 7, 1958.

This paper describes the construction of, and gives experimental results from, a simple thermocouple probe with, $r > 1$.

A recovery factor > 1 is accomplished by having the thermocouple surrounded by a chamber into which air enters by means of a frontal hole of smaller diameter than that of the chamber. The initial jet of air after reaching the thermocouple streams back along the walls of the chamber to exit through the side holes which are quite close to the entrance hole. (As distinct from the more usual probe with the side holes quite close to the thermocouple bead).

The temperature of this returning jet is higher than that of the initial jet since it has a lower velocity and heat transfer takes place raising the temperature of the air before it reaches the thermocouple bead.

A probe with an outside diameter of 3·2 mm. was tested at up to $M = 2{\cdot}5$ with a free-stream stagnation temperature of 20°C. A recovery factor above 1 was obtained, between $M = 0{\cdot}7$ and $2{\cdot}5$ with a maximum of 1·037 at $M = 1{\cdot}72$.

The machining on probes of this nature has to be very accurate, since the front and side hole diameters have a very great influence on r. The instrument was insensitive to angles of incidence up to $\pm 5°$.

I.8. *Improved Technique for Measuring Heat-transfer Coefficients.*

Anderson, B. H., 4th A.F.B.M.D./STL Symposium, *Advances in Ballistic Missile and Space Technology*, 1961.

The technique described in this report makes use of the response of the skin temperature of a high speed vehicle model to sinusoidal free-stream temperature oscillations. The gas temperature is oscillated at a constant amplitude of about 15°F and a frequency of from 0·01 to 1·0 c/s. The wall temperature will also oscillate but will lag the gas temperature by some angle $\tan^{-1}(w\tau)$ where w is the forcing frequency and τ is a time constant from which the heat-transfer coefficient can be obtained directly.

Details are given of an experimental investigation carried out to demonstrate the technique. The gas temperature was oscillated by oscillating the gas burner supply valve. Oscillations of $\pm 7\frac{1}{2}°$ about mean temperatures of 240° and 300° at Mach 2·0 and 3·0 respectively were obtained. The heat-transfer measurements were made on a 10° stainless steel cone. The gas temperature was measured with a high-response thermocouple located outside the boundary layer and both gas and wall temperatures were recorded on an oscillograph. A typical oscillograph trace is given at a forcing frequency of 0·03 c/s. with gas amplitudes $\pm 7\frac{1}{2}°$F, and wall amplitudes $\pm 1\frac{1}{2}°$F, the phase shift was about 45°.

Results are given for one position on the cone for a range of forcing frequencies from 0·01 to 1·0 c/s. Date are also given for laminar and turbulent flow. Theoretical and experimental data agree well, except at the higher forcing frequencies. Heat-transfer coefficients are presented in the form of Stanton number for a number of positions on the cone for both laminar and turbulent flow.

The report concludes that the technique can be used with good accuracy and that it avoids the use of either cumbersome cooling shoes or starting-and-stopping tunnel facilities to induce step changes in temperature on the heat-transfer model. The technique may be used on large and complicated models or in problems where large changes in flow conditions cannot be tolerated.

I.9. *An Instrument for the Direct Measurement of Intense Thermal Radiation.*

Gardon, R., *Rev. Sci. Inst.*, Volume 24, pp. 366–370, May 1953.

A new type of radiometer is described suitable for the measurement of the intensity of thermal radiation in the range 1 – 100 cal/cm^{2}sec. (3·7 – 370 B.T.U./ft^2 sec.). The instrument produces an e.m.f. directly proportional to intensity and can be made to have a time constant of the order of 0·001 sec. Equations are derived to predict the performance of the instrument, and their results compared with experimental data obtained from three prototypes.

The radiation strikes the blackened surface of a thin circular foil of constantan which is soldered around its circumference over a hole in a massive block of copper. The energy absorbed by the foil flows radially to the copper block, which acts as a constant-temperature heat reservoir, so that the temperature of the centre of the foil thus rises above that of its circumference. This temperature difference is related to the intensity of the radiant flux striking the foil and is measured by fastening a fine copper wire to the centre of the foil. A thermocouple is thus formed between the wire, the constantan foil and the copper block, which measures the radial temperature difference across the foil.

In the solution of the differential equation describing the operation of a circular foil radiometer it is coincidental that if copper/constantan is used, the non-linearity in its e.m.f.-temperature characteristic cancels the variation in thermal conductivity of the foil with respect to temperature. This results in a very simple equation for the sensitivity of the instrument.

The temperature limit of the foil is dependent upon the type of solder used (limit 600°C for silver solder).

The foil diameter of the smallest radiometer used was 0·034 cm., (0·013 inches) with a foil thickness of 0·00025 cm. This gave a theoretical sensitivity of 0·21 m.v./cal./cm^{2}sec. and a theoretical time constant of 0·001 sec. Larger sized radiometers are also described.

The experimental data supports the linearity of the e.m.g.-intensity relationship predicted by the theoretical analysis and the adequacy of characterizing the response by a single time constant. Discrepancies were observed between the theoretical and experimental sensitivity and time constant values which indicate that these instruments must be calibrated experimentally before use.

Trouble has been experienced with radio meters built to the above specification (*see* Ref. V.6.) because of creep. This has been eliminated by water cooling.

·I.10. *A Transducer for the Measurement of Heat-flow Rate.*

Gardon, R., *Trans. ASME, J. Heat Transfer* 82 Ser. C. 4, pp. 396–8, 1960.

The instrument described in this paper is the circular foil radiometer of Ref. I.9. (An instrument for the direct measurement of intense thermal radiation) by the same author, adapted to measure surface heat-transfer rates.

The instrument is mounted in the body with the foil flush with the surface, the dimensions being such that for all practical purposes it is always in thermal equilibrium with the body. When the surface of the body loses heat, the heat lost from the foil is replaced by a radial flow of heat from the body into the foil. The centre of the foil thus assures a temperature slightly lower than that of its circumference, this temperature difference being measured as explained in the above reference. A linear heat-flow rate *versus* e.m.f. relationship is obtained.

Mechanically these transducers differ from the circular foil radiometers described in Reference I.9. by their miniaturization and their all-metallic construction. By being mounted in the body under study, they are especially valuable for the study of convective heat-transfer coefficients and their rapid response also permits the measurement of transients.

As in the above reference a chart for the design of copper/constantan heat flow meters is given, together with graphical results of local convective heat transfer rates for a hot plate exposed to jets of air.

I.11. *A Proposed Method for Determining Heat-flow Densities in Rocket Motors.*

Ziebland, H., *Proc. Gen. Discussion on Heat Transfer*, I. Mech. E. and A.S.M.E., London, 1951.

A simple system using a 'Thermoelectric Heat Flux Element' is described. The method utilizes the measurement of the temperature gradient in the wall to determine the heat flux. An element of the rocket motor walls is constructed of three metallic layers. In the experiments, a layer of pure nickel is sandwiched between two layers of high conductivity copper. Heat flowing radially through the wall results in temperature differences at the interfaces of the intermediate layer. Since the nickel and copper acts as a thermocouple, this temperature difference can be measured directly and from a knowledge of the thermal conductivity and thickness of the nickel layer the heat flux can be determined.

The thickness of the intermediate layer can be reduced to a few tenths of a millimetre and still give sufficient potential difference by a suitable selection of materials.

The application of this method was checked experimentally on a rocket motor. The heat flow densities evaluated from measurements from the heat flux element, were compared with the average values of heat flow density over a sectional chamber determined from the temperature rise of the coolant and its flow rate. A considerable, but constant percentage discrepancy between the two results was found, which was attributed to imperfect contact and surface roughness between the metallic layers.

Better results were obtained from an element with 2 m.m. wall thickness. The deviations of $\pm 6\%$ were of the same order as the experimental accuracy for the mean heat-flow density.

I.12. *New Technique for Obtaining Heat-transfer Parameters of the Wall and Combustion Gas in a Rocket Motor.*

Ellion, M. E., Trans. *A.S.M.E. 73*, p. 109, 1951.

A test programme is briefly described which was initiated to extent the accuracy and range of available basic data for the three main types of heat transfer encountered in regenerative cooled rocket motors, and to broaden the fundamental basis for generalizing the cooling design.

Combustion pressures of 20 atm. and temperatures of the order of 5000°F are required for good performance; heat fluxes up to 7·0 (B.T.U./in.^{2} sec.) are required for cooling: and gas velocities of sonic and above occur at the throat and divergent sections of the motor. As a consequence, the heat-transfer coefficients for the liquid coolant, metal wall and combustion gas may be of the same order of magnitude.

The four parameters which define these three types of heat transfer; *hl* (liquid film), thermal conductivity *k*, allowable metal surface temperature and *hg* (gas film) must be determined before the analysis may be reduced to an analytical solution. A detailed description of the heat transfer through the metal wall is presented.

A test method is discussed for obtaining the gas side wall temperature in a rocket motor in order to evaluate the suitability of various alloys. Eight alloys have been studied by employing a thick-walled water-cooled nozzle into which specimens were inserted for tests. The heat flows and wall temperatures were determined by employing the nozzle as a heat meter and by using a new calculation method that accounts for variable thermal properties with temperature.

A description is given of an apparatus suitable for determining the liquid-film coefficient up through the nucleate-boiling region. A description is also given of an extension to the heat-meter method for measuring the effective gas temperature and overall gas-film heat-transfer coefficient.

I.13. *Probing Methods.*

Combustion Studies *J.P.L.*, Combined Bimonthly Summary No. 29, pp. 13–16, May 1952 (Confidential).

Probing methods are discussed and results are presented for rocket-motor combustion chamber. The objects of the tests were to correlate internal measurements of temperature, mixture ratio, pressure, velocity and local heat flux with conventional external measurements of characteristic velocity or specific impulse.

The temperature probe used, its method of application, and the preliminary results obtained with it can be found in two previous J.P.L. Combined Bimonthly Summaries Numbers 25 and 26.

A comparison is made between the temperature distributions in the chamber of a rocket motor equipped with two types of injector: a three unit, 'like-on-like' multi-orifice injector and a 24 pair multi-orifice injector with a splash plate. Radial-temperature distributions were obtained at three locations along the axis of the motor and at circumferential positions. Data is presented in graphical and tabular form.

The first injector gave radial variations of more than 3800°F whereas the variations were less than 1000°F for the second type of injector. The highest temperatures were measured at the centreline of the motor. The axial variations in average temperature indicated that the initial mixing and combustion are important if good performance is to be achieved. Pressure differentials were also measured and some indirect information on the velocity distribution was obtained by using the probe as a local heat-flux meter.

The quantities measured by the probing techniques were consistent with the variations in externally observed characteristics.

Investigations with optical methods are described. These were concerned with transparent-motor tests and the deposition on transparent windows. High-speed film studies are also discussed. Gas-analysis work is briefly dealt with.

I.14. *Determination of Rocket-motor Heat-transfer Coefficients by the Transient Method.*

Greenfield, S. P., *North American Av.* (Aerophysics Lab.), Report AL–985, March, 1950.

An experimental procedure is described to measure gas-film heat-transfer coefficients in rocket combustion chambers and nozzles. The transient temperature rise of the uncooled, segmented walls of a rocket motor was utilized to determine the rates of heat transfer.

This transient method was used to determine axial variation of film heat-transfer coefficients of gases at temperatures up to 3000°F flowing through a de Laval-type supersonic nozzle. Prior to testing the nozzle on a rocket motor, tests were conducted with air at 1400°F to check the various thermocouple installations and instrumentation and to judge the effectiveness of the transient method under similar but more controllable conditions. The tests with air used mass velocities varying between $1{\cdot}4 \times 10^5$ $16/ft^2$ and temperatures of 3000°F.

For the transient method the nozzle was built up in segments (copper) each segment acting as a thermal capacitor insulated axially from the others by an air gap, and essentially insulated on the outside surface by the surrounding air. Heat was assumed to be transferred to the segment by forced convection only, and then conducted radially through the segment. The average temperature rise of the segment with time reflected the amount of heat which was absorbed by the capacitor.

The temperatures were sensed with iron-constantan thermocouples and recorded on appropriate automatic recording instruments.

The thermocouple within each axial segment was installed at the location of the segment average temperature (calculated).

The effect of radiation on the heat-transfer coefficients was calculated to be less than 1 % when the slope of the tangent to the average temperature – time curve was taken at the earliest time in the test after steady operating conditons had been obtained.

The square-root relation of measured specific thrust of the rocket motor was used to calculate the effective combustion temperature. For the low-temperature work unshielded chromel/alomel thermocouples connected for radiation and recovery factor were used.

Experimental values of gas-film heat-transfer coefficients both for the rocket motor and the lower temperature tests were satisfied by the relation:

$$h_g = 0{\cdot}029 \frac{G^{0\cdot 8}}{D^{0\cdot 2}} C_p \, \mu^{0\cdot 2}$$

Where: h_g = Gas-film heat-transfer coefficient; G = mass velocity, (at mid point of segment); D = diameter (mid point), C_p = sp. heat of combustion gases; μ = Viscosity of gas at the adiabatic wall temperature.

I.15. *A Method for the Determination of Local Transient Heat Flux in Uncooled Rocket Motors.*

Powell, W. B., Howell, G. W. and Irving, J. P., *J.P.L.* Tech. Report No. 32–257, July, 1962.

The technique described required the experimental determination of the temperature-time histories of two independent points in the motor wall which are on the same radial path. These points provide boundary conditions for the solution of the transient-conduction equation, enabling the temperature distribution through the wall to be calculated. Heat flux is then computed as the product of the temperature gradient and the thermal conductivity at the surface.

The inner boundary temperature was obtained by the use of thermocouple plugs of which two types were used. One type employed 0·005 in Chromel/Alomel wires welded into a hole in the plug, the junction being some 0·020 in from the surface. A second type was the thermocouple plug mentioned in Reference III.11. in which the thermocouple wires were brought through the surface, machined flush and the junction formed by plating with nickel. The outer boundary temperature was obtained by welding a thermocouple to the outside of the chamber wall.

Numerical techniques are presented and sources of error are analysed. Experimental means for implementing the techniques are described, and experimental results obtained from rocket motor tests are discussed. Heat flux determined by the above procedure was found to agree closely with average heat flux measured calorimetrically at corresponding locations in sectional water-cooled motors operating under similar conditions.

A programme has been written for the I.B.M. 7090 high-speed digital computer to perform the calculations to determine the heat flux from the thermocouple transient-temperature data. This programme is available upon request.

I.16. *Application of Various Techniques for Determining Local Heat-Transfer Coefficients in a Rocket Engine from Transient Experimental Data.*

Liebert, C. H., Hatch, J. E., Grant, R. W., *NASA* T.N.D. – 277, April 1960.

Six analytical techniques for determining heat-transfer coefficients from transient experimental data are discussed and applied to obtain local values of heat-transfer coefficients in an ammonia-oxygen rocket. The time-temperature data as obtained from Chromel-Alumel thermocouples attached at different positions along a small copper plug inserted in the wall of the uncooled rocket engine. The copper plug was insulated from the chamber wall with Sauereisen cement so that it would approximate a one-dimensional finite slab.

Data for the comparison of the six methods was taken from both the chamber and the nozzle throat. The gas temperature was estimated from a knowledge of the rocket performance, and the inside wall temperature was obtained by extrapolating the plug temperatures. It took some 0·9 seconds from ignition before the plug temperatures rose at a linear rate.

The following methods were compared and discussed:

1. Integration method, in which the time rate of change of the integration heat content must be equal to the rate of heat flow through the surfaces. This method was taken to be the best of the six. The heat transfer coefficients were, chamber 0·00176 and nozzle throat 0·00286 B.T.U./sec.sq.in.°F.
2. Constant *h* method. The transient heat-flow equation is solved in difference form using a fine grid spacing on a high-speed computer. Percentage variations from Method I were chamber 0, throat -12.
3. Cresci-Libby method, in which the general one-dimensional partial differential equation of transient heat conduction for a finite slab with arbitrary surface-temperature distribution and constant diffusivity is used (solved by Carslaw and Jaeger). Percentage variations Chamber $+16$, throat -7.
4. Numerical method suggested by Max Jacob to solve linear unsteady-state conduction problems in a rod by following Dusinberre's procedure. Percentage variations – chamber $+7$, throat $+2$.
5. Greenfield method, (I.14.) in which the rocket wall is considered as a thermal capacitor. Percentage variations – chamber -2, throat -7.
6. Semi-log extrapolation method. In which log (temperature) is plotted against distance from the heated surface, extrapolated, and the results substituted in a simple equation for the heat-transfer coefficient. Percentage variations – chamber $+23$, throat $+17$.

The paper concludes that methods 1 to 5 are comparable near the end of burning time; that method 1 is easy to apply and good when running times are short; that method 2 is easiest to apply, is good when running times are long and requires only one thermocouple; that method 3, although rigorous is most difficult to apply; that method 5 is less accurate than methods 1 and 2, and that method 6 is too inaccurate.

I.17. *Errors Associated with a Method for the Experimental Determination of Heat-transfer Coefficients in Uncooled Rocket Nozzles.*

Clem, J. D., Rohm and Hass, *Quart. Prog. Report* No. P–60–5.

The experimental method referred to utilizes a mathematical model which duplicates the wall of the experimental rocket nozzle and is based upon the non-linear partial differential equation describing one-dimensional (radial) transient heat conduction with temperature-dependent properties. Temperatures are matched between the model of the nozzle and the nozzle itself.

Accurate transient-temperature data was obtained from a 'thermo plug'. This consists of a solid cylinder machined from the same material as the nozzle with a shallow channel across the flat face to accept the thermocouple element and with two insulation channels milled axially along the curved surface to carry the thermocouple leads. The 'thermo plug' was installed into a flat-bottomed hole in the nozzle with a malleable foil between the plug face and nozzle to reduce thermal contact resistance. Model wall temperatures were computed numerically using explicit finite-difference methods.

The error analysis of the heat-transfer coefficient was made in terms of nozzle-wall temperature errors which were then related to corresponding heat-transfer coefficient errors. The temperature errors considered are:— Errors caused by the perturbation of the temperature field, errors caused by inexact agreement between the mathematical model of the nozzle and the nozzle itself and errors in the temperature recording and data reduction procedure.

The perturbation errors considered are, 1. Interface contact resistance, 2. Insulation channels, 3. Thermocouple-element channel, 4. Lag of thermocouple wire, 5. Thermo-plug circuit. With the exception of the insulation channels these errors were concluded to be within acceptable limits.

The sources of correspondence errors considered were the adiabatic boundary, sensing-element location, circumferential and axial heat flow, thermal properties and model mesh size. These were analysed separately and all were considered small, as was the recording error.

The paper concludes that of the errors associated with the temperatures to be matched between the experimental nozzle and the mathematical model all are small with the exception of the insulation-channel error. Consequently the heat-transfer coefficients determined by the described method will have an error of the same order of magnitude as the error in the temperature-time history and that the magnitude of the effects may be found by investigating the effects of the upper-bound insulation channel error.

I.18. *Rapid Response Heat-flux Probe for High Temperature gases.*

Blackshaw, P. L. and Fingerson, L. M., *A.R.S.J.* 32, pp. 1709–15, November, 1962.

The probe is an anemometer consisting of a hollow internally-cooled pyrex tube 0·15 mm.o.d., 0·1 mm.i.d. having on its surface a thin film resistance element – a platinum coating 0·1μ thick, the length of the sensing portion being 2 mm.

The surface of the film is kept at constant temperature by a compensating power supply, the resulting power requirement represents the heat flux from the electrically heated surface to the surroundings and to the internal coolant. This heat-flux probe can be designed to operate at gas temperatures up to about 3000°K. at atmospheric pressure and subsonic velocities. The response of the probe to a rapid temperature change of 1560°K in 10^{-4} seconds gives an indication of the frequency response which is nearly flat to at least 10 000 c.p.s.

The probe is in effect a constant-temperature hot-wire anemometer that can be operated in high-temperature flames. The heat flux to or from the film depends upon the mass flow per unit area approaching the sensing element, the enthalpy difference between the free stream and surface conditions, and the physical properties of the approaching stream. An application is described in which the sensing element is placed in an aspirating probe upstream or downstream of a choked orifice so that the approach mass flow is linked to the other two properties of the stream, i.e. this virtually eliminates the influence of approach-flow velocity fluctuations. The application of the cooled anemometer to a dilution probe is also discussed.

Representative measurements made in non-reacting turbulent mixtures, chemically-reacting high-temperature gases and electrically heated dissociated plasmas are described.

I.19. *The Experimental Examination of the Local Heat Transfer on the Surface of a Sphere when Subjected to Forced Convective Cooling.*

Wadsworth, J., Rpt. M.T.–39, *National Research Council of Canada*, September, 1958.

The local heat-transfer distribution on the isothermal surface of a sphere was measured under forced convective cooling conditions. The results obtained were compared directly with other work and the discrepancies noted were partially explained as a difference of turbulence level in the respective flow facilities.

The local heat transfer on the surface of the sphere was measured (as Schmidt and Wenner), in the following manner. A small portion (called a plug) of the surface of an electrically heated 4 in. diameter copper sphere was isolated thermally from the rest of the sphere and provided with its own electrical heater and thermocouple. The sphere itself was also furnished with a thermocouple in the immediate vicinity of the plug. Under test the sphere was supplied with electrical energy at a constant rate and the sphere allowed to reach thermal equilibrium in the cooling air stream. The plug heater was then supplied with electrical energy and its temperature adjusted to that of the sphere thermocouple. All the heat supplied to the plug therefore had to escape *via* its surface exposed to the airstream. This heat transfer measured over the plug surface was taken as local value since its surface area was some 1/450 of the total surface of the sphere.

Copper/constantan thermocouples with mechanical thermojunctions were used. A slug of copper was caused to flow around a clean mechanically twisted contact of copper and constantan.

It was felt that this method of forming the junctions was superior to that of soldering or welding with regard to extraneous e.m.f.s. which had to be avoided owing to the low temperature differences measured.

I.20. *Physical Measurements in Gas Dynamics and Combustion.*

Section D, Temperature Measurements P. 167, Series – *High Speed Aerodynamics and Jet Propulsion*, Volume IX, publishers—Oxford University Press.

This volume, number nine of a series of twelve, contains a useful section on temperature measurements applicable to gas dynamics and combustion.

The subject is dealt with in several sections:

1. *Wall Temperature Determination.*

The principles of wall-temperature measurements are briefly dealt with. Several methods of measuring wall temperatures are then described: (a) *Thermocouples.* The simple method of soldering a small plate into the surface and attaching the thermocouples to the centre of the plate is described and several other methods including film thermocouples and a heated thermocouple-junction technique are mentioned. (b) *Infra red radiation.* Several experimental methods are described in the literature for this section. The lead-sulphide photoconductive cell is described and curves showing the spectral sensitivity of this cell and the detectable temperature change *versus* source temperature are given together with an experimental arrangement for temperature measurements. The accuracy of infra-red techniques is also dealt with. (c) *Phosphor luminescence.* The properties of super-linear phosphors are discussed. Surface temperatures from room temperature to 200°C are considered. A number of phosphors having the strongest temperature dependence are listed. Thermography is also dealt with. (d) *Applications.* Two applications of wall-temperature measurement are discussed in more detail: 1. The determination of temperature recovery factors, and 2. The determination of heat-transfer coefficients. Reference is made to Volume V, Section F. of this series for the physical principle and theoretical aspect of aerodynamic, heating and high-speed heat transfer. Several interesting photographs relevant to temperature measurement are given. Twenty-seven references on wall-temperature determination are cited.

2. *Shielded Thermocouples.*

This section deals with the temperature measurement of moving gases. (a) The theoretical considerations are briefly dealt with together with the temperature-sensing element, radiation shields, vent holes and the shape of the probe. (b) The influence of conduction and radiation is dealt with. Formulae to enable these errors to be calculated are given. (c) The design of temperature probes is dealt with in detail. Details and drawings of seven different types of temperature probe are given. Useful curves of recovery factor *versus* air velocity are given for several of these. (b) Miscellaneous temperature measuring devices are mentioned such as thermocouple wires in perpendicular flow, vortex thermometers, hot-wire resistance thermometers etc. Eighteen applicable references are cited.

3. *Temperature Measurement by Sound-Velocity Methods.*

A few methods are mentioned in this brief section and a total of five references are given.

I.21. *The Equilibrium-Temperature Probe, a Device for Measuring Temperatures in Hypersonic Boundary Layers.*

Danberg, J. E., *U.S. Naval Ordnance Laboratory*, NO L.T.R. 61–2, December, 1961.

The equilibrium-temperature probe is essentially a sharp-angled cone made from low-emissivity metal and supported by a thermal insulator. A thermocouple is installed to measure the cone temperature. The cone is held with its axis parallel to the flow. Ideally, the indicated temperature is the adiabatic wall temperature, a property of the flow which when combined with other more easily obtained properties (Mach number and cone geometry) and established relationships (cone flow and laminar recovery factor) provides sufficient information to determine the total temperature of the flow.

The design of the probe is discussed and a sketch showing the dimensions of an experimental probe is given. The cone tip is 1·168 cms. long, 10° included angle and made of stainless steel. The theoretical considerations and the calibration procedure is discussed, account being taken of the conduction and radiation errors. Some experimental results are presented and a comparison is made with a conventional total-temperature probe.

It is concluded that the equilibrium temperature probe can be made very small without excessive conduction and radiation effects. This is claimed to be the main advantage obtained from using the equilibrium-temperature probe over the conventional total-temperature probe. In addition, the conical configuration minimizes the probes interference with the flow.

I.22. *Instrument for Measuring the Wall Shearing Stress of Turbulent Boundary Layers.*

Ludwieg, H., *NACA. TM* 1284, May 1950.

This report describes a method by which the shear-stress measurement is reduced to a heat-transfer measurement. It is shown that the velocity profile on a smooth wall in a turbulent boundary layer is dependent only on the shear stress transmitted to the wall, apart from the material constants of the flowing medium, even with pressure gradients.

Theoretical considerations are presented to show that the wall shear stress can be defined by means of a heat-transfer measurement with a suitable instrument mounted in the wall.

Such an instrument is described. A copper block (2mm. × 9mm. × 6mm.) was cemented to a celluloid diaphragm 1/10 mm. thick and inserted into a brass casing insulated from it by the surrounding layers of air. The unit was set into the wall with the celluloid film flush. The copper block carried a 0·13 watt electric heater and its temperature was measured by a thermocouple located near the heat-transfer surface. The element had a higher temperature than that of the flowing medium.

The method of shear-stress measurement and the determination of the calibration curve are described. The calibration tests were based on friction coefficients computed from Schultz-Grunow test data. A measurement of the heat flow per unit time and the temperature difference, $(T_w - T_\infty)$ were found and a Nusselt number was plotted against a function of the shear stress. A straight line relationship was obtained which did not pass through the origin due to the insulation heat loss of the element.

The directional sensitivity of the instrument and the measurement of the direction of the shear stress is discussed and the directional sensitivity curve is presented.

I.23. *A Radioactive Krypton Diffusion Technique for Temperature Mapping of Turbine Blade Surfaces.*

Wisnieff, S. F. and Bardach, H., *S.A.E.* Paper 650704, October 1965.

When a kryptonated material is heated at a specific temperature for a period of time the activity decreases, exponentially approaching a limiting value. If it is reheated in an inert atmosphere there will be no significant activity losses until the reheating temperature rises above the previous maximum temperature. Krypton was chosen because it has a 10·6 year half life, weak beta emmissions and is chemically inert. The krypton can be introduced into the metal by ion bombardment 2–5 kev. or by forcibly diffusing the 5% kr. 85, 95% kr. 84 mixture into the metal in a pressure vessel held at 600°C, 1000 p.s.i. for 48 hours.

Two methods of determining the temperatures are discussed. In the 'Residual Counting Method', the material is reheated in a stepwise fashion and the activity counted after each heating. A curve of activity against temperature shows two distinct slopes with the intersection giving the previous maximum temperature. In the 'Gas Evolution Method' the tested blade is cut into several sections, each section is tack welded to a thermocouple and placed in a Lindberg furnace. The reheating can be linearly programmed and the activity is counted by using argon as a carrier gas from the furnace to the counter. A curve of activity against temperature shows a sharp increase in activity at the previous maximum temperature.

A brief description of the krypton release mechanism is given. The paper concludes that the effectiveness of the methods depends primarily upon the activity of the blade after engine testing and upon the sensitivity of the counting system used during the subsequent reheating process. The amount of initial activity diffused into the component is also important.

The accuracy of surface-temperature estimation is given as ±20°F for temperatures as high as 1800°F.

I.24. *Kryptonates – KR 85 Becomes a Universal Tracer.*

Chleck, D., Maehl, R. and Cucchiara, O., *Nucleonics* 21 7, pp. 53–5, July, 1965.

'Kryptonates' is the term given to any solids in which krypton can be stably incorporated and any solid can now be converted to a radioactive source with Kr. 85 as the radioisotope. These include alloys, inorganic compounds, glasses, rubbers, proteins and plastics. The advantages of krypton 85 are given as a 10·6 year half life and 0·7 mev. beta radiation with very little gamma. Safety problems are minor since it is chemically inert and diffuses rapidly into the atmosphere when released.

The two methods of impregnating krypton into a material given are those given in the previous reference, only they are given here in more detail. The preparation of kryptonates is discussed and it is shown that the amount of gas collected by any solid through the more versatile diffusion process has an exponential dependence on temperature, a linear pressure dependence and a square-root dependence on time. The ratios of krypton used were as in the previous reference 5 % kr. 85 to 95 % kr. 84. A higher concentration of kr. 85 would make specific activities of hundreds of curies/gm. feasible.

Some of the properties of kryptonates are briefly discussed, depth of penetration, stability, etc.

The applications upon which work is being carried out are detection and measurement of reactive gases, detection and analysis of species in solution, chemical kinetics studies, surface-temperature measurements and friction and wear studies.

I.25. *Methods for Measuring Temperatures of Thin-walled Gas-turbine Blades.*

Stepka, F. S., Hickel, R. O., Lewis Flight Propul. Lab., *NACA* RM, E 56, G 17. [*NACA/TIL* 5165(21)], November 1956.

The accuracy and durability of two means of measuring metal temperatures of thin walls of air-cooled turbine blades (< 0·040 inches) in a turbo jet engine are presented.

The methods are cemented thermocouples and temperature-indicating paints. Both methods were subjected to a gas temperature of 1650°F and an engine speed of 11 500 r.p.m. subjecting the thermocouple junctions to a force of 42 000 g.

In the first method, 0·005 inch Chromel-Alumel wires were cemented in (a) a single groove 0·008 × 0·010 inch with ceramic cements. The grooves were electrolytically etched in a phosphoric/hydrochloric solution. Their readings were compared to reference thermocouple installations that have been used in the past by NACA (0·040 inch O.D. Inconel sheathed, chromel/Alumel wire). The agreement was good, about ±5°F with a maximum deviation of ±15°F over most of the speed range, and of the various methods of cementing thermocouples investigated, no one method was better than any other. The durability of the cemented thermocouples was good, 47 of 55 were operated in the engine without failure for 2–30 hours, with an average of 12 hours each, eight thermocouples failed mechanically.

The paints did no more than indicate temperature distributions with an average temperature indication 50°F below the reference thermocouple. They could not be subjected to more than 15 minutes of engine operation. The paper concludes that the paints were neither as accurate nor as durable as the cemented thermocouples.

I.26. *Temperature Measurements at High Temperatures and High Speeds – a Literature Survey.*

Ogale, V. A. and Van Montfoort, A. J. M. S., *Technische Hogeschool Delft*, Report No. 10. M003, August 1965.

A survey is made of the possible methods of temperature measurement for the high speeds and high temperatures encountered in a cooled gas turbine project. High temperatures and high speeds in this survey are taken as blade temperatures 300 – 900°C (gas temperatures up to about 1200) and circumferential speeds of the order of 500–800 ft/second.

The possible methods of measuring temperatures surveyed are:

1. Indirect measurements; temperature-sensitive paints, fusible plugs, hardness tests.
2. Pyrometers, optical and radiation.
3. Thermocouples.

These methods are reviewed in the light of their accuracy, stability, characteristics, simplicity (mechanical), size and weight, useable life and their safety in operation.

Indirect methods and pyrometers are dealt with only briefly. Most attention has been paid to installations with thermocouples and copper, silver or other metal sliprings and brushes as these methods have been used and are still in use in many applications and give satisfactory results.

Several methods of transmitting the thermocouple signals are discussed; these are: the inductive method, mercury sliprings, metal sliprings, (sub sections are – mechanical properties of materials, choice of brush and slipring material, transition resistance, influence of thermovoltages and noise). Various investigations into slipring methods and constructions are described.

The problems arising with the fixing of the thermocouples to the turbine blades are briefly discussed.

The paper concludes that thermocouples combined with silver-morganite sliprings and silver graphite brushes would be the most suitable for their cooled gas turbine project. The thermocouples being kept as small as possible, to minimize centrifugal forces.

I.27. *Method of measuring thermal diffusivity and specific heat of an ablating body.*

Kendall, J. M., *Navord* Report 5771, Aeroballistics Research Report, No. 23, AD 267655, July 1961.

A method is presented for measuring the thermal properties of a material as functions of temperature. The heat capacity per unit volume $\rho\, c(T)$ (ρ = density, c = specific heat) is determined by measuring the temperature rise of an adiabatically heated sample. Adiabatic conditions are produced by employing uniformly distributed heat sources in a model composed of the material. The thermal conductivity $K(T)$ and the thermal diffusivity $\alpha(T)$ are determined by combining the results of this measurement with an ablation test on a bar of the material. An oxyacetylene torch was found capable of producing a rate of ablation of 0·02 cm/second for a Melamine-bound glass-cloth laminate. A one-dimensional steady-state thermal layer is quickly established. The following formula is obtained for the thermal diffusivity:

$$\alpha(T) = \frac{K(T)}{\rho c(T)} = \frac{\left(u^2 / \frac{dT}{dt} \cdot q(T)\right)}{\frac{dq}{dT}}$$

In this equation u^2 and $\frac{dT}{dt}$ are determined from the ablation test. u is the rate of ablation of the bar in cm/sec, $\frac{dT}{dt}$ is the rate of temperature rise in °C/seconds, recorded by a thermocouple mounted in the bar. $q(T)$ and $\frac{dq}{dT}$ are obtained from the heat capacity measurement. $q(T)$ is the heat absorbed per unit volume, as a function of temperature, in cal/cm^3, and $\frac{dq}{dT} = \rho\, c(T)$ is the heat absorbed per cm^3/°C temperature rise. A method is also decribed for obtaining an effective value of the thermal diffusivity from the ablation test alone.

Measured values of the thermal conductivity, diffusivity and specific heat of a Melamine-bound glass cloth laminate are presented over a range of temperatures up to 1000°C. In models made from resin-bound fibres, irreversible endothermic reactions occur which effectively increase the specific heat. The values of the thermal properties which were found therefore hold only for montonically rising temperatures. The thermal diffusivity of the material tested was found to range from about 0·002 to 0·0002 cm^2/second, and was strongly dependent on the orientation of the fibres in relation to the direction of heat flow.

Since this report was published, a facility has been developed at the above laboratory which employs the methods described here.

I.28. *Heat-flow Meters for Industrial Furnaces.*

Haupin, W. E., *Inst. Soc. of America*, Preprint No. 16, 7th April, 1964.

Specialized heat-flow meters developed for industrial furnaces are decribed. One designed for insertion into powdered or granular insulation, consisted of a thermocouple embedded in a refractory disc having the same thermal conductivity as the insulation it displaced. Another for measuring the heat flow through a steel plate with surfaces ranging from 200 to 450°F consisted of a steel plug containing a differential thermocouple. The third type, for surface measurement, consisted of a porcelain enamel bonded sandwich of synthetic mica and steel containing five parallel connected iron-constantan differential thermocouples. Calibration and correction, when needed, for the added thermal resistance of the transducer, contact resistance, and differences in surface emissivity are described. Reasons are given for the rejection of certain transducers tested.

I.29. *A Discussion of the Standard Procedure for Calibrating Heat-flux Transducers.*

Rall, D. L. and Stempel, F. C., *Inst. Soc. of America*, Preprint No. 16, 7th January 1964.

Several methods have been employed in the past in attempts to establish a standard for calibrating heat-flux transducers. These may be summarized as 1. Radiant methods, 2. Convective methods, 3. Conductive methods, 4. Miscellaneous methods (arc imaging and water-flow calorimeters). These methods are discussed and it is concluded that the most practical and useful system for establishing a reliable, reproducible and transferrable heat-flux standard traceable to N.B.S. for organizations working in the field of heat-flux measurement. The use of a transfer standard calorimeter calibrated in the black-body cavity, together with a grey-body graphite block, establishes a simple, convenient system for accurately calibrating calorimeters and radiometers on a production basis. Such a system can also be used for various controlled-heating studies and thermal-materials investigations.

I.30. *Errors in High-temperature Probes for Gases.*

Moffatt, E. M., *A.S.M.E.* Paper No. 48–A–52, December 1948.

This paper sums up the theoretical background for calculating temperature-probe errors and discusses uncertainties in the theory. These results are applied to analysing some typical errors incurred with temperature probes in high-temperature gas streams. The errors are calculated for several different types of probe which can be divided roughly into two classes; simple bare probes and shielded probes. The former type are known to be subject to large errors at high temperatures and their readings are frequently corrected theoretically. Errors in the corrected as well as the uncorrected readings are discussed. The shielded types are commonly used without any corrections and some probable errors in these uncorrected readings are calculated. The emphasis is on probable errors inherent in 'corrected' as well as uncorrected temperatures with existing instrumentation.

I.31. *Measurements in Industrial Flames.*

Brand, Y. and Mineur, J. M., Doc. nr.K 20/A/38, *International Flame Research Foundation*, Ijmuiden, October 31st 1966.

This report presents the methods and principles of some instruments for making measurements in industrial flames. The report contains some 33 useful sketches and diagrams of the instruments.

The positioning of cooled probes is first discussed together with furnace control in general.

Temperature measurements with suction pyrometers are described under the headings of: Principle, Efficiency, Normal pyrometers, Miniature pyrometers and multiple pyrometers to measure near the hearth.

Velocity measurements with Pranotte and various other tubes are discussed together with the main causes of errors. The analysis of gases and solids is dealt with in detail.

A section on heat transfer discusses:

1. Radiation measurements in flames.
2. Heat exchange at a charge or wall; subsections are:
    - (i) Ellipsoidal radiometers,
    - (ii) Total-heat flux meters,
    - (iii) Water-calorimeters,
    - (iv) Analysis of results.
3. Black-body calibration furnace.

A small bibliography is included.

I.32. *Heat Meters and Heat Metering.*

Sparham, G. A., *The British Coal Utilisation Research Association*, Monthly Bulletin, Vol. XXX, No. 10, Review No. 256, October, 1966.

This review is concerned primarily with the metering of heat used for domestic and industrial space heating. The applications of such a meter are discussed mainly with regard to group central-heating systems.

The requirements of a heat meter are discussed and then several methods of metering are described. These methods are divided into three groups:

(A) True B.T.U. meters. These register heat consumption in heat units and have been subdivided into:

1. Direct multiplication meters, which obtain a product of a flow measurement and a temperature difference between flow and return.
2. Indirect multiplication meters; these attempt to obtain the product above without an integrating mechanism. Two types are described, the short meter, and the BCURA heat meter.
3. Simplified multiplication meters. The flow temperature or the water flow rate must be kept constant.

(B) Proportioning devices. These proportion the heat used by a group of dwellings and are based upon an assumed radiator heat emission. Those described are: 1. Evaporative-type meters, 2. Creep meters, 3. Thermo-electrical meters, 4. Electrical portioning meters.

(C) Other metering methods: 1. Water flow measurement only, 2. Inferential metering, (i) Fan-blown warm air, (ii) Thermo-control system, (iii) Metering system with on-off control of radiators.

I.33. *Temperature Measurements.*

British Standard Code B.S. 1041.

This temperature measurement code deals in a general manner with nearly all methods of measuring temperature. Although many of the methods are dealt with very briefly, (thermocouples are dealt with very cursorily in Part 4) much useful data is presented and a small section is included on heat-flow instruments.

This code is at present being revised and will be issued in separate parts. B.S.1041, Part 3 1960, *Industrial Electrical Thermometers*, is available.

The code is divided into several sections:

Part 1. *General.* Temperature scales, technical temperature measurements, classification of methods, choice of methods, sources of error and precautions to be taken (Introduction, liquid expansion thermometers, thermocouples, radiation pyrometers).

Part 2. *Expansion Thermometers.* Solid expansion and differential thermometers, liquid expansion thermometers, constant-volume gas expansion dial-type transmitting thermometers, vapour-pressure thermometers.

Part 3. *Electrical resistance thermometers.*

Part 4. *Thermocouples.*

Part 5. Radiation pyrometers. Optical pyrometers, total-radiation pyrometers, light sensitive cell pyrometers.

Part 6. Electrical and other auxiliary instruments used in temperature measurement. Instruments for thermocouples, for resistance thermometers, for radiation pyrometers, optical pyrometers, and photoelectric pyrometers.

Part 7. Change of state of testing body. Principle of the method, Seger cones, Watkin heat recorders, Holdcroft thermoscope bars, Bullers rings, temperature indicating paints.

Part 8. Calorimetric measurement of temperature.

Part 9. Temperature in the interior of solids. Good conductors, bad conductors, fuel beds.

Part 10. Surface of solids. Contact methods, radiation methods.

Part 11. Liquids. Sub-division of the problem, flow in pipes, stationary liquids.

Part 12. Gases. Contact methods, radiation methods, special problems.

Part 13. Calibration and testing.

Appendices. A. Heat-flow instruments. B. Temperature conversion and fourth power tables. A small bibliography is included.

II. *Thermocouples.*

II.1. *Thermocouple Calibration.*

Anon., N.B.S. *Technical News Bulletin*, pp. 44–48, March 1961.

This paper describes the N.B.S. procedure for the calibration of thermocouples. Information is given in both tabular form and in the text. Thermocouples and thermocouple wires are calibrated over the range −190°C to 1100°C.

The types of thermocouples described are chromel-alomel (−190 to 1100°C), iron constantan (−190 to 300°C) and two types of platinum *versus* platinum-rhodium (0 to 1450°C).

Base-metal thermocouples are compared with a platinum resistance thermometer over the range −190 to 538°C. They are also compared with a standard platinum *versus* platinum 10% rhodium thermocouple. Platinum thermocouples are compared with the standard thermocouple or if greater accuracy is required, they are checked at fixed points on the International Practical Temperature Scale. The points used in the calibrations are the freezing points of gold (1063°C), silver (960·8°C), antimony (630·5°C) and zinc (419·5°C). The antimony point being the limit of the International Practical Temperature Scale.

Comparison measurements between 0 and 538°C are made in water, oil and liquid tin baths, 538°C being the limit of the liquid bath technique.

II.2. *Methods of Testing Thermocouples and Thermocouple Materials.*

Roeser, W. F. and Lonberger, S. T., N.B.S. *Circular 590*, February 1958.

This report describes the more important methods of testing and calibrating thermocouples and thermocouple materials and points out certain precautions that must be observed to secure reliable results. In particular, the methods that have been developed and used at the National Bureau of Standards are outlined in detail, and some guidance is given to the reader in the selection of the method best adapted to a given set of conditions. The essential features of many of the methods and much of the apparatus described in this report have been devised and described in whole or in part by various writers and reference is made to their papers when it is felt that a more detailed description will be helpful to the reader. A total of 25 references is given.

It would appear to be more helpful to list the various sections and subsections dealt with rather than briefly to summarise the various methods. Consideration is given primarily to the calibration of platinum/platinum-rhodium, copper-constantan, chromel-alomel, and iron-constantan thermocouples.

The work is listed under the following sections: 1. Introduction, 2. General considerations, (a) Temperature scale, (b) General methods, (c) Homogeneity, (d) Annealing, (e) Instruments, 3. Calibration at fixed points, (a) Freezing points (protection tubes, depth of immersion, reference-junction temperature control, purity of freezing-point samples, crucibles, furnaces, procedure), (b) Melting points, (c) Boiling points (water, sulphur benzophenone and naphthalene, oxygen, carbon-dioxide point), 4. Calibration by comparison methods, (a) Platinum *versus* platinum-rhodium thermocouples, (b) Base-metal thermocouples in laboratory furnaces, (c) Thermocouples in fixed installations, (d) Thermocouples in stirred-liquid baths, 5. Methods of interpolating between calibration points. (a) Platinum *versus* platinum-rhodium thermocouples, (b) Copper-constantan thermocouples, (c) Chromel-alomel thermocouples, (d) Iron-constantan thermocouples, 6. Reference junction corrections, 7. Testing of thermocouple materials, (a) Platinum, (b) Platinum-rhodium alloy, (c) Base-metal thermocouple materials at high and low temperatures, (d) Reference-junction corrections, 8. Accuracies obtainable.

II.3. *Calibrating Thermocouples.*

Roeser, W. F., *Instruments and Control Systems*, pp. 706–7, Volume 33, May, 1960.

This article is abstracted from N.B.S. Circ. 590, 'Methods of Testing thermocouples and thermocouple materials', by W. F. Roeser and S. T. Lonberger (II.2). It describes briefly the calibration services provided by the N.B.S. The application of the method of calibrating thermocouples at fixed points is described.

A table is given showing the temperature ranges, calibration points and the accuracy at observed points for four types of thermocouple: chromel-alomel, iron-constantan, copper-constantan and platinum/platinum-rhodium (either 10 or 13% rhodium).

A second table is given showing the fixed points available for calibrating thermocouples. This table also contains expressions for temperatures of equilibrium as functions of the pressure between 680 and 780 m.m. of mercury.

II.4. *Effect of Uncertainties in Thermocouple Location on Computing Surface-heat Flux.*

Chin, J. H., *A.R.S. Journal*, p. 273–4, Volume 32 No. 2, February, 1962.

This paper concerns the measurement of surface-heat flux from temperature-time data obtained by thermocouples located at a small distance from the surface of the body.

A mathematical analysis is given of a one-dimensional slab with one face insulated to estimate the effect of uncertainties in the thermocouple location. Parametric results are given for a measured cosine heat pulse of various durations. The paper gives as an example the maximum heat flux uncertainty for a 1·1 inch thick beryllium slab ($\alpha = 2{\cdot}38 \times 10^{-4}$ ft^2/sec.) with a cosine heat-pulse period of 40 seconds as measured by a thermocouple located 0·1 inch from the surface. This is about 0·0165 Qp per 0·010 inch of uncertainty in the thermocouple depth (where Qp is the peak heat flux). This uncertainty is not very large but curves are given showing that if the thermal diffusivity or the heat-pulse duration is small, the uncertainties in the surface-heat flux may become significant.

II.5. *Utilisation of Thermocouples at Heat-transfer Gauges.*

Marlow, W. C., General Research in Flight Sciences, Volume III, Fluid Mechanics, *Lockheed Missile and Space Division* T.R.L.M.S.D. – 48381, pp. 179–86, January, 1959.

This paper presents the results of a preliminary investigation, theoretical and experimenta, into the use of thermocouples as thick-film temperature gauges for shock-tube instrumentation.

The thermocouple measures the heat-transfer rate directly by using a half-embedded thermocouple as a calorimeter. A simple expression is given in which the heat-transfer rate varies directly with the rate of increase in temperature of the junction.

The experimental results agree well with the theoretical predictions and the paper concludes that these thick-film thermocouples may be used to advantage for high heat-transfer rates, and that their ruggedness allows strong shocks to be run repeatedly on the same thermocouple.

II.6. *Welding a Thermocouple Junction.*

Moeller, C. E., *Instruments and Control Systems*, p. 895, June, 1959.

This short article describes how 0·010 in. diameter platinum – 10% rhodium wires were welded to a platinum sheet to form thermocouples. The sheet provided one arm of the thermocouple, the wire the other.

So that welding parameters could be evaluated a method was developed for standardizing the head on the wire before contact welding. This method is briefly discussed. The welds were evaluated by microscopic examination of the sectioned and etched welded joints.

Extraordinary reproducibility for the technique is reported. Very few details are given in the article and no references are given.

II.7. *Two Simple Methods for Spot-welding Wires.*

Radcliffe, S. V. and White, J. S., *Journal Sci. Inst.*, pp. 363–364, Volume 38, September, 1961.

The techniques described in this paper were initially developed to permit the use of small-diameter wire-specimen materials for studies of solid-state transformations in steels. Accurately positioned potential leads were welded to the steel specimen wires. The specimens were 0·010 in. diameter and the leads were 0·002 in. diameter chromel wire.

Both methods of welding described are of the arc-discharge method. The first method described uses the arc formed by the discharge of a capacitor. A simple circuit diagram is given together with a micrograph of a weld formed by this technique.

A list of capacitors and charging voltages is given for a number of different wires.

The second method, that of fuse limited arc discharge welding was considered inferior to that of capacitor discharge welding and is dealt with very briefly.

II.8. *Welding Fine Thermocouple Wires to Large Metal Bodies.*

Colclough, C. D. and Smillie, J., *The Engineer*, pp. 696–698, November, 1959.

A portable welding unit is described which operates on the condenser discharge flash method and which was specially designed to attach fine-wire thermocouples to large metal bodies. In this method a charged bank of condensers is connected in series with the wire and the body to which it is to be welded. This portable set has the advantage that the wires can be accurately positioned by hand. A switching device is incorporated to initiate the weld and this reduces the tendency for violent flashes. Since the electrical energy required to melt the wire is proportional to the cross-sectional area of the wire the unit has an adjustable voltage and capacitance range so that it can be used for wires with diameters varying from 0·002 inch to 0·048 inch.

The most reliable and consistent results were obtained with wire diameters in the range 0·005 inch to 0·025 inch both with single wires and double wires with the thermocouple bead preformed. Outside this range the success of the weld depends largely on trial and error.

A full circuit diagram is given together with a table for chromel and alumel wires showing the capacitance and voltage requirements for various wire diameters. Photographs of the apparatus and of sections through two sample welds are given and a list of operating instructions is included in the appendix.

II.9. *Measurements of the Response of Various Thermocouple Arrangements.*

Irvine, F. H., Picken, J., and Greenwood, G. H., *R.A.E.* T.N. Aero 2959, N.L.L. 86783B, April, 1964.

This note presents some laboratory measurements of the response of chromel and alumel thermocouple arrangements currently used or proposed for free-flight investigations at R.A.E. These show that a thermocouple constructed by welding wires individually to a calorimeter wall is greatly superior to one which uses a pre-formed bead.

The material of the calorimeter wall and the diameter of the thermocouple wires may also be significant. A tentative empirical relationship describing the effect of these parameters is given.

To measure the response times, a short-duration pulse of electric current was passed through an element of conducting material representing a calorimeter wall, thus subjecting it to an approximate step-rise in temperature. Test thermocouples were welded to this element in various arrangements and their responses measured. The responses were interpreted as an effective displacement of the thermocouple junction from the calorimeter element.

The parameters examined were (a) Thermocouple constructions, (b) Insulation of the thermocouple wires, (c) Thermocouple wire diameter, (d) Calorimeter element material, and (e) Calorimeter element thickness. Of these (a), (c) and (d) were found to be significant; (a) appeared to have a dominant influence and a thermocouple junction consisting of two wires joined separately to the surface gives effective displacements (i.e. responses) of about 1/10 of those of bead thermocouples. To reduce effective displacements arising from (c) and (d) the thermocouple-wire diameter should be small and the thermal diffusivity of the calorimeter wall material large.

II.10. *The Use of Microthermocouples in the Investigation of Heat Exchange.*

Minashin, V. E. et al, *Voprosy Tablabmena* (Problems of heat exchange), 1ZV, Amm. SSSR Moscow, 1959.

By microthermocouples is meant, m.i.m.c. (mineral insulated metal covered) thermocouples of external diameters of 0·5 to 1 m.m. (0·020 – 0·040 inch) with thermoelectrode diameters from 0·07 m.m. to 0·15 m.m.

A brief list of the errors arising from sealing-in thermocouples is given. The method of welding thin thermocouple wires is then described in detail. A circuit diagram is given together with a photograph of the equipment. The method uses an arc which is formed by discharging a block of condensers between the thermoelectrodes to be welded and a metallic foil. The use of the foil has a beneficial effect on the quality of the weld. A number of welding conditions are presented.

The technique of preparing and sealing microthermocouples into the heat-transfer surface is then presented. The capillary end of the sheath is flattened for a length of 1 to 1·5 m.m. and is welded across the end together, with the thermoelectrode wires. The wires are laid in a groove, the junction is caulked into the surface and the groove filled by a metallizing unit. Two examples for the conditions of welding a thermocouple to a jacket are given.

A description is given of the technique of covering the thermoelectrode leads with heat resistant alundum insulation. The unit was designed to coat electrodes of copper, constanine, chromel, alomel, nichrome, platinum, etc. by immersing the wire in a suspension of alundum and then drying and baking the coating. This insulation is said to withstand severe bending and temperatures of 600°C and higher.

II.11. *Thermocouples: their Instrumentation, Selection and Use.*

Billing, B. F., *Inst. Eng. Inspection*, London, Monograph 64/1, 1964.

This paper deals in a general manner with all aspects of thermocouples.

The several sections of the paper are: Reference junctions, Current-sensitive measuring instruments, Potentiometric measuring instruments, D.C. amplifiers, Thermocouples and using the thermocouple. The section on thermocouples is subdivided into sections entitled Base metal, Rare metal, High temperature (properties in tabular form), Low temperature (a revised low temperature calibration is given for Ni.Chr./Ni.Al. thermocouples), and Mineral-insulated Metal-covered.

The first four sections above describe basic methods and give fairly elementary information.

The section on thermocouples is more specific; thermocouples are specified for different types of work and temperature limits. Data on calibration and linearity of the various types is given together with the appropriate B.S. numbers. The information is given more fully in tabular form in the appendices together with the appropriate references and makers trade names.

The appendices contain: 1. Standards of temperature, 2. Calibration equipment and methods, 3. E.m.f. of thermocouples, 4. Physical properties of thermocouple wires, 5. Thermal e.m.f.s. of some elements relative to platinum, 6. E.m.f.s. of thermocouples at very low temperatures, 7. Specifications and trade names for thermocouple materials (including manufacturers or publishers).

II.12. *Thermocouples: a Critical Survey.*

Billing, B. F., *R.A.E.* Tech. Note No. CPM.18, May, 1963.

This survey paper summarises data on commercially available thermocouples. Additional calibrations have been made at low temperatures to supplement or comment on existing data. Physical properties which are significant in the selection of thermocouple wires have been tabulated. The following are discussed, 1. Standards of temperature, 2. Calibration equipment and methods, 3. Base-metal thermocouples; (Nickel-chromium *versus* nickel-aluminium, Iron *vs.* constantan, copper *vs.* constantan, other combinations, variants of the nickel-chromium *vs.* nickel-aluminium thermocouple (BS 1827), stability of base-metal thermocouples), 4. Rare-metal thermocouples: (Platinum *vs.* 10% platinum and 13% rhodium, platinum-rhodium alloys for 1500 – 1890°C, high-output rare-metal thermocouples of pallador, platinel, 417, palladium *vs.* platinum – 15% iridium: iridium *vs.* iridium – rhodium, platinum – 8% gold *vs.* platinum – 2% ruthanium, stability of rare-metal thermocouples platinum and platinum-rhodium alloys, high-output alloys), 5. High temperature thermocouples: (iridium *vs.* iridium-rhodium, iridium *vs.* tungsten, tungsten *vs.* tungsten- 27% rhenium, tantalum and niobium, silicon carbide, graphite and tungsten), 6. Low-temperature thermocouples, 7. Mineral-insulated thermocouples, 8. Reference junctions: (Definition, reference-junction temperatures, preparation of the junction, ice for reference junctions), 9. Compensating cable.

The following tables are included:

1. E.m.f. (millivolts) of thermocouples, 2. Physical properties of thermocouple wires, 3. Platinum *vs.* platinum – 13% rhodium, 4. Nickel-chromium *vs.* nickel-aluminium, 5. Nickel-chromium *vs.* nickel-aluminium (corrected), 6. Properties of high-temperature thermocouples, 7. Thermal e.m.f.s. of some elements relative to platinum, 8. Thermal e.m.f.s. of some alloys relative to platinum, 9. Specifications and trade names for thermocouple materials, 10. E.m.f. (microvolts) of thermocouples at very low temperatures.

Illustrations given are:

Rate of change of output – microvolts per degree Celsius, calibrations of various Ni-Cr. *vs.* Ni-Al. thermocouple batches, calibration of some nickel alloys against platinum, resistance of wires.

II.13. *Vacuum-deposited Thin-film Thermocouples for Accurate Measurement of Substrate Surface Temperatures.*

Bullis, L. H., *J. Sci. Instruments*, *40* (12), pp. 592–3, December, 1963.

This paper shows that, under certain conditions, a more accurate measurement of the surface temperature of glass substrates, for deposition work, can be obtained by using thin-film copper-nickel thermocouples deposited directly on the surface of glass substrates than by using conventional wire-type thermocouples.

In the experiments, the temperature of a 1 inch square glass substrate was measured simultaneously by a copper-nickel thin-film thermocouple and by a copper-eureka wire thermocouple over the range 0 – 550°C. The wire thermocouple was clamped to the same glass surface as that supporting the thin-film thermocouple and copper and nickel wires 0·010 in diameter were attached to the copper and nickel films. The films were from 1500°A to 3000°A in thickness 1/16 inches wide and were deposited at right angles to each other giving a junction area 1/16 inch square.

When the substrate was heated from one direction and cooled from the other significant differences between the thermocouples occurred. At temperatures above 300°C the temperature of the thin-film thermocouple was always lower by as much as 25%, the difference increasing with substrate temperature.

It was considered evident that the temperature of the surface of a heated glass substrate could differ considerably from that of the substrate as a whole.

II.14. *Two Thermocouples Suitable for Measurement of Temperature up to* 2800°C.

Davis, D. A., *J. Sci. Instruments*37pp. 15–17, January, 1960.

The characteristics of two thermocouples are described. Tungsten/26% rhenium-tungsten and tantalum/26% rhenium-tungsten. A method of determining the e.m.f. of the couples to a temperature of 2800°C is given. In the temperature range 1000 – 2000°C the sensitivity of the tungsten/rhenium-tungsten couple is 16·2μ V/°C and that of the tantalum/rhenium-tungsten couple is 13·6μ V/°C.

The couples were heated by the passage of current and the temperatures determined by means of a modified disappearing-filament optical pyrometer.

The paper points out that the upper temperature limit of thermocouple operation is governed by the evaporation losses of the materials and the three metallic elements having the lowest vapour pressures and the highest melting points are tungsten (3380°C), rhenium (3167°C) and tantalum (3000°C). At 2750°K a 0·020 inch wire of 26% rhenium-tungsten alloy loses 0·2% material in 80 minutes. It has been shown that a fine alloy wire attached to a tungsten filament will maintain its calibration unchanged after one hour at 2750°K (experimental error ±20°C).

The paper concludes that the thermocouples would be suitable for use in a vacuum, hydrogen, nitrogen argon or any other inert atmosphere. They would not be suitable for use under oxidizing conditions or in the presence of hydrocarbon vapours, (which rapidly attack tungsten above 1000°C). The couples would require careful handling because of the brittleness induced by recrystallization.

II.15. *Application and Performance Data for Tungsten-Rhenium Alloy Thermocouples.*

Hall, F. H. and Spooner, N. F., Nat. Aero and Space Engineering and Manufacturing meeting, *S.A.E. 750C*, September, 1963.

Temperature measurement above 3000°F can usually be served by the two thermocouple combinations:
1. W/W – 26% Re, 2. W – 5% Re/W – 26% Re.

The status of this measurement at the time of writing is discussed.

The availability of these materials with respect to quantity and quality is discussed and a plot of e.m.f. deviation from a standard calibration curve against temperature for 13 production lots of W – 26% Re is given.

A discussion of field and fabrication problems and methods is presented. One problem is the limited ductility of W or W – 5 % Re wire. The insulation problem is also discussed and several precautions to be taken are outlined. Calibration hysteresis is also dealt with and plots are given of calibration shifts for bare wire and swaged W–Re alloy thermocouples.

The performance in a variety of applications of bare wire and swaged-construction thermocouples is evaluated and data are presented. The e.m.f. stability data available is summarized for protective atmosphere tests, for vacuum application and for sheathed units.

Two experimental thermocouples of the same type are mentioned and comparison is made between their calibrations.

II.16. *New Developments in Tungsten/Tungsten-Rhenium Thermocouples.*

Lachman, J. C., *Proc. Inst. Soc. of America 16* Paper No. 150–LA–61.

This very full and detailed report details the progress in the commercial development of W/W – 26 % Re thermocouples. Calibrated tungsten – 26 % rhenium wire is considered readily available in all standard sizes and commercial lengths for widely diversified practical applications. Even by random selection of wire from commercial lots it was found possible to meet a given calibration to 4200°F within ±1 %.

The results of an extensive test show excellent e.m.f. reproducibility for both tungsten and tungsten – 26 % rhenium wire of a given diameter. It is believed now that a standard calibration for W/W – 26 % Re thermocouples can be reproduced consistently within even closer accuracy tolerances by wire-lot screening and matching procedures. Since wire diameter was found to affect the e.m.f. reproducibility of tungsten at low temperatures it was necessary to determine e.m.f. departure as a function of wire size as well as wire lot in the selection of this material for thermoelements.

The thermal e.m.f. of both W/W – 26 % Re and W – 5 % Re/W – 26 % Re thermocouples was found to be very stable under thermal cycling after the wires were annealed by heating initially to 1600°C. The e.m.f. shifts observed at 800°C as a result of this heat treatment were 9°C for W/W026 % Re and 18°C for W – 5 % Re/″ – 26 % Re. Subsequent thermal cycling as high as 2300°C resulted in additional shifts of only 2°C and 7°C respectively for the two types of thermocouple. In respect to overall e.m.f. stability the thermocouple using the tungsten – 5 % rhenium alloy has an advantage in that this material remains ductile after annealing while tungsten becomes extremely brittle. Thus tungsten – 5 % rhenium thermocouple wire can be supplied by the wire manufacturer in the stabilized condition whereas tungsten must be conditioned after the thermocouples are fabricated and installed.

Drift characteristics for W/W – 26 % Re thermocouples were studied at both 1800°F and 4000°F in flowing argon. The changes in e.m.f. after 500 hours of uninterrupted operation at 1800°F and 100 hours at 4000°F were found to be insignificant and may have reflected test errors rather than drift.

A series of calibrations was performed and a final table of temperature-millivolt equivalents for W/W – 26 % Re thermocouples was adopted. This calibration was indicated to be the basis for future production of tungsten and tungsten – 26 % rhenium thermoelements. A tentative calibration was also established for W – 5 % Re/W – 26 % Re thermocouples.

II.17. *A Design Procedure for Thermocouple Probes.*

Haig, L. B., Paper No. 158C, S.A.E., Committee A.E.2., Physical Measurement Sensing, 1960.

A method of designing thermocouple probes is presented which, by using stagnation tubes, produces a suitable environment for measuring gas temperatures.

The errors in temperature measurement of this kind are discussed; these are velocity error, radiation error and conduction error. The equations and variables available to the designer are dealt with and precautions are outlined for use if calculations are made on the general procedure given. These precautions are that, 1. Error calculations must be made at the maximum and minimum condition of temperature, mass velocity and Mach number, 2. No dimensions should be assigned to the thermocouple or its envelope until that dimension is required for a numerical solution of an error equation, 3. If a dimension must be changed all errors must be recalculated.

An example of probe design procedure is given which was required for the determination of the efficiency of a single stage of an axial-flow gas-turbine compressor. In this application the temperature and mass velocity increased with Mach number. The maximum allowable error was set at 0·2°F and this was distributed as velocity error 0·1°F, radiation error 0·09°F and conduction error 0·01°F.

The considerations of envelope selection are discussed, this selection being determined by the most significant error.

Further improvements to the general design are also discussed.

This paper is part of a set of papers on temperature measurement by the physical Measurement Sensing Committee AE–2 of the S.A.E.

II.18. *Thermocouple-Research report for the Period November 1st, 1956 to October 31st, 1957, Progress Report I.*

McElroy, D. L., Oak Ride National Laboratory O.R.N.L.–2467 Instruments, March 1958.

This report describes the progress in fundamental thermocouple research at the University of Tennessee. Attention is focused on the nickel-base thermocouples (e.g. Chromel-Alumel) because these are almost universally used in the temperature range 500 – 1100°C.

A description is presented of the experimental equipment constructed and operated for (a) Thermocouple calibration, (b) Time-temperature studies of changes in thermal e.m.f., (c) Heat treating of wires. A brief literature survey, based on nearly 4000 references, has been included to summarize the large amount of information existing on thermocouple technology.

The following conclusions were drawn from the work.

1. Major variations in calibrations of individual thermocouples are caused by compositional variations in the alloys.
2. A mercury U-tube in the centre of a Dewar flask reduces the reference-junction error to less than 0·1°C.
3. The e.m.f. generated by a thermocouple is not influenced by the method of hot-junction preparation provided it has adequate electrical continuity and mechanical strength.
4. Large errors in thermal e.m.f. have been observed in thermocouples containing both mechanical and chemical inhomogenieties.
5. The recrystallization temperature for chromel is 1160°F for 70% cold work and for alumel it is 1100°F.
6. Microstructures show that chromel is extremely resistant to oxidation whereas alumel is not. Grain growth is evident when both are exposed for long times to high temperatures.
7. There is a drift in e.m.f. with time for chromel-alumel thermocouples in the range 500° to 1100°C.
8. Accurate calibrations performed on chromel and alumel wires indicate that the calibration on the first heating differs from that on cooling and from that on subsequent reheatings and coolings. Changing the depth of immersion of a thermocouple caused a change in calibration.

Treatments are suggested for available thermocouples to give improved performance.

II.19. *Thermal Properties of Thermocouples.*

Nanigian, J., *Instruments and Control Systems* 36(10) pp. 87–8, Index Aeronauticus 64–735, October 1963.

This article describes an experiment designed to evaluate the accuracy of temperature data obtained with thermocouples made from various materials.

The surface of the liner of a rocket nozzle was used to test the thermocouple reactions. During the test programme, comparisons were made using plastic and metallic thermocouple wells. Four thermocouples with identical design characteristics and thermal elements (Pt/Pt – 10%Rh) were used. The different thermocouple-well materials were: 1. Asbestos Phenolic (same as rocket-nozzle exit-cone liner, 2. Molybdenum sheath with asbestos phenolic at the sensing tip, 3. Stainless steel – type 310, 4. Commercial-grade molybdenum.

It was assumed that the asbestos-phenolic sensing tip recorded the true exit-cone surface temperature. The other thermocouples reached much lower temperatures during the first eight seconds. After this period, ablation of the surface caused these other thermocouples to record higher temperatures by varying amounts.

The article concludes that there is little advantage to metallic thermocouples when used to measure temperatures in non-metallic items, particularly when short time periods are involved. Only relative measurements will be obtained depending on the time duration and transducer thermal properties. Metallic thermocouple wells, because of their high conductivity act as heat sinks, in non-metallic test materials, and indicate lower than actual temperatures.

II.20. *Thermocouple Application for Ballistic Missiles.*

Paludan, C. T. N., *Missiles and Rockets*, October 1957.

The methods of obtaining accurate thermocouple measurements in missiles such as 'Restone' and 'Jupiter' are outlined. The thermocouple's insulation resistance is considered to give it an advantage over resistance type measurements at high temperatures.

Three primary problems are dealt with, 1. Low output, 2. Lead resistance and resistance change and, 3. The reference junction temperature.

The low output can be solved by using stable, high gain d.c. amplifiers. The change in lead-resistance error is reduced by avoiding long leads of thermocouple material. Copper extension leads can be used and the reference junction can be placed near the measuring junction.

The greater part of the article deals with the reference junction problem. In the systems described automatic or semi-automatic corrections are made for changes in ambient temperature. Higher than ambient temperature ovens have been used in the 'Restone' missile but were troublesome.

Two circuit diagrams are given, an early system and an improved version for use in 'Redstone' missiles. In these systems a resistance thermometer senses the reference junction temperature, operates into a deflection-type Wheatstone bridge which draws power from a mercury cell, and applies a correction across a ten-ohm load resistor which is in series with the overall thermocouple circuit.

The reference setting can be varied to give artificial reference temperatures at levels other than 0°C. The compensator circuit does not track the reference-thermocouple output perfectly, however, but it sufficiently accurate over a considerable span of ambient temperature.

The dependability of the whole system is largely a function of the stability of the mercury cells used.

II.21. *Effect of an Axial Cavity on the Temperature History of a Surface-heated Slab.*

Masters, J. I. and Stein, S., *Rev. Sci. Inst.* 27(12), December 1956.

A theoretical study is made of the surface of a front-heated slab in the presence of small holes drilled to within a fraction of a centimetre of the heated surface. In addition, equations and calculations are presented which yield an estimate of the error incurred when the surface temperature is measured by a transducer located at the end of such a hole.

In the absence of a practical exact solution to the problem, the method of attack chosen here leads to an upper bound on the additional surface temperature or hot spot caused by a cavity. The upper bound is justified because it is a close upper bound and, for cavity dimensions in the range of interest, the resulting hot spot is quite small. It is shown for interest, that a $\frac{1}{2}$ m.m. hole drilled to within 1 m.m. of the exposed surface will cause a time-variant surface hot spot that is no more than 1·5% of the surface temperature. If the hole depth is reduced to $\frac{1}{2}$ m.m., then the hot spot is less than 5·5% of the surface temperature.

An additional finding is that the magnitude of the hot spot is nearly independent of the temporal shape of the surface heat pulse for a large variance in the latter.

The authors are concerned only with transient results and do not show steady-state hot-spot temperature.

II.22. *Effect of Thermocouple Cavity on Heat Sink Temperature.*

Beck, J. V. and Hurwicz, H., *J. Heat Transfer* (*Trans. A.S.M.E.*), Volume 82, Series C No. 1, February 1960.

An analysis is made of problems associated with prediction of and correction for temperature disturbances created by thermocouples placed beneath and normal to the surface of a heat sink exposed to heat flux. The problem is similar to the determination of the temperature errors caused by an insulated cylindrical void near the surface since the effective thermal conductivity of the thermocouple is much lower than a heat sink material. Two of the important factors affecting temperature measurement are discussed: (a) The disturbance created by the thermocouple itself, 'hot spot' and (b) The fact that the thermocouple has to be placed at some distance from the heat-flux surface and thus not measuring the surface temperature.

The magnitude of the surface hot spot caused by the presence of the thermocouple is determined, and optimum location of the thermocouple is found where the undisturbed surface temperature may be read with least over-all error. The report gives analytical and machine analyses which investigate a comprehensive range of the important parameters. An important contribution of this investigation is the inclusion of *steady-state* as well as transient solutions.

A comparison is made with the transient results of Masters and Stein (II.21), a lack of agreement is apparent which was attributed to the analysis of the problem. Masters and Stein were concerned only with transient results and only with the upper bound of void effect. Solutions presented in this report give the actual hot-spot temperatures and other effects and show the upper and lower bounds.

The order of magnitude of the hot-spot error is shown to depend upon the sink material and the surface heat flux, the temperature increase being inversely proportional to the thermal conductivity.

II.23. *A Special Thermocouple for Measuring Transient Temperatures.*

Bendersky, D., *Mech. Eng.* 75(2), pp. 117–121, February 1953.

The special thermocouple described in this paper has a construction rugged enough to enable extremely rapid temperature changes to be measured in regions of high stress. It was developed for measuring gun-bore surface temperatures.

The thermocouple is constructed from a thick-walled steel probe tube, 0·090 inch diameter, inside which a nickel wire, 0·012 inch diameter is mounted. This nickel wire is electrically insulated from the steel tube by a coating of nickel oxide. One end of the probe is polished flush and coated with a thin layer of nickel 1 micron (0·000039 inch) thick. The interface between the nickel plating and the underlying end of the steel tubing is the plane at which the thermal e.m.f. is generated.

The fabrication of the thermocouple probe is explained in detail and photomicrographs are given which show the relative thicknesses of the nickel plating and the nickel oxide insulation.

The installation and recording equipment depends on the particular application but equipment for one application, that of a recoilless rifle, is described.

The characteristics of the thermocouple are briefly discussed. The time constant has been calculated to be of the order of $\frac{1}{4}$ microsecond and this rapid response is illustrated in a time-temperature oscillogram taken from the barrel of a recoilless rifle. The calibration of these steel-nickel thermocouples is described and a typical calibration curve is given.

The paper concludes that this thermocouple is particularly suited to the measurement of metal surface temperatures.

II.24. *Precision of Heat-transfer Measurements with Thermocouples Insulation Error.*

Mohun, W. A., *Canadian Journal of Research.* Volume 26, Sec. F, pp. 565–583, 1948.

A method is described for calculating the temperature variation in insulated thermocouple lead wires that do not follow an isothermal path. The difference between the temperature of the junction and that of the surrounding material that it purports to measure has been called 'insulation error'. This quantitative analysis should help investigators, not only to estimate the magnitude of errors that cannot be avoided but more particularly to choose experimental arrangements that will minimise these errors.

The problem is discussed in terms of a single insulated wire completely embedded in solid metal in a chordal hole in the tube wall. A table is given showing the temperature difference across a fine thermocouple lead for different heat fluxes and different tube metals.

A simple expression for the insulation temperature drop is first derived. The wire temperature equation is then found which defines the temperature of the wire metal at any point from the junction outwards. This equation is derived for a known ambient (metal wall) temperature curve. An approximate method of solving this equation is then presented. This is a simple incremental method, certain integrals being approximated by breaking them up into constituent increments along the length of the wire. In order to illustrate the calculation procedure more clearly the wire temperature has been calculated for three typical cases.

The calculations deal with only single wires but a procedure is given which allows calculations to be made for two wires having different values of '*k*' and diameter. This procedure shows that when the thermocouple wires differ greatly in conductivity, the temperature of the junction approaches very closely to that calculated for the better conductor alone.

A typical calculation shows that for a bare wire 0·010 inch diameter, No. 30 B and S with enamel insulation 0·00025 inch thick (installed in a chordal hole in a tube 0·500 inch deep with a heat flux giving a temperature gradient of 50°F/inch in the metal wall of the tube and an ambient temperature distribution varying from 0 to +1·5°F over the 0·500 length) the insulation error was 0·351°F. For insulation 0·001 inch thick this rose to 0·648°F.

It is concluded that experimenters should strive for a minimum of thermal insulation on thermocouple wires near the tip and that the path of the lead wires from the junction need only be isothermal for a certain 'critical distance' – an expression is given for this distance. Other factors that tend to reduce insulation error are small wire diameter and low specific conductivity of wire metal.

II.25. *Developments on High-temperature Thermocouples Using Noble Metals.*

Zysk, E. D., Instrument Practice *14*, No. 11, P.1205, November, 1960.

This article is a summary of a paper by E. D. Zysk, bearing the above title, which appeared in a publication issued by Engelhard Industries No. 1, Volume 1, which gives full details of this company's high-temperature thermocouples.

This summary indicates the scope of the original paper:

Revised temperature limits are presented:

Pt.95 % Rh. 5 %/Pt.80 % Rh. 20 %. 1700°C continuously or 1770°C intermittently.
Pt.94 % Rh. 6 %/Pt. 70 % Rh. 30 %. Just above 1700°C.
Pt.80 % Rh. 20 %/Pt. 60 % Rh. 40 %. 1800°C continuously or 1850°C intermittently.
Ir./Ir.-Rh. – 3 possible combinations are available. 2000°C continuously.
Ir/W. 2100° continuously.

A table is given which provides provisional reference figures for temperature-e.m.f. relations for the thermocouples. Only the main values are shown, every 100°C upwards from 1400°C whereas the main article gives values every 10°C upwards from 1400°C.

Work on other thermocouples is mentioned, such as W/Ir., W/W026 % Re, and W/Re. thermocouples.

The effect of atmospheres is discussed and attention is drawn to the difference in effects between still and moving atmospheres. The choice of thermocouple-pocket materials is also discussed. (*See* also 'Temperature its measurement, etc. . . . ', Volume III, Part 2, Dahl, A. I., p.135, also II.15.)

II.26. *Designing Thermocouples for Response Rate.*

Moffatt, R. J., *Trans. A.S.M.E.*, Volume 80, p. 257.

Experimental data has been analysed and the results presented as an empirical equation for the characteristic time in terms of the geometry of the probe and the flow conditions. This equation, it is claimed, predicts the characteristic time within 10 % for bare wire-loop-junction thermocouple from 0·016 to 0·051 in. diameter wire, mass velocities from 3 to 50 lb/sec. ft.^{2} and temperatures from 160 to 1600°F. All data taken at a static pressure of 1 atm.

A plot of the temperature-time record of the starting of a jet engine, taken with different thermocouple arrangements in different locations, is given to illustrate the problem and show that a transient temperature record must be corrected for the lag of the thermocouple.

Raw data from engine transients was corrected to yield the gas temperatures by the use of an equation obtained by equating the rate of heat addition to the rate at which heat is stored in the junction. This results in a definition of characteristic time given as: the number of degrees of lag per second per degree temperature change. However, the definition most useful in comparing probes for transient use is 'the time required to complete 63·2% of its response to a step change in gas temperature'.

The effect of total temperature, mass velocity and wire diameter on the characteristic time is examined in detail. The characteristic time decreases as the temperature goes up and also as the mass velocity goes up. It is proportional to the diameter of the wire to the 1·25 power.

Five common deviations causing error in the empirical equation were investigated, the first three were found to be significant:

1. Conduction from loop to stem. This was the most troublesome and is reduced by having a long junction. Experimental data is presented.
2. Weld bead size. Experimental data is given together with an empirical equation to approximate this effect.
3. Junction shape. The characteristic times of seven junction shapes are given.
4. Radiation from probe to walls. The most severe condition gave only a 10% error in the characteristic time (not to be confused with the error in the thermocouple signal). Data is given in tabular form.
5. Orientation of junction to the angle of the gas stream. Some experimental data is presented.

II.27. *Effect on the Static Strength of Aluminium-alloy test specimens of the Attachment of Thermocouples by a Welding Technique.*

Wright, D. F. and Acheson, G. F., *R.A.E.* Tech. Note Structures 345, January 1964.

This note records the results of tests made at the R.A.E. on five aluminium-alloy sheet materials – specifications L.71, L.72, DTD 686A and DTD 5070, to determine the effect on the strength, modulus and elongation values obtained from tensile tests when thermocouple wires are welded to the specimens. The above materials were chosen as being representative of those used in aircraft construction. Extracts from the specifications of the materials are given.

The thermocouple wires were welded independently to the surface of the test specimen ensuring that the junction was within the material under test. 100 test specimens were used for each of the alloys except L.72 where only 50 were used. Half the specimens had thermocouple wires attached, the other half did not.

The tests showed that the thermocouple welds had a negligible effect on the proof and ultimate stresses and on Young's modulus. There was, however, a marked tendency for the specimens to fail at the thermocouple welds with a considerable decrease in the elongation at fracture.

The paper concludes that the reduction of elongation and failure at the weld suggests that it would be prudent to avoid the welding method of thermocouple attachment for specimens where the measurement of elongation at fracture is required, and for specimens and structural parts subject to fatigue load, but this method is recommended for calibration of other temperature measuring devices, including thermocouples attached by other means. It is also mentioned that information from other sources suggests that for steels, the welding of thermocouple wires to test specimens has little or no effect on the position of fracture or the elongation.

II.28. *A Technique for Welding Thermocouples On and Below the Surface of Gun or Mortar Barrels.*

Newton, T. E. and Heal, J. W., *R.A.R.D.E.* Trials Memo, F1/14/65, September 1965.

The technique, developed in 1954 by the former Instrument Section of the Armament Design Establishment for welding thermocouples to gun barrels for gun calorimetry is described together with the apparatus designed to standardize the welding operation.

The thermocouples, measuring the temperature of different parts of a gun barrel against a time base during gunfire, were taken directly to sensitive recording galvanometers since all the heat pulses concerned took more than $\frac{1}{4}$ second to reach a peak value.

The first part of the report concerns the fixing of thermocouples for temperatures near the bore surface. For these temperatures radial holes (0·067 inch diameter for a three inch gun as described) were drilled side by side to within 0·2 inches of the bore surface. Iron and constantan wires of 19 S.W.G. (0·040 inch diameter) were welded to the base of these holes by an arc technique.

The development of the welding process is described in detail with a discussion of: (a) The thermocouple hole (special drills etc.) (b) Supply voltage (96 volts in this case), (c) Length of arc (lift of thermocouple wire in hole), (d) Arc times, (e) Welding current (this was found to be critical) and (f) Mechanical characteristics of the welding tool.

The welding apparatus is also described with full circuit diagrams and drawing presented. The welding procedure is given together with various precautions to be taken to obtain good results. The preparation of the holes, the thermocouple wires and insulators are included in this section.

Part 2 of the report concerns the fixing of thermocouple wires to the outer surface of a gun barrel. It was considered that this presented no great problem. The same method and materials as in Part I were used but using thinner wires (26 S.W.G.).

The preparation of the wires for welding is presented together with several illustrations of the technique. The iron and constantan wires were welded separately to the surface so that the thermocouple junctions were formed in the surface metal.

II.29. *Precision of Heat-transfer Measurements with Thermocouples – Geometric Errors.*

Mohon, W. A. and Peterson, W. S., *Canadian Chemistry and Process Industries*, October, 1947.

This paper describes a precision method of embedding thermocouples in a tube wall in order to measure its surface temperature. It also analyses the geometric errors involved in the measurement.

When the temperature indicated by a thermocouple junction corresponds to a point in the tube wall, the temperature difference between that point and the surface may be calculated from the known location of the junction, the thermal conductivity of the tube wall, and the measured heat flux.

A table of the maximum errors allowable in the thermocouple location for 1% error in the film coefficient is given which shows that high precision is required in locating the junction, especially when the film coefficient is high or the tube wall conductivity is low. For a steel tube (K at 400°F = 300 B.T.U./(hr.) (ft^2.) (°F/in.)) with a film coefficient of 4,000 B.T.U./(hr.) (ft^2.) (°F) the allowable error in thermocouple location for 1% error in film coefficient is given as 0·0008 inches.

The authors describe a technique for installing thermocouples in tube walls to within less than 0·005 inches and claim that the greatest gain to be made is by increasing the dependability of the method of gauging.

One of the authors (Mohon), has presented an analysis of the 'Insulation Error' present in thermocouple installation (II.24).

III. *Surface Temperatures.*

III.1. *Selection of Surface Thermometers for Measuring Heat Flux.*

Kurzrock, J. W., *Cornell Aero. Lab.*, CAL Report 124, February, 1963. (A.D. 404770).

Classical one-dimensional heat-conduction theory is applied to a finite slab in perfect thermal contact with a semi-infinite slab, for the constant heat flux case under transient heating conditions, to determine the operating limits of surface thermometers. The rate of heat transferred from the finite slab to the infinite slab is shown to be a function of two dimensionless parameters (the Fourier modulus and the thermal properties), which specify the operating range of thick- and thin-film surface thermometers. A surface thermometer is selected on the basis of these dimensionless parameters, the heat-flux range, the testing time, and output sensitivity. The thin-film surface thermometer records the instantaneous surface temperature of the mounting material from which the instantaneous heat flux can be calculated. The thick-film surface thermometer stores the heat in the film with negligible heat conduction to the mounting material. The instantaneous heat flux is determined from the slope of the temperature-time curve.

Experimental results of thin and thick-film surface thermometers are compared with solid conduction theory to indicate the effect of thermal contact resistance between the film and the mounting material, and to verify the theoretical film thickness. The results indicate that thick-film thermometers (calorimeters) can measure heat flux one or two orders of magnitude higher than thin-film thermometers for the same time interval. The thin-film thermometers are useful for measuring lower heat flux where high sensitivity is required.

A comparison of experimental heat-flux results using thin and thick-film thermometers indicated that the thin-film data was 15 to 40% below the thick-film data. This difference was postulated to be the use of thin-film thermometers with thicknesses of 1μ instead of the required thickness of $0{\cdot}1\mu$ or less.

The paper concludes that over-all accuracies of thin- and thick-film thermometers are proably ±5% to ±15% if the designer is careful in his surface-thermometer selection.

III.2. *Further Comments on Analogue Networks to Obtain Heat Flux from Surface-temperature Measurements.*

Meyer, R. F., *N.R.C. Canada* Aero. Report L.R.375, March, 1963, A.R.C. 22197.

The title implies reference to the author's earlier work, 'A heat-flux meter for use with thin-film surface thermometers', *N.R.C. Canada* Aero. Report L.R.279, April, 1960.

This report compares two electrical analogue networks which convert surface-temperature measurements from thin-film surface thermometers directly into heat flux.

In the relationship between heat flux $Q(t)$ and surface temperature $T(t)$ it is in general necessary to determine $Q(t)$ by numerical integration. Input data must be obtained by measurement of oscilloscope records and the process is long and tedious. In the electrical analogue described the analogue of the heat-conducting slab (the thin-film thermometer) is driven by a voltage proportional to $T(t)$, available directly from the thermometer and yields a signal proportional to $Q(t)$.

The electrical analogue is based on the observation that the governing equation for heat conduction in a semi-infinite solid, the thin-film thermometer, is identical to that for a semi-infinite electrical line with distributed series resistance and short capacitance.

$$\frac{\partial T}{\partial t} = \frac{k}{\rho s}\cdot\frac{\partial^2 T}{\partial x^2} \equiv \frac{\partial v}{\partial t} = \frac{1}{rc}\cdot\frac{\partial^2 v}{\partial x^2}$$

T = temperature
x = distance

v = voltage
r = resistance/unit length
c = capacity/unit length

The product of the resistance and capacitance is analogous to the thermal diffusivity, and the current in the system $I(t)$ is the analogue of the heat flux $Q(t)$. Complete simulation of the problem would require the line to be semi-infinite, but in practice it is found that lumped circuit elements approximate the problem well.

This report compares in detail the response of a filter Network (Skinner's) and a simple T-section advocated in the reference above. Two specific applications are considered and the report concludes that there is little to choose between the two networks, the simple T-section network giving only slightly better output.

III.3. *Transient Surface-temperature Measurements.*

Vidal, R. J., Symposium on measurement in unsteady flow, *A.S.M.E.* Hydraulic Division Conference, p. 90, May, 1962, also Cornell Aero Lab. Report 114, March, 1962.

This paper describes the recent developments in transient surface-temperature measurements and indicates the problem areas remaining. The fundamentals of surface thermometry for transient measurements are briefly reviewed, the construction and application of the thin film and thick-film calorimeter are described and the performance capabilities of each instrument are examined. The development of both techniques subsequent to 1958 are also described. Emphasis has been given to thin-film techniques but many apply directly to thick-film technology.

Regarding thin-film thermometers the primary problems encountered are:

1. Data reduction methods for determing heat-transfer rates. This problem has been solved to a certain extent by the use of analogue methods (*see* III.2). The calibration of the analogue circuit, however, becomes an important practical problem. Several plots are given comparing the heat-transfer rates from numerically integrated data with rates from electrical analogue circuits directly.

2. Gauge calibration techniques. (a) Calibration of the temperature coefficient of resistance for the metal film and (b) Calibration of the thermal properties of the mounting material. The refinements in technique have been aimed at eliminating inaccuracies from uncertainties in the gauge dimensions etc. and generally increasing the accuracy of (b).

3. Temperature effects on thermal properties. This is of no significance for small temperature changes but is important for those of the order of 100°C. Recent investigations made include temperature-dependent thermal properties in the conduction equations. The temperature effect on thermal conductivity dominates.

4. Applications of thin films in ionized media. In high-temperature air flows dissociation of the air causes the thin-film thermometer to be short circuited. Various methods are given which have proved useful in eliminating this effect. Other problems which arise in ionized media are also mentioned.

Regarding thick-film thermometers recent work has been devoted to new techniques and to applications in ionized media. Thermocouples as thick films are mentioned (*see* II.5) together with ceramic resistance elements and thermistors. Interest in this section is focused on piezo-electric materials which generate an electric charge proportional to temperature change. In the author's opinion these materials show the most promise in thick-film thermometry.

The problems of thick films in ionized media are virtually the same as those for thin films.

III.4. *Surface-temperature Measurement Errors.*

Malone, E. W., *I.E.E.E.Trans.* Aerospace A.S.–1 (1) U.S.A. p.15, February 1963.

Analytical and experimental methods of determing temperature-measurement errors are presented for typical installations. Measurement errors have been determined for a variety of sensor configurations. These are: Thermocouples attached to the surface by 1. Stalking, 2. Spot welding and 3. Bonding, and resistance thermometers bonded to the structure. The heat-flux-induced temperature errors were determined by a one-dimensional analysis and verified experimentally.

The test results provided comparisons between the temperature rise with time of two or more transducer configurations under identical heating conditions.

The effect of a partial short between thermocouple wires occurring near a thermocouple junction is dealt with. This error can be either positive or negative depending upon the temperature of the unknown junction. Experimental curves given for partial shorts show considerable errors.

The effect of exposed thermocouple wires is discussed. An equation is presented which relates the lengths of exposed wire to the induced-temperature error, it includes the effect of the wires being bonded to the front surface with a cement. This equation shows that the thickness of the cement should be minimized, the thermal conductivity should be as great as possible and the diameter of the wires kept small to reduce this error. Experimental results are given.

The effects of the thermocouple-junction geometry are evaluated for crossed thermocouple wires and individual wires spot welded to the surface. The experimental results support the analytical solution.

The effect of thermal impedance on bonded temperature sensors such as resistance thermometers and thermocouples is evaluated. Again agreement is claimed between calculated and experimental values of the error.

III.5. *A Survey of Techniques for Measuring Surface Temperatures.*

Watson, G. G., *N.E.L.* Report 153, June 1964.

This is a comprehensive and very useful survey of the surface-temperature measuring techniques for solid bodies.

Surface-temperature measurement is discussed in general giving an outline of the available techniques, thermocouples, resistance thermometers, radiation methods, etc. The various techniques are then dealt with in sections: (a) Unmounted sensors. Thermocouples, resistance thermometers and crayons, (b) Sensors mounted on the surface; thermocouples (installation, errors, film types), resistance thermometers (commercial types, film types), paints, papers and pellets, and contact thermography. (c) Sensors mounted below the surface. Thermocouples (installation, errors), resistance thermometers (embedded sensors, resistance of the body). (d) Radiation techniques. Optical pyrometry, radiation pyrometry, projection thermography, photographic techniques. (e) Other techniques. Electromagnetic effects, metallurgical techniques, miscellaneous techniques. (f) Special applications. Wall of a heat-transfer tube, Current-carrying bodies, unsteady temperatures, moving bodies, metal working.

An extensive bibliography is presented with 380 references listed.

III.6. *On the Error in Plug-type Calorimeters Caused by Surface-temperature 'Mismatch'.*

Westkaemper, J. C., *J. Aerospace Sci.*, p. 907, November, 1961.

The simplicity of measuring convective heat-transfer coefficients with plug-type calorimeters is reviewed. Apart from the insulation problem of the plug another source of error is due to surface-temperature mismatch. This short note examines the results of two treatments of the basic problem; one by Rebesin, M. W. 'The effect of an arbitrary surface-temperature variation along a flat plate on the convective heat transfer in an incompressible turbulent boundary layer', NACA TN 2345, April, 1951; the other by Reynolds, W. C., Kays, W. M. and Kline, S. J., 'Heat transfer in the turbulent incompressible boundary layer II – Step wall-temperature distribution'. NASA Memo 12–2–58W, December, 1958.

Rubesin's expression for the local heat-transfer coefficient of turbulent, incompressible flow with a step change in surface temperature is given. This was used to determine the ratio of the average heat-transfer coefficient which would prevail at the centre of the calorimeter if the plate were at a constant temperature. This relationship is given also.

Rubesin's expression, modified by Reynolds, Kays and Kline, is then presented which holds over a wider range of Reynolds numbers. A modified form of the average heat-transfer coefficient is then given and from this, several functions plotted by Rubesin are considered to be erroneously high. From plots of these revised functions and the modified form of the average heat-transfer coefficient the performance of a calorimeter may be determined for any set of test conditions. From a comparison of this modified form with the results of Rubesin it is considered that the latter predicts errors that are excessively large but that the original conclusion of Rubesin's is still valid.

This conclusion was that temperature mismatch can result in very large errors in calorimeter results.

III.7. *Errors in the Measurement of Transient Surface Temperatures.*

Yaryshev, N. A. and Makhnovetskiy, A. S., *W.P.–A.F.B. Translation*, October, 1961.

This analysis presents equations for the calculation of errors in the measurement of transient wall temperatures with a heat flux and medium temperature which change monotonically with time. The measuring devices used in the analysis were small resistance thermometers. The errors are calculated as a function of the heat-exchange conditions and the thermophysical properties of the gauge and the wall. On the basis of the solutions, with given accuracy and measurement conditions, the requirements for the design of gauges and their properties can be formulated.

The paper has five sections entitled:

1. Statement of the problem, in which the heat exchange equations are obtained for the gauge located on the heated side and on the medium side.
2. The temperature field in the wall.
3. The error due to non-uniform temperature distribution in the wall.
4. The error caused by a drop in temperature throughout the heat receiver.
5. Examples of error calculations.

An estimate of the errors, and also a calculation of the temperature distribution in the system can also be given in the case of sign-changing non-monotonic heat action, provided the basic assumptions of the theory are not invalidated (uniform temperature distribution throughout the wall, and rectilinear temperature distribution throughout the heat receiver).

The equations can be used to analyse a number of other problems, e.g. when studying the influence of insulation, heat capacity of thermal flux on the temperature régime of walls and the restricting designs of industrial objects, when studying the operation of thermometers in a transient heat-exchange régime.

III.8. *Recent Advances in Transient Surface-temperature Thermometry.*

Hall, I. G. and Hertzberg, A., *Jet Propulsion.* Volume 28, No. 11, 1958.

This article reviews the advances made in transient surface-temperature thermometry and calorimetry between the years 1953 – 1958.

Developments during this period were made largely in the field of shock-tube research and this review concentrates on two basic techniques successfully evolved for shock-tube heat-transfer measurements, these are thin-film surface thermometry and thick-film surface calorimetry. The former method records instantaneous surface temperature from which instantaneous heat-transfer rate is calculated. The latter method records total heat input at the surface and instantaneous heat-transfer rate is given by the corresponding time rate of change.

The thin-film resistance thermometer, given as the most successful is capable of 5% accuracy in measurement of surface temperature and heat-transfer rate and can have microsecond response. Current research is in ionized flows.

Some 38 references are given.

III.9. *Solution to some Problems of Wall-temperature Determination.*

Crabol, J., *Office National D'Etudes et de Recherches, Aérospatiales,* (France), Publ. 108, 1962.

This paper (in French) discusses the effect of various parameters on wall-temperature measurements by optical methods. These parameters are: the emissivity of the wall, the transmission of the media crossed by the radiation beam and the selectivity of the receiver. The measurement errors due to a lack of precise knowledge of the true values of these parameters are evaluated.

Several pyrometers designed and built for this study are described as are also the measurements carried out with these pyrometers.

A detailed analysis of each of the above points is presented, the results being expressed in graphical form wherever possible.

One of the experiments described in this lengthy report is a method of measuring the temperature of a gas-turbine blade with an infra-red pyrometer. The results show good agreement with the temperature as measured with a thermocouple in the range 600 – 800°C.

The report lists some 40 references.

III.10. *The Application of Surface-temperature Measurement Techniques to Thermal Insulators – A Literature Survey.*

Purslow, D., *R.A.E.* Tech. Note Structures 340.

This survey describes existing methods and techniques which might find application in the measurement of the surface temperature of thermal insulators under transient radiant-heat inputs.

These methods include:

1. Thermocouples. Portable thermocouples, wire thermocouples, film thermocouples and probe thermocouples. The errors associated with thermocouples are discussed.
2. Resistance thermometry. Wire resistance, film resistances and semi-conductor resistance thermometers. The errors associated with resistance thermometry are discussed.
3. Paints and thermography are dealt with briefly.
4. Radiation pyrometry. Optical pyrometers, total-radiation pyrometers (including thermoelectric types and resistance or thermistor bolometers) and photoelectric radiation pyrometers. The errors in radiation pyrometers are discussed.
5. Infra-red photography.
6. Other methods, work on extensometer and molecular beam techniques is mentioned.

A total of 140 references is given.

III.11. *Construction of a Thermocouple for Measuring Surface Temperatures.*

Ongkiehong, L. and Van Duijn, J., *Journal Sci. Instruments,* Volume 37, pp. 221–222, June, 1960.

The construction of a modified form of Bendersky's thermocouple (II.23), is briefly outlined.

A 1 m.m. hole is drilled through the wall and two bare thermocouple wires are inserted through (iron and constantan 0·25 m.m. diameter) and cemented in with heat-resistant 'Devcon' cement. After the cement has hardened, the protruding part is polished flush with the surface. The hot junction is then made by plating the wires and their immediate surroundings. The best results were obtained with an electroless nickel-plating process, a description is given of this process. The surface was polished after plating and satisfactory lengths of life were obtained with nickel layers having a thickness of 25μ.

When used under static conditions the possible errors were considered small as long as the hole diameter was small in comparison to its length.

IV. *Kinetic Heating.*

IV.1. *Notes on Experimental Techniques in Aerodynamic-heating Problems.*

Argabright, L. R., Johnson, C. H. and Smith, W. K., *NAVWEPS Report* 7652, (Confidential), April, 1961.

This report is a collection of four papers on experimental techniques connected with aerodynamic heating. Experimental results have been included where appropriate to illustrate the use of the technique, or to indicate problem areas.

Section I. *Construction of a temperature-telemetering round.* This consists of all external hardware components of an operational missile with the warhead and fuse replaced by the telemetering package, etc. Alteration of the missile for instrumentation purposes was minimised. The telemetering system was an FM/FU system with commutated input to the single voltage-controlled sub-carrier oscillator. The thermocouple instrumentation is described in detail, 30-gauge duplex chromel/alumel thermocouples were used for the dome, ogive and fin thermocouple groups. No preformed beads were used, the dome thermocouple hot junctions utilized silver paint to complete the junction, the fin thermocouple wires were set into a stainless-steel disc bonded into the fin and the inside-surface thermocouple wires were spot welded to a steel disc simply bonded to the surface. The thermocouple attendant instrumentation is also described: temperature-reference junction assembly, thermistor-monitored reference block, reference-mass preparation, installation of reference masses in junction block. The motor thermocouple, wing thermocouple and aft TM adaptor thermocouple installations are described. The temperature-calibration procedure to check the response of the round under heating and cooling conditions is also described.

Section II. *Captive- and free-flight tests of a temperature telemetering round.* This section discusses the experimental aspects of the programme and presents examples of the data obtained. Seven captive-flight tests were made on a F–104 aircraft to determine the temperature profiles experienced by a missile at Mach 2·0. The test programme culminated in the firing of the round during the final flight. Typical temperature data is presented for captive and free-flight tests.

Section III. *Thermal lag of insulated thermocouple-reference junction block.* This section briefly describes the method of keeping a constant reference-junction temperature. A 2 in. × 2 in. diameter steel block wrapped in styrafoam in a wooden box was used in the tests. When this block at room temperature was placed in an oven at 220°, 20 minutes elapsed before any temperature rise could be detected, this rise was then only 2°F in 5 minutes.

Section IV. *Radiant heating tests of a nose cone.* The nose cone, made from a stainless-steel shell covered with phenolic asbestos, was tested to determine how well desired environments could be simulated and to test some ideas concerning a light-weight nose cone. Temperature/time curves are presented for the stagnation point, side of cone and internal positions.

Photographs are given showing the nose cone before and after testing, a sectioned nose cone after testing is also illustrated. This section concludes that the radiant-heating simulation was not completely satisfactory and although a time-varying heat flux could be accurately simulated, the heat-flux variation with position on the test surface could not.

IV.2. *New Methods in Heat-flow Analysis with Applications to Flight Structures.*

Biot, M. A., *Journal of the Aeronautical Sciences*, Volume 24, pp. 857–873, December, 1957.

This paper presents new methods for the analysis of transient heat flow in complex structures, leading to drastic simplifications in the calculation and the possibility of including non-linear and surface effects. These methods are, in part, a direct application of some general variational principles developed earlier for linear thermodynamics; references 1, 2, 3 in the paper. They are further developed in the particular case of purely thermal problems to include surface and boundary-layer heat transfer, non-linear systems with temperature-dependant parameters and radiation. The concepts of thermal potential, dissipation function and generalized thermal force are introduced, leading to ordinary differential equations of the Lagrangian type for the thermal flow field. Because of the particular nature of heat-flow phenomena compared with dynamics, suitable procedures must be developed in order to formulate each problem in the simplest way. This is done by treating a number of examples.

The concepts of penetration depth and transit time are introduced and discussed in connection with one-dimensional flow. Application of the general method to the heating of a slab, with temperature-dependant heat capacity, shows a substantial difference between the heating and cooling processes. An example of heat-flow analysis of a supersonic wing structure by the present method is also given and requires only extremely simple calculations. The results are found to be in good agreement with those obtained by the classical and much more elaborate procedures.

IV.3. *Techniques de Mesure de l'Echaufflement Cinetique á l'Aide du Missile 'Autores'.*

le Boiteux, H. J., *A.G.A.R.D.*, Report 377, 1961.

This report describes the techniques used by O.N.E.R.A. for the study of the kinetic heating phenomena associated with the return of a missile at high velocities ($M = 8$) into the atmosphere.

The performance of a four stage 'Antares' missile used by O.N.E.R.A. especially for this research is indicated.

The methods of measurement used and particularly the one relating to the thermal flux are described and discussed. The temperature measuring instrument used consisted of a copper plug, containing a chromel/alumel thermocouple, insulated from a monel casing by quartz and mica. The unit was set into the projectile surface with the copper plug flush. The heat flux was calculated from a knowledge of the temperature/time history and the thermal conductivity.

A plot given for one position on the projectile shows excellent agreement between experimentally and theoretically-calculated heat flux.

The appendix lists a total of 23 papers, presented at a meeting on 'The Use of Rocket Vehicles in Flight Research', held at Scheveningen, Holland in July, 1961.

IV.4. *Approximate Temperature Distributions and Streamwise Heat-conduction Effects on the Transient Aerodynamic Heating of Thin-skinned Bodies.*

Conti, R. J., *NASA TN*, D–895, September 1961.

An approximate method is presented to determine temperature distributions during the transient aerodynamic heating of thin-skinned, heat-conducting bodies. The investigation was initiated to obtain an approximate solution that would predict the effect of longitudinal conduction; (a) in relieving thermal concentration in the skin and especially, (b) on the distortion of heat-transfer computations based on measured skin-temperature history.

The method is valid for a large range of body shapes and thickness distributions within the limitations of one-dimensional (streamwise) heat conduction, quasi-isothermal surface, constant adiabatic wall temperature and negligible radiative heat transfer.

Numerical computations were carried out for flat plates, wedges, and conical, hemispherical, and hemicylindrical shells. The results are presented in the form of non-dimensional charts that permit a rapid evaluation of a ten per cent error threshold in transient heat-transfer measurements.

IV.5. *The Influence of Conduction on Experimental Heat-transfer Measurements on Continuous-flow Facilities.*

Meleason, E. T. and Renfrol, P. G., *A.S.R.M.D.F. T.M.* 61 – 29, October 1961.

This report presents an investigation into the conduction problem in the experimental determination of aerodynamic heating rates. In wind-tunnel experiments, which attempt to measure aerodynamic heating distributions, erroneous measurements are obtained due to the variation of temperature with time caused by the rapid conduction of heat over the model surface.

The paper assumes a time-dependent heating input and a thin-skinned model with negligible heat transfer normal to the surface and so greatly simplifies the three-dimensional time-dependent heat-conduction problem. Analytical treatments of the conduction problem based on this simplified theoretical model are applied to the leading edge and nose regions of experimental configurations. The percentage of error due to conduction is presented parametrically as a function of radius and measurement time. A variety of well-instrumented models of identical material and skin thickness under similar tunnel flow conditions were used.

This work indicated that the time of data acquisition can become an important factor in transient heat-transfer measurements due to the influence of conduction. This data was therefore re-presented in A.S.R.M. D.F. T.M., 62 – 37, (IV.6 in this survey), using different measurement times. A much clearer indication of the conduction error is afforded.

IV.6. *Experimental Determination of Conduction Errors in Aerodynamic-heating Test Data.*

Meleason, E. T. and Burke, G. L., *A.S.R.M. D.F. T.M.*, 62 – 37, June 1962.

An initial treatment of the conduction problem in the experimental determination of aerodynamic heating rates has been presented in A.S.R.M. D.F. T.M., 61 – 29 (IV.5). A limited correlation of conduction theory with experimental data was included in this report based on available measurement times of 2·5 and 4·5 seconds. In an attempt to obtain further information on the variation of conduction with time, the original data was reproduced at measurement times ranging from 1·1 to 9·4 seconds. Analysis of the new data gave a clearer description of the time dependence of measurement error due to conduction in the stagnation region of wind-tunnel models. Data was compared with theory for a widely used model material (Type 304 Stainless Steel) and excellent correlation was obtained. The theory used was that of Conti presented in NASA TN D–895 (IV.4).

Design curves are presented which describe regions of significant and negligible conduction errors as a function of measurement time and model radius. In addition, an approximate treatment of the theoretical relationship between measurement time, model radius and conduction error is presented, which reduces this correction relationship to a simple logarithmic function.

The resulting charts may be employed to determine the proper conduction correction factors for stagnation heat-transfer rate measurements.

IV.7. *A Method for Correcting Measurements of the Heat-transfer Factor through the Skin of a Wind-tunnel Model.*

Piggot, B. A. M., *R.A.E. T.N.* Math 110, May 1964.

In an experiment in which it is required to measure the heat-transfer coefficient at the outer surface of the skin of a wind-tunnel model, the temperature of the skin is measured at various points on this surface and the heat-flow rate across the skin is measured at the corresponding points on the inner surface.

The method of calculation for the heat-flow rate across the outer surface of the skin, described in this note, in which longitudinal heat conduction is not neglected, involves the solution of Laplace's equation in a rectangular region with mixed boundary conditions, assuming only that there is no heat flow across the ends of the section.

A numerical method of solution is described and illustrated by an example and a comparison between the calculated values of heat-flow rate with and without longitudinal conduction is given for a specific case.

IV.8. *An I.B.M. Programme for Solution of the Heat-conduction Equations in the Nose of a Projectile.*

Tremblay, R., *C.A.R.D.E. T.N.*, 1593/64, February 1964.

This note presents a Fortran programme for solving the equations of one-dimensional heat conduction through a semi-infinite slab with variable heat flux.

The problem of heat conduction through the hemispherical nose of a high-speed projectile, considered by Ardouin, has been reconsidered by Heckman to incorporate more realistic representations for velocity, stagnation temperature and heat flux, which are appropriate to conditions encountered during the launch and free-flight phases of a projectile fired in a hypersonic range. Ardouin's approach is followed, and account is taken of Heckman's re-formulation.

During the short time of flight of the projectile, it is assumed that the depth of heat penetration is small enough to allow the problem to be treated as one of a variable heat-flux input to a semi-infinite slab. The one-dimensional heat-conduction equation is approximated as a finite-difference equation and the computer programme is written in Fortran II for the I.B.M. 1620 machine.

IV.9. *Measurement of Air Temperature on an Aircraft Flying at High Subsonic and Supersonic Speeds.*

Woodfield, A. A. and Haynes, P. A., *R.A.E.*, Report No. Aero 2678, September 1963.

Flight tests were performed on two different designs of impact air thermometer in the altitude range from 30 000 feet to 40 000 feet at Mach numbers between 0·50 and 1·82. Four thermometers were used in the tests; two Penny and Giles (A. and A.E.E. type) with nickel wire sensing elements, one Penny and Giles (A. and A.E.E. type), with thermistor sensing elements and one Rosemount Engineering Company model 102E with a platinum-wire sensing element. The performance of these thermometers is described by two parameters, the recovery factor and the time constant, values of which were obtained. The unusual behaviour of the recovery factor for one of the thermometers is discussed (ther thermistor thermometer). At subsonic speeds it is shown that the normal straight-line method of analysis, plotting indicated temperature *versus* (Mach number)^2 can be invalid. At supersonic speeds, the use of an apparent recovery factor, which includes the effects of both the normal shock wave and the thermometer recovery factor is recommended.

It was found that there was a large difference between the flight values and some laboratory values of time constant for one of the thermometers which suggested that the normal laboratory tests were not fully representative.

The flight test technique is critically examined and suggestions are made for any future investigations into the behaviour of air thermometers. The need for an accurate, independent method of measuring static temperature during the tests is stressed.

IV.10. *Heat Conduction in Single-layer and Double-layer Walls with Boundary Conditions Appropriate to Aerodynamic Heating.*

Jepps, G., *W.R.E.*, Report H.S.A. 16, July 1963.

General solutions of the one-dimensional Fourier heat-conduction equation, for walls bounded by two parallel planes, are found by means of the Laplace transformation for wall boundary conditions such that either surface heat flow or temperature is a prescribed function of time.

These solutions have been used to examine single-layer insulated walls subjected to aerodynamic heat transfer.

Simple thin-wall approximations have been derived from the general solutions and applied to thin walls under conditions of aerodynamic heat transfer. A wall was considered to be thermally thin when the product of heat flow and the thickness divided by the thermal conductivity was small compared with the wall temperature.

Two layer walls with one surface conducting and the other insulated have been treated and a general solution has been derived in terms of surface conditions. This general solution is cumbersome and some two-layer problems have been reduced to equivalent single-layer ones.

The methods presented in this report have been applied to some particular problems for which numerical solutions were known.

As an example it is shown how the heat-transfer coefficient can be derived from the temperature at the inner insulated surface of a thin wall. Examples illustrating other important results are also given.

The report concludes that effective analyses can be made of many transient aerodynamic-heating problems, especially those arising from the use of double-layer walls.

IV.11. *Development and Application of a Technique for Steady-state Aerodynamic Heat-transfer Measurements.*

Hartwig, F. W., *Guggenheim Aero Lab. C.I.T. Hypersonic Research*, Memo No. 37, June, 1957.

A useful technique is described in detail for measuring steady-state heat transfer on a hemispherically-ended cylinder. The experimental results obtained by using this technique are compared with theory.

In the experiments the nominal Mach number was 7·8, the stagnation pressure ranged from 100 to 350 p.s.i.g. and the stagnation temperature from 300 to 500°F. Models were water cooled and made from metal and ceramic. The ceramic models with their low thermal conductivity gave a larger ΔT per unit thickness than the metal models and gave greater sensitivity to the heat-flux meters.

These heat meters consisted of miniaturized thermo-piles of silver-constantan thermocouples. The thermocouples were located top and bottom of a thin glass sheet so as to measure the temperature on the two surfaces. A temperature difference ΔT was obtained proportional to the rate of heat flow. Constantan wire 0·001 inch dia. was wound around a glass slide 0·5 in. × 0·062 in. × 0·007 in. Half was coated in silver giving junction either side of the glass, 50 thermocouple pairs in series and resulting in an overall size of 1/8 in. × 1/16 in. × 1/100 in. The repeatability of the readings with this device was found to be excellent.

The surface temperature was measured at the same time as the heat flux was measured. Constantan wire 0·001 in. diameter was laid on the surface of each model from nose to near. The wire was coated with a thin solution of low melting silicate flux and fired at 1,100°F. This flux bonded the wire to the surface under a 0·001 in. thick glass-like coating. This coating was removed at selected points by making a cut with a knife blade. The exposed wire was contacted with silver paint so that a silver/constantan junction was formed at each cut. The silver paint formed a lead common to all thermocouples, and a constantan lead for each different thermocouple completed the loop.

The heat-flux meters were installed in both a ceramic hemispherically-ended cylinder and in a similar metal one. Three different heat-flow rates were obtained at each of six different combinations of tunnel pressure and temperature.

The results compared very well with a theory developed by Lester-Lees based upon the assumption of local similarity.

V. *Thermal Radiation.*

V.1. *Pyroelectric Transducers for Heat-transfer Measurements.*

Perls, T. A. and Hartog, J. J., Lockheed Missiles and Space Division Tech. Report, L.M.S.D.–325500.

Heat-transfer gauges in general are briefly reviewed with reference to their usefulness and their limitations. The devices mentioned are thin-film gauges, thick-film gauges, thermocouples, thermistors and inductance-type gauges. General considerations on differentiation are made and an R.C. differentiator is discussed.

It is shown that a particularly simple type of temperature-measuring device followed by an electrical differentiator is provided by a pyroelectric element delivering its output into a suitably chosen resistor. Materials mentioned are modified barium titanate and lead zirconate titanate, both are ceramics. Theoretical considerations are presented but in general a polarized ceramic releases a charge in response to an increase in temperature and if this charge is allowed to flow through an external resistor, the current is a measure of the time rate of change of temperature of the ceramic, and hence of the rate at which heat is transferred to the sensing element. The response time is said to be essentially instantaneous provided the heat reaches the sensitive portions of the gauge (due to coatings), with a minimum of delay time and provided no delay is introduced by the electrical-output generating mechanism.

In a typical application, the pyroelectric gauge and its cable have a capacitance of 500 pf., so that the time constant becomes 0·5 m.second when the 1 megohm input resistance of a typical commercial oscilloscope is used as the resistive load. This electrical response time is readily reduced, at the expense of sensitivity, by the use of short resistors at the input of the recording device.

Since these materials are also piezoelectric their sensitivity to pressure and acceleration is also discussed.

Evaluation and calibration procedures (estimated accuracy ±2%), applications, advantages, limitations, as well as typical circuitry and installations are discussed. Some test results are presented and it is concluded that, in practical use, pyroelectric transducers offer advantages of small size, low cost, ready adaptability to a wide range of installations, good intrinsic frequency response, easily adjustable electrical time constant, extremely simple associated instrumentation, high output, good ageing properties and linearity and small dependence of sensitivity on temperature. Further investigations were planned.

V.2. *Development of an Experimental Gas-radiation Pyrometer.*

Dolin, S. A. and Jackson, E. A., W.A.D.C. T.R. 56–360 PT.II, January 1959.

This reports the second part of a development to provide an aircraft engine-mounted radiation detector having fast response and long life which would measure the extreme temperatures of turbo jet, ramjet and rocket engine exhaust gas.

The first phase of this development concerned the investigation of feasible means of determining temperatures from radiation measurements. (W.A.D.C. T.R. 56–360 Part I). This second phase was concerned primarily with the development of experimental prototype detector heads that would operate in a 1500°F ambient whilst subjected to vibrational stresses of up to 100 g. The instrument was required to operate with gas temperatures in the 4000°F range to overcome the limitation of present thermocouples in the vicinity of 2200°F.

The instrument utilizes a selective type detector, the theory of which is covered in Part I of this report. In the design considerations independent investigations were performed to evaluate such factors as: the electrical resistance of ceramics, cements, etc. at 1500°F, the usefulness of various window materials as well as sealing techniques, the corrosion resistance of metals as well as their mechanical strength and mounting and fastening techniques.

The prototype detector for jet aircraft burning hydrocarbon fuels has its chamber filled with CO_2 and absorbs radiation (at two distinct wavelengths) from the CO_2 in the exhaust gas. A thermoelectric type element is used to measure the difference in temperature between the CO_2 in the active chamber exposed to radiation from the flame and the CO_2 in a reference chamber. Methods of compensating for errors in the measurements are described and plots are presented showing the effect of these compensations.

Various tests are described and some results are presented. Experimental models have been constructed and evaluated on the afterburner of a J–47 engine. Tests showed a roughly linear electrical output as a function of temperature in the range measured from 1000 to 3000°F. The inherent sources of error are discussed in detail.

The characteristics of the instrument are: Output, 5·8 millivolts at 3000°F. Time constant, $0{\cdot}5 \pm 0{\cdot}05$ seconds. Operating ambient, 1500°F maximum for continuous operation. Temperature measurement range, 1000°F to 4000°F linear to a first approximation. Size (lens housing), $1\frac{1}{2}$ inches diameter × $1\frac{5}{8}$ inches long. Weight (less housing), 10·1 ounces. Type, Selective carbon dioxide gas radiation detector. Life expectancy, life of engine.

V.3. *An Apparatus for Measuring the Thermal Emissivity of Metal Surfaces and Surface Finishes.*

Carpenter, W. G. D. and Sewell, J. H., *R.A.E.* Report No. Chem. 528, February 1962.

This report describes the design and construction of an apparatus for measuring the thermal emissivity of metals and coatings over a temperature range from ambient to 250°C with a high degree of accuracy.

The principle of its design is the comparison of the rate of cooling of the surface at a known temperature with that of a theoretical black body radiating at the same temperature.

The apparatus consists of a copper cube, containing an electrical heater and a thermocouple, suspended inside a black-painted hollow sphere, normally evacuated. The outer shell is water cooled. The copper cube, suspended on a fine wire, begins to lose heat when the heater is switched off and the rate of heat emission from the surfaces of the cube, or of the coating, determines the cooling rate of the metal. Its temperature is recorded at regular intervals using the thermocouple.

The range of temperatures to a 250°C limit was taken as the practical limit of present-day paint finishes.

With suitable selections of heater and block material it is claimed the equipment should enable emissivities to be measured at temperatures up to at least 600°C.

The theoretical considerations for the apparatus are presented together with a discussion of the errors to be expected when measuring emissivity with the apparatus. These are estimated as not exceeding ±3%.

Emissivities of some typical paints on a copper surface are given. These are Aluminium-pigmented nitrocellulose paint, white-pigmented nitrocellulose paint and Britannia black paint. The emissivity of a polished copper surface only is also given.

V.4. *Measurement of Thermal-radiation Properties of Solids.*

NASA SP.–31, 1963 (Symposium sponsored by Aeronautical Systems Division USAF, NASA and NSS).

This volume contains the proceedings of a symposium sponsored because of the very great increase in interest in, and need for, data on the thermal radiation properties of solids as a consequence of the national space programme. These proceedings are a valuable reference on measurement techniques for evaluating thermal-radiation properties of solids, particularly for those with limited experience in the field.

The proceedings are presented in five sessions and because of the strong dependence of emitted flux on temperature the first session was devoted to a discussion of the problems of temperature measurement. The four remaining sessions were devoted to discussions of measurement techniques in each of the four temperature ranges given.

The various sessions and the papers presented in them are given below:

Session I: *Temperature Measurements.*

1. Pitfalls in Thermal Emission Studies, Harrison, W. N.
2. Temperature measurements below 1000°K, Riddle, J. L.
3. Thermocouple and radiation thermometry above 9000°K, Kostkowski, H. J. and Burns, G. W.

Session II: *Measurements at Low Temperatures* (0° to 200°K)

4. Thermal radiation properties of solids at low temperatures, Corruccini, R. J.
5. Space-chamber emittance measurements, Butler, C. P. and Jenkins, R. J.
6. Cryogenic emittance measurements, Caren, R. P.
7. An apparatus for measuring total hemispherical emittance between ambient and liquid nitrogen temperatures, Haury, G. L.
8. Errors of the Calorimetric method of total emittance measurement, Nelson, K. E. and Bevans, J. T.

Session III: *Measurements at Satellite Temperatures* (200° to 450°K)

9. Requirements for emittance measurements of thermal control surfaces of spacecraft, Heller, G.
10. The reflectivity of solids at grazing angles, Brandenberg, W. M.
11. A dynamic thermal-vacuum technique for measuring the solar absorption and thermal emittance of spacecraft coating, Fussell, W. B., Triolo, J. J. and Henniger, J. H.
12. Portable integrating sphere for monitoring reflectance of spacecraft coatings, Fussell, W. B., Triolo, J. J. and Jerozal, F. A.
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45. A 500° to 4500°F thermal-radiation test facility for transparent materials, Clayton, W. A.
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V.5. *Symposium on Thermal Radiation of Solids.*

Edited by Katzoff, S., *N.A.S.A.*, S.P.55.

This symposium was intended to provide for presentation and discussion of significant developments in the *theory* of thermal radiation of solids and in the understanding of the important effects of surfaces and interfaces and of surface imperfections on this radiation, of the effects of the space environment on radiation properties, and of the application of this information to the thermal designer's problems.

Developments in measurement techniques were not considered basic to the main theme, since it was the theme of the preceding symposium. One section was devoted to it, however, because the subject remains of continuing concern. This preceding symposium was published as 'Measurement of thermal radiation properties of solids', Richmond, J. C., NASA S.P.–31, 1963.

The symposium was organized into five sessions. I. Fundamentals, II. Surface effects, III. Measurement techniques, IV. Space environment effects, V. Applications.

Although the topics of the five sessions are fairly clearly differentiated, material pertaining to any one may be found in any of the others. A subject index has been added to help the reader locate desired information; in addition, the editor has inserted footnotes calling the reader's attention to related papers in the symposium.

V.6. *Calibration Experiments with Radiometers and a High-intensity Arc Source.*

Lane, W. R., Prowett, W. C. and Stone, B. R. D., *Porton Technical Paper* No. (R)39, (Restricted), December 5th, 1961.

This paper gives a brief description of the construction and calibration of a high intensity arc source. The source consisted of a 12·5 KW, 90V, d.c. carbon arc and employed an ellipsoidal aluminium mirror 24 inches in diameter, focal lengths 11 and 55 inches and provided an intensely irradiated circular area at the exposure plane near to one focus. The maximum heat flux at the centre was about 10 cal.cm^{-2}sec^{-1}, with 90% of the maximum over an area of 3 cm.dia.

Venetian blind type shutters were used to give timed pulses of radiation and the heat flux could be kept constant within ±5% over periods of a few minutes.

A photograph and a diagram of the apparatus is given. A 16 mm. film with sound track describing the operation of the arc source and associated equipment is available.

A constantan disc radiometer is described. It is basically that of Gardon (I.9 in this bibliography) but with the incorporation of water cooling to eliminate the troublesome creep experienced with a radiometer built to the original specification. A scale drawing of this radiometer is given.

A constant-flow calorimeter is also described. This consists basically of a black-body cavity around which are soldered metal coils through which water flows at a constant rate. Radiation entering the cavity causes the temperature of the water to rise.

In the calibration procedure the radiometer was exposed before and after exposure of the calorimeter. The average value of the radiometer output was taken as corresponding to that of the calorimeter. The flux for this was calculated accordingly to

$$Q = \frac{\Delta T W}{A} \text{cal.cm.}^{-2}\text{sec.}^{-1}$$

where ΔT is the water temperature rise, W the water flow rate and A the area of the aperture.

The radiometer output plotted against the flux measured by the calorimeter was not linear. This was investigated by inserting a heater coil into the calorimeter. This arrangement is described and the results discussed.

VI. *Phase-change Methods.*

VI.1. *Metallographic Study of Heat Flow in Rocket-motor Walls.*

Sanz, M. C. and Ihsen, H. C., *Metal Progress, 56* 5, pp. 685–7, November 1949.

The temperature distribution of a water-cooled rocket-motor wall is determined by a metallographic method. The rocket motor had a thrust of 1000 lb., gas temperatures of 5000°F and water-coolant temperatures of 400°F (at 20 atmospheres). These conditions gave extremely steep temperature gradients of the order of 17 000°F per inch across the 0·100 inch thick cooled inner wall which was made of normalized A.A.E. 4130 steel.

This metallographic method is based on the fact that part of the rocket wall undergoes temperature changes that both austenize and quench the steel during firing. The microstructure of the wall section shows a sharp line of demarcation at the transformation temperature.

Micrographs are given which clearly show this line of demarcation of structure – martensite on the hot side and the original normalized structure on the coolant side. It is assumed that this line corresponds to the transformation temperature $A.C_3$(1485°F) for S.A.E. 4130 steel, and that one point on the temperature gradient has been fixed. The temperature on the coolant side of the wall was then calculated from the coolant temperatures, Reynolds numbers and other data. For a coolant temperature of 415°F the calculated wall temperature was 465°F.

Assuming a straight line temperature gradient the hot surface temperature was calculated to be 1995°F. This was a first approximation and a correction was then applied for variable thermal conductivity (a temperature-conductivity plot is given), this gave the hot surface as 2145°F.

A summary is given of the possible errors in the calculations. The maximum possible error is given as 5% and the maximum probable error as 3%.

Reference VI.2 discusses this method and suggests a more accurate method of solution. Reference VI.3 shows that the assumption that the isothermal temperature at the line of demarcation is the $A.C_3$ temperature for the steel is *not correct* for short periods of heating. This isothermal is given as corresponding to the $A.C_1$ temperature.

VI.2. *The Application of Phase-Transformation Methods of Measuring Temperature to Rocket-motor Research.*

Maddock, D. P., R.A.E. Tech. Note R.P.D. 46, February 1951.

The heat transfer to rocket motor walls is first discussed in general terms and the importance of accurate measurements of the wall temperatures is pointed out. Objections to measurement with thermocouples or resistance thermometers are given, the main objection being the very accurate positioning of the sensor required since the temperature gradients in rocket motor walls are very steep. Sealing also presents a problem.

The phase-transformation method of measuring temperature is considered a better method. The method discussed is that described by Sanz and Ihsen (VI.1). It is pointed out that the accuracy of the method depends fundamentally upon the validity of the assumption that the line of demarcation of the micrographed section corresponds to the A.C_3 (upper critical) temperature. [It was later shown by Bradley (VI.3) that this was a false assumption and that the demarcation line corresponds to the A.C_1 (lower critical) temperature.]

It is shown that provided the variation in thermal conductivity is accurately known, a more exact solution for the temperature at any point in the wall can be obtained by the method of graphical integration. This method is presented.

The advantages of a material with two phase transformation points are discussed.

VI.3. *A Note on the Method for Obtaining a Precise Temperature Isothermal in the 'Phase'-Transformation Method of Measuring Heat Flow in Rocket-motor Walls.*

Bradley, P., *R.A.E.* Tech. Note. R.P.D. 58, November 1951.

This note is on the method of 'phase transformation' described by Sanz and Ihsen that the line of demarcation of the micrographed section of the rocket-motor wall corresponds to the A.C_3 temperature is not correct for short periods of firing. Micrographed sections are presented which give this line as the A.C_1 temperature which, depending upon the steel, can be considerably below the A.C_3 temperature.

The reasons for the error in the original assumption are discussed and the illustration presented shows that in the hypo-eutectoid steels used the crystals of ferrite and pearlite change, when heated, to crystals of austenite and ferrite at the A.C_1 temperature. (When quenched, the austenite crystals form martensite and this gives the sharp line of demarcation.)

A modification to the original method is suggested. This is to locate the line of the transformation of pearlite to austenite within a pearlite crystal to give a very precise isothermal. Then with a knowledge of the firing period of the rocket motor a factor can be applied from a knowledge of the rates of diffusion of an eutectoid steel (Roberts and Mehl) to obtain the true temperature of the isothermal.

It is concluded that in practice the method is capable of giving extremely accurate results.

VI.4. *Use of Fusible Temperature Indicators for Obtaining Quantitative Aerodynamic Heat-transfer Data.*

Jones, R. A. and Hunt, J. L., *NASA* TR. R–230, February 1966.

Some of the methods used for obtaining quantitative aerodynamic heat transfer data by means of temperature sensitive coatings are described and discussed. A detailed description is given of the phase-change method. With this method data can be obtained on arbitrary shapes without the use of a reference body. The heat-transfer coefficients depend only upon the thermal properties of the model material and the time required for a visible phase change (from an opaque solid to a clear liquid) of a fusible temperature indicator which is applied to the model as a thin surface coating. In effect the entire surface of a model is instrumented and lateral conduction effects are minimized by the very low thermal conductivity. The phase change coatings are described in detail and calibrations of the phase change temperatures are given for a range of heating rates and ambient pressures. The apparatus, test technique and model construction are discussed. The coated model is introduced suddenly into the tunnel air stream and the phase change is recorded by motion-picture photography. Charts are given which relate the time required for the phase change to occur to the heat-transfer coefficient.

Data obtained by this method are compared with aerodynamic theory and with data obtained by conventional thermocouple-calorimeter technique, close agreement is shown which indicates that accurate data can be obtained with this method.

The accuracy of the method is dealt with in detail and charts are given showing the maximum percentage error in heat-transfer coefficient as a function of time. The error in indicated heat-transfer coefficient was calculated assuming errors in the thermal properties ($\pm 3\%$ in K, $\pm 2\%$ in cp, $\pm 1\%$ in ρ), the phase-change temperature ($\pm 1\%$) and in time (0·1 second). The curves show that for a phase-change temperature of 250°F and a time from exposure of the model to the airstream of 10 seconds the maximum error in h is 5%. The error increases for decreasing time and phase-change temperature.

Several configurations were tested in the Langley Mach 8 variable density tunnel and the report concludes that this method is useful for complex configurations which are difficult to instrument with thermocouples. Materials for the coatings can be obtained with phase-change temperatures that range from 100°F to 2500°F in increments as small as 3°F. The models were cast from plastic, can be made quickly at low cost and the data can be rapidly and easily reduced without complicated recording apparatus or electronic computers.

VII. *Resistance Thermometers.*

VII.1. *High Temperature, Thin-film Resistance Thermometers for Heat-transfer Measurement.*

Bogdan, L., (Cornell Aero. Lab.) *NASA* C.R.–26, April, 1964.

The development of a high temperature, thin-film resistance thermometer for heat-transfer measurements is described. A thin film, 4 micro inches thick, of a platinum alloy was deposited on a pyrex substrate by brushing on a solution of platinum and firing the unit to 1250°F to drive off the volatile components and effect a glass-metal bond. The dimensions of the film were 0·030 × 0·25 inches and the room temperature resistance was adjusted to 100 ± 25 ohms by firing additional overlayers of platinum.

Since the gauge had to operate at steady-state temperatures to 1000°F a special technique was developed to embed the platinum terminal leads into the pyrex substrate before the film deposition. The platinum ribbon leads were inserted between a concentric pyrex rod and tube and the whole moulded into the desired form whilst hot and viscous. The substrate was trimmed to shape and then ground and polished. The high-temperature gauge electrical characteristics were stabilized by heating to 1000°F for 4 hours followed by a slow cooling to room temperature. Two such cycles were generally sufficient. The platinum film was protected by an evaporated coating of magnesium flouride although this was not completely satisfactory. The thickness of the substrate generally exceeded $\frac{1}{16}$ inch to satisfy semi-infinite body criteria.

Details of the calibration procedure employed to evaluate the thermal and electrical characteristics of the gauge are described. The relation linking heat-transfer rate, surface temperature and time contains a lumped parameter of the substrate thermal properties. The calibration procedure determined the value of this lumped parameter at room temperature and also the temperature dependence of it. An electric pulse method was used to develop a known constant heat flux and this procedure is described in an appendix. The calibration data are presented and compared with other published data in the temperature range where direct comparison is possible.

The paper concludes that the feasibility of these gauges has been demonstrated and that:

1. The variation in the value of the lumped parameter of the thermal properties of pyrex is sufficiently small that in most cases calibration of individual gauges is unnecessary. The temperature dependence of this parameter was found to be smaller than indicated by other published data.
2. The resistance-temperature function of the platinum-alloy film was non-linear and was best defined by a second degree equation in temperature. The gauge sensitivity $\frac{dR}{dT}$ thus varied linearly with temperature.

VII.2. *Measurement of Radiative Heat Transfer with Thin-film Resistance Thermometers.*

Bogdan, L., Cornell Aero. Lab. *NASA* C.R.–27, March, 1964.

The use of a dual-element thin-film resistance thermometer for measuring simultaneously the convective and radiative components of heat-transfer rate is described. The use of the transducer described in VII.1 has been extended to sense radiative flux. The measurement of radiative heat flux required an understanding of both the electrical and the optical properties of the film and substrate in the spectral region of interest. Of prime interest in the calibration tests was the spectral absorbtion of the thin-film resistance thermometer.

A typical radiative heat-transfer gauge comprised a disc-shaped fused quartz substrate with one resistance element (as described in VII.1) deposited on each face. The long dimensions of the two elements were at right angles to one another to minimize shadowing of the lower element by the upper. Radiant and convective heat flux is sensed by the upper element and only radiant flux by the lower.

In addition to the determination of the spectral absorption intermediate objectives involved the determination of, (a) Spectral reflection and absorption ascribable to the fused-quartz substrate and, (b) to the magnesium-fluoride protection coating. (c) Dependence of thin-film optical properties on: 1. Position relative to incident energy on the front and near surfaces of the substrate, 2. On the angle of the incident energy, 3. On tolerances associated with fabrication techniques.

For the particular application of interest peak-radiative energies were taken to lie between wavelengths of one and two microns. In the calibration procedure the following are described; 1. The test specimens, 2. The test apparatus, 3. Transmission measurements and, 4. Reflection measurements. The spectral absorption of radiant energy was evaluated in the wavelength range 0·8 to 2·6 microns.

A summary of the test data, applicable to ambient room temperature conditions is given and the paper concludes that: 1. Absorption within the fused-quartz substrate is negligibly small. Reflection is typical of naked glass surfaces, 2. Effects of thin dielectric films like magnesium fluoride must be evaluated in conjunction with the base material (substrate), 3. Platinum films on the rear surface of the substrate composite are relatively uniform in the wavelength range from 1·0 to 2·2 microns, 5. For front-surface films, the absorbtion increases with decreasing angles of incidence, for rear-surface films the converse is true, 6. The apparent effect of the magnesium-fluoride coating is to increase absorption in the front-surface film and decrease absorption in the rear-surface film, 7. Transmission of the platinum films is uniformly low, 8. Variability in the optical characteristics ascribable to fabrication techniques is small.

VII.3. *The Construction and Application of a Rapid-response Resistance-thermometer Probe.*

Vidal, R. J. and Hilton, J. H., *Cornell Aero. Lab.* Report No. IM–1062–A–1, April, 1956.

This resistance-thermometer probe was designed to sense small transient surface-temperature rises on the surface of a body occurring in time intervals of $\frac{1}{2}$ – 1 millisecond. It is claimed that the probe will operate continuously at 500°F and will withstand 1000°F for $\frac{1}{2}$ minute.

A thin metal-film resistance element was deposited on the spherical tip of a 0·06 in. diameter pyrex rod using a commercial printed circuit paint, Hanovia liquid bright Platinum 05–X. The element was painted on the glass and fired to 1250°F in a well-ventilated oven. A continuous metal film $\frac{1}{10}$ micron thick was formed and was found to be very durable and well bonded to the glass. A printed circuit paint was also used to paint the lead wires to the element onto the glass, the lead wires were then silver plated using silver cyanate, thus reducing the lead resistance to about $\frac{1}{10}$ ohm. For strength purposes the glass rod was sleeved with metal using glass-fibre insulation.

The important results of an analysis of thin resistance thermometers are given, the reference to the full analysis by Vidal, R. J. being given in the bibliography.

The probe was calibrated in a water bath between 40°F and 110°F (the resistance was measured on a Wheatstone bridge) and resistance versus temperature calibrations were checked over a temperature range 70°F – 850°F in order to determine the calibration linearity in the high temperature range. At high temperatures the resistance was found to increase slowly with ageing.

A second calibration, indicated by the analysis, to determine the glass thermal properties was carried out by subjecting the probes to known flow conditions in a shock tube.

The recording circuits suitable for this probe are discussed and a simple circuit suitable for most applications is given.

The temperature rise on the probe element due to the energising current has been calibrated as a function of power for still air only. In certain circumstances errors can result from this source.

VII.4. *Rugged Film-resistor Thermometer for the Measurement of Surface Temperatures.*

Thun, R. E., Candle, G. F. and Pasciutti, E. R., *Rev. Sci. Insts.*, Volume 31, No. 4, p. 446, April 1960.

A resistor thermometer element consisting of a nickel or palladium film protected by an SiO or didymium fluoride coating. This vacuum-deposited film thermometer was used for the inflight measurement of skin temperatures on gun-fired missile models with accelerations up to 10^5g. The resistance element forms part of an R.L.C. circuit, readout being accomplished by inductive coupling to a number of fixed instrument stations on the flight path.

The influence of the following deposition parameters were studied: substrate temperature, pressure, rate of deposition and film thickness. Curves are presented showing the influence of these parameters for nickel and palladium films. The films were vacuum deposited on glass substrates with embedded Kovar contacts, the evaporation technique being described in detail.

The overall size of the resistance element was about 0·5 cms. x 0·2 cms. by 1000A thick and had a resistance of 2 ohm. After annealing, the film strips were calibrated to the exact resistance value by reducing their width. Above 400°C in the air, palladium films showed better oxidation resistance than nickel although both were used with protective films 300A thick. Drift free and reproducible resistance-temperature curves could be obtained only by using annealed films and by keeping the maximum temperature about 50°C below the annealing temperature.

Within the accuracy of ±0·5% the palladium films had a linear resistance-temperature coefficient; nickel films were not linear. It is shown that both films can be obtained with a (TCR) considerably higher than previously reported. When connected for the anomalous skin effect, a resistivity and a TCR approaching the bulk values were measured. The necessary conditions were found to be high deposition rates of about 200A/second, moderate substrate heating and annealing after deposition (in this case for 20 minutes at 450°C).

VII.5. *A Platinum-resistance Thermometer for use at High Temperatures.*

Barber, C. R. and Blauke, W. W., *Journal of Sci. Inst.*, Volume 38, p. 17, January 1961.

A platinum resistance thermometer suitable for use up to the freezing point of gold, 1063°C is described. This type of instrument is the chosen interpolation instrument for the International Temperature Scale for the temperature range from −182·97°C to 630·5°C. The paper concludes that the upper range may be raised to this upper limit of 1063°C.

The thermometer bulb, containing the resistance element, is 36m.m. x 5·5m.m. and is contained in a recrystallized alumina sheath 500m.m. long and 8m.m. external diameter. The coil is wound from very pure platinum wire ($\alpha = 0{\cdot}003926$) of diameter 0·3 m.m. and is freely exposed to dry air. The resistance of the thermometer is about 1·4 ohm at 0°C and about 6·4 ohm at 1063°C and can be measured with sufficient precision on the N.P.L. design of Smith bridge to give a sensitivity of 0·002°C.

It is shown that heating the thermometer for successive one-hour periods at 1063°C caused a rise of the resistance at 1063°C corresponding to 0·002 deg/hour; this is regarded as a satisfactory degree of stability for use as a standard instrument up to 1063°C.

VII.6. *Accuracy in Resistance-thermometer Measurements.*

Bird, F. F. and Jackson, W. E., *Proc. Inst. Soc. America, 16* Paper No. 157–LA–61 1961.

This paper discusses the accuracy of temperature measurement by resistance thermometry in military and commercial applications with severe environments. The information is presented in tabular form including a discussion of errors originating in the bridge and thermometer stem and performance criteria such as time constant, self-heating and surface perturbations. The discussion is non-mathematical, the intent being to survey the accuracy problem. Emphasis is placed on wire-wound, chemically pure platinum devices, although other materials, notably tungsten and nickel, present district advantages in certain applications. Photographs of the various types of resistance thermometer are presented.

The paper concludes that although the manufacturers of the high accuracy, difficult-environment devices, have co-operated with their customers, primarily in the aerospace industry, there is still room for improvement, particularly in the high-temperature region and in integral bridge probes where the bridge section of the probe sees wide temperature excursions.

VII.7. *Modern Trends in Resistance Thermometry.*

Stirling, P. H. and Ho, H., *Industrial Eng. Chemistry*, 52 (7), p. 49A, July 1960.

This article briefly compares the modern developments in thermocouples and resistance thermometers. They are compared in the light of their precision, long term stability, response, linearity and sensitivity. It is stated that although the thermocouple has held the preferred place in industrial temperature measurement for the last three decades, the picture is now changing to more complex systems.

Modern developments in thermocouples are briefly described such as semi-conductor thermocouples using inter-metallic compounds *versus* graphite, tungsten-rhenium, iridium-rhenium and noble metal thermocouples.

Resistance thermometers are described chiefly with regard to their precision and their suitability for control equipment and switching devices. Developments in semi-conductor resistance elements are described including thermistors, doped germanium or silicon elements, etc. A new thermistor material is mentioned capable of temperature measurement to 800°C.

Developments in control equipment and methods are briefly mentioned and the article concludes that the low cost of present day miniature platinum resistance bulbs of fast response usable to 1100°C is changing the emphasis of resistance thermometers *versus* thermocouples.

VII.8. *Resistance Elements for Missile Temperatures.*

Norton, H. N., *Instruments & Control Systems*, Volume 33, p. 922, June 1960.

This article describes the various types of resistance element used for measuring missile temperatures. Platinum resistance thermometry was selected because of its accuracy, repeatability and linearity. Most transducers used are of the probe type, the probe stem containing the element protrudes into the fluid to be measured. The sensing element is usually a plain coil of pure platinum wire between 0·6 and 3m.m. diameter, and is annealed at 500°C for 30 to 60 minutes to remove any residual strain.

A description is given of various types of elements both exposed and enclosed. Time constants of less than 50 milliseconds have been obtained. All probe designs described passed vibration tests up to 35g and 2000c.p.s., and burst pressure tests of 12 000 p.s.i.

Electrical requirements of the associated circuitry used in missiles requires a resistance change from exactly 500 to 600 ohms in the thermometer for any given temperature range. This is achieved by varying the amount of platinum wire used. The thermometer constitutes one arm of a Wheatstone bridge balanced for zero output voltage at 500 ohm transducer resistance, and full scale sub-carrier oscillator excitation voltage (3·4 V.D.C.) at 600 ohm transducer resistance. A commutator is used to connect a number of transducers sequentially into the bridge network. Intermediate temperatures are obtained from a calibration curve for the particular transducer used. In the calibrations, the Callendar-Van Dusen equation is used which defines the resistance versus temperature characteristics of the platinum resistance thermometer between $-182{\cdot}97$°C and $+630{\cdot}5$°C. Tolerances of $\pm 1{\cdot}0$ to $\pm 2{\cdot}0$ ohms are usually specified. The temperatures which can be accurately measured, range from below -400°F to above $+1500$°F and these platinum-wire resistance thermometers have given satisfactory data during numerous missile flight and ground tests.

VII.9. *Transient Local-heat Flux in Nucleate Boiling.*

Cooper, M. G. and Lloyd, A. J. P., Proceedings of the 3rd International Heat Transfer Conference. *American Institute of Chemical Engineers*, August 1966.

This paper is concerned with the measurement of temperature fluctuations on the surface of a heated glass plate as individual vapour bubbles form, grow and move off.

The temperatures were measured by small resistance thermometers consisting of thin films of metal and semiconductor. For the experiments the specific resistance of the element had to be several orders of magnitude higher than that of the leads with leads of the same size as the element. Copper was used for the leads and a semiconductor, because of its high coefficient of resistance change with temperature, for the element.

The materials were deposited by evaporation through masks, to form thermometers with elements 0·003 inch square, with spacings between them down to 0·010 inch. Typical thicknesses were 0·25μm for the leads and up to 0·5μm for the element.

The response of the thermometers to changes in temperature and heat flux was estimated from the time of diffusion of heat through the film, which was of the order of 10^{-8} seconds. In the work described in this paper bare unprotected thermometers were used, which necessitated toluene being used as the boiling fluid. With a coating of epoxy resin 0·0005 inch thick, the thermal diffusion time is of the order of 0·001 to 0·005 seconds.

The thermometers were placed in the feed back loop of a high gain operational amplifier, arranged to give a constant current through the thermometer. The amplified signal was fed through matching equipment into galvanometers in an ultra violet recorder. The main limitations on the response of the equipment arose from the galvanometers, which had a natural frequency of 1650 c/s, and the accuracy of reading time on the chart which was about one millisecond.

High-speed photographs (3,000 to 4,000 frames/sec.) were synchronised with the temperature readings by means of a 100 c/s square wave applied to a neon bulb in the camera and also to one channel of the ultra-violet recorder trace.

The thin-film resistance thermometers are also described in another paper by the same authors: Thin-film thermometers with rapid response. *Jour. Sci. Inst.* 42. 791 (1965).

AUTHOR INDEX

Printed in Wales for Her Majesty's Stationery Office by
Allens Printers (Wales) Limited.

Dd. 129527. K.5.

R. & M. No. 351

Published by
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TABLE A1

```
INVEPSE OF MATRIXAS
          -1;
           2;
          12;
          12;

  2.10098 ₁₀- 1;     1.95552 ₁₀- 1;     5.40148 ₁₀- 2;     1.31278 ₁₀- 2;     6.65400 ₁₀- 1;     4.21100 ₁₀- 1;
  6.81456 ₁₀- 2;     2.26129 ₁₀- 1;     1.51867 ₁₀- 1;     4.32211 ₁₀- 2;     7.45335 ₁₀- 1;     7.24085 ₁₀- 1;
  4.22419 ₁₀- 2;     8.27944 ₁₀- 2;     1.78416 ₁₀- 1;     1.62067 ₁₀- 1;     1.24255 ₁₀- 1;     2.67197 ₁₀- 1;
  1.51957 ₁₀- 2;     4.33981 ₁₀- 2;     6.11682 ₁₀- 2;     8.43771 ₁₀- 2;     4.93372 ₁₀- 2;     1.40839 ₁₀- 1;
  3.07151 ₁₀- 1;     5.82805 ₁₀- 3;    -1.85837 ₁₀- 2;     9.91593 ₁₀- 4;     1.61495 ₁₀- 1;    -6.85658 ₁₀- 2;
  1.81547 ₁₀- 2;     2.85409 ₁₀- 1;     5.30423 ₁₀- 3;    -1.62444 ₁₀- 2;     5.65062 ₁₀- 2;     2.48246 ₁₀- 1;
 -1.83478 ₁₀- 3;     1.60086 ₁₀- 2;     3.58134 ₁₀- 1;     4.71423 ₁₀- 2;    -1.90399 ₁₀- 2;     9.95514 ₁₀- 2;
  2.42423 ₁₀- 3;     7.63279 ₁₀- 3;     2.39200 ₁₀- 2;     5.41104 ₁₀- 1;     2.48815 ₁₀- 2;    -3.09517 ₁₀- 2;
  8.58125 ₁₀- 1;    -5.10410 ₁₀- 2;     1.19259 ₁₀- 2;     4.86196 ₁₀- 3;    -2.38896 ₁₀+ 0;    -9.09416 ₁₀- 2;
  1.24691 ₁₀- 1;     9.14634 ₁₀- 1;    -1.14104 ₁₀- 1;     3.08523 ₁₀- 2;    -4.04400 ₁₀- 2;    -2.16102 ₁₀+ 0;
 -5.86696 ₁₀- 2;     1.92184 ₁₀- 1;     1.17413 ₁₀+ 0;    -2.14337 ₁₀- 1;     2.59922 ₁₀- 2;     2.19619 ₁₀- 2;
  4.09790 ₁₀- 2;    -8.48581 ₁₀- 2;     2.84219 ₁₀- 1;     2.19230 ₁₀+ 0;    -1.73499 ₁₀- 3;    -1.02145 ₁₀- 2;


  5.94339 ₁₀- 2;     2.24242 ₁₀- 2;     1.11957 ₁₀+ 0;     3.51325 ₁₀- 1;     1.17903 ₁₀- 2;     3.63917 ₁₀- 2;
  3.01321 ₁₀- 1;     2.42583 ₁₀- 2;     4.62112 ₁₀- 1;     1.36829 ₁₀+ 0;     1.13771 ₁₀- 1;     3.53193 ₁₀- 2;
  7.06738 ₁₀- 1;     3.77979 ₁₀- 1;     1.53354 ₁₀- 1;     6.57528 ₁₀- 1;     1.44545 ₁₀+ 0;     1.15237 ₁₀- 1;
  2.02642 ₁₀- 1;     4.93744 ₁₀- 1;     1.05126 ₁₀- 1;     1.82054 ₁₀- 1;     5.67168 ₁₀- 1;     1.63697 ₁₀+ 0;
 -1.72275 ₁₀- 2;    -1.26719 ₁₀- 4;    -5.09074 ₁₀- 1;    -9.17618 ₁₀- 2;     4.37402 ₁₀- 3;    -8.42679 ₁₀- 3;
 -6.62265 ₁₀- 2;    -2.93694 ₁₀- 3;    -4.82008 ₁₀- 2;    -4.97119 ₁₀- 1;    -3.65506 ₁₀- 2;     1.94506 ₁₀- 3;
  3.37862 ₁₀- 1;    -8.72553 ₁₀- 2;     2.25409 ₁₀- 2;    -4.24577 ₁₀- 2;    -6.01223 ₁₀- 1;    -5.13201 ₁₀- 2;
  1.61989 ₁₀- 1;     5.52195 ₁₀- 1;    -5.86006 ₁₀- 3;     3.96992 ₁₀- 2;    -7.46594 ₁₀- 2;    -8.22130 ₁₀- 1;
  5.25726 ₁₀- 2;    -1.54156 ₁₀- 2;     1.55758 ₁₀+ 0;     1.58773 ₁₀- 1;    -1.73423 ₁₀- 2;     1.20921 ₁₀- 2;
 -5.16094 ₁₀- 2;     4.52950 ₁₀- 2;    -8.39934 ₁₀- 2;     1.24762 ₁₀+ 0;     1.17538 ₁₀- 1;    -2.63489 ₁₀- 2;
 -2.75607 ₁₀+ 0;    -1.88841 ₁₀- 1;     3.53296 ₁₀- 2;    -1.55751 ₁₀- 1;     1.55338 ₁₀+ 0;     2.31443 ₁₀- 1;
  4.74860 ₁₀- 2;    -4.36873 ₁₀+ 0;    -2.93249 ₁₀- 2;     1.05466 ₁₀- 1;    -1.74751 ₁₀- 1;     2.47311 ₁₀+ 0;
```

TABLE A2

```
MATRIXAIBAI
           -1;
            2;
           12;
           12;

  3.88817 ⏨- 1;     4.90910 ⏨- 2;    -3.09332 ⏨- 2;    -9.37118 ⏨- 3;     4.21877 ⏨- 1;    -2.10153 ⏨- 2;
 -2.88094 ⏨- 2;     2.84321 ⏨- 1;     2.01229 ⏨- 2;    -2.05380 ⏨- 2;    -8.01858 ⏨- 2;     3.19816 ⏨- 1;
 -5.12853 ⏨- 2;    -8.35342 ⏨- 2;     3.57446 ⏨- 1;     9.51555 ⏨- 2;    -1.91736 ⏨- 1;    -1.74618 ⏨- 1;
 -3.33916 ⏨- 2;    -4.84930 ⏨- 2;    -1.65198 ⏨- 2;     5.44662 ⏨- 1;    -9.01687 ⏨- 2;    -1.87925 ⏨- 1;
 -3.96018 ⏨- 2;    -2.31689 ⏨- 2;     1.06505 ⏨- 3;     4.12633 ⏨- 4;    -1.89197 ⏨- 1;    -3.03568 ⏨- 2;
  2.80377 ⏨- 3;    -2.60165 ⏨- 2;    -2.02874 ⏨- 2;    -7.16813 ⏨- 4;    -8.42147 ⏨- 3;    -1.71759 ⏨- 1;
 -5.70995 ⏨- 3;     2.93077 ⏨- 3;    -2.61841 ⏨- 2;    -3.41146 ⏨- 2;    -7.16796 ⏨- 3;    -1.51373 ⏨- 2;
 -1.65141 ⏨- 3;    -1.21948 ⏨- 2;     3.17311 ⏨- 4;    -6.63110 ⏨- 3;    -1.16688 ⏨- 2;    -2.49001 ⏨- 2;
 -1.62772 ⏨- 1;     8.42530 ⏨- 3;     5.79646 ⏨- 3;    -1.10984 ⏨- 3;     3.90684 ⏨- 2;     3.56133 ⏨- 2;
 -2.63056 ⏨- 2;    -1.79650 ⏨- 1;     1.05281 ⏨- 2;     4.78486 ⏨- 3;    -3.82832 ⏨- 2;    -1.96084 ⏨- 2;
  1.07221 ⏨- 2;    -3.00543 ⏨- 2;    -2.22814 ⏨- 1;     4.91094 ⏨- 3;     1.45197 ⏨- 2;    -4.24555 ⏨- 2;
 -1.28627 ⏨- 2;     3.76941 ⏨- 3;    -5.58952 ⏨- 2;    -3.60123 ⏨- 1;    -2.54427 ⏨- 2;    -1.07485 ⏨- 2;



 -7.89253 ⏨- 2;    -2.08022 ⏨- 2;    -8.56827 ⏨- 2;    -2.18166 ⏨- 1;    -8.37091 ⏨- 2;    -3.87816 ⏨- 2;
 -4.48568 ⏨- 2;    -4.16064 ⏨- 2;    -2.62470 ⏨- 1;    -2.48764 ⏨- 1;    -1.18478 ⏨- 1;    -5.57390 ⏨- 2;
  5.04913 ⏨- 1;     5.08528 ⏨- 2;    -3.15222 ⏨- 1;    -4.17448 ⏨- 1;    -3.67965 ⏨- 2;    -6.62743 ⏨- 2;
  5.90142 ⏨- 2;     7.54850 ⏨- 1;    -1.83353 ⏨- 1;    -2.96008 ⏨- 1;    -9.69459 ⏨- 2;     1.28699 ⏨- 1;
  8.84380 ⏨- 3;     3.01117 ⏨- 5;    -3.75123 ⏨- 2;     1.68060 ⏨- 2;     8.51165 ⏨- 3;     2.76239 ⏨- 3;
 -2.53976 ⏨- 2;     2.29691 ⏨- 3;    -3.60853 ⏨- 3;    -5.36840 ⏨- 2;     2.35628 ⏨- 3;     1.12127 ⏨- 3;
 -2.14442 ⏨- 1;    -4.82595 ⏨- 2;    -8.20120 ⏨- 3;    -2.26393 ⏨- 2;    -7.92788 ⏨- 2;    -3.62988 ⏨- 3;
 -2.71977 ⏨- 2;    -2.78617 ⏨- 1;    -2.35917 ⏨- 2;    -3.07667 ⏨- 2;    -3.10246 ⏨- 2;    -1.10548 ⏨- 1;
  6.46414 ⏨- 5;    -1.33517 ⏨- 4;     2.88072 ⏨- 1;     1.41802 ⏨- 2;    -7.37072 ⏨- 3;     5.91629 ⏨- 4;
  3.45736 ⏨- 2;     1.51823 ⏨- 3;    -1.56146 ⏨- 2;     2.41541 ⏨- 1;     2.10377 ⏨- 2;    -5.88362 ⏨- 3;
 -3.17987 ⏨- 2;     4.68486 ⏨- 2;     1.24539 ⏨- 2;    -2.39785 ⏨- 2;     3.06201 ⏨- 1;     4.62850 ⏨- 2;
 -7.30121 ⏨- 2;    -8.41436 ⏨- 2;    -3.57984 ⏨- 2;    -1.79936 ⏨- 2;    -7.06534 ⏨- 2;     4.71380 ⏨- 1;
```

TABLE A3

```
SYMMETRICAL CASE

               ALPHA 1                ALPHA 2              NCASELHS
                                                                  -1;
                                                                   2;
P = 1
          +1.00000 0000 ⏨ +0    +3.15816 2432 ⏨ -1                12;
          +1.00000 0000 ⏨ +0    +9.53621 9638 ⏨ -1                 3;
          +1.00000 0000 ⏨ +0    +1.60246 8661 ⏨ +0
          +1.00000 0000 ⏨ +0    +2.03601 4164 ⏨ +0      3.75681 ⏨- 1;    4.08255 ⏨- 1;    4.82662 ⏨- 2;
                                                         4.19732 ⏨- 1;    6.09797 ⏨- 1;   -2.36902 ⏨- 2;
P = 2                                                    3.93679 ⏨- 1;    7.45282 ⏨- 1;   -7.10178 ⏨- 2;
          +1.00000 0000 ⏨ +0    +7.38821 6111 ⏨ -1      2.42917 ⏨- 1;    5.31468 ⏨- 1;   -3.63451 ⏨- 2;
          +1.00000 0000 ⏨ +0    +1.37662 7332 ⏨ +0     -2.60362 ⏨- 2;   -7.58509 ⏨- 2;   -3.57480 ⏨- 2;
          +1.00000 0000 ⏨ +0    +2.02547 4029 ⏨ +0     -1.91310 ⏨- 3;   -4.85807 ⏨- 2;   -3.38936 ⏨- 2;
          +1.00000 0000 ⏨ +0    +2.45901 9532 ⏨ +0      1.26535 ⏨- 2;   -1.66086 ⏨- 2;   -3.90490 ⏨- 2;
                                                         2.73770 ⏨- 2;    2.97818 ⏨- 2;   -3.65022 ⏨- 2;
P = 3                                                    9.52352 ⏨- 3;    4.22799 ⏨- 2;    2.71048 ⏨- 2;
          +1.00000 0000 ⏨ +0    +1.07804 5578 ⏨ +0     -1.70056 ⏨- 3;   -1.76678 ⏨- 3;    7.23634 ⏨- 4;
          +1.00000 0000 ⏨ +0    +1.71585 1299 ⏨ +0     -3.66449 ⏨- 3;   -1.59064 ⏨- 2;    2.81880 ⏨- 3;
          +1.00000 0000 ⏨ +0    +2.36469 7996 ⏨ +0      3.05051 ⏨- 2;    5.03372 ⏨- 2;   -2.84888 ⏨- 2;
          +1.00000 0000 ⏨ +0    +2.79824 3499 ⏨ +0



               ALPHA 1                ALPHA 2                ALPHA 3

  IL      +2.97494 8308 ⏨ +0    +4.70574 3876 ⏨ +0    -1.94400 6381 ⏨ -1

 -IM      +3.51325 5630 ⏨ +0    +6.39610 5310 ⏨ +0    -1.10246 2074 ⏨ -1

 -IMS     +5.04259 7838 ⏨ +0    +1.00269 7455 ⏨ +1
```

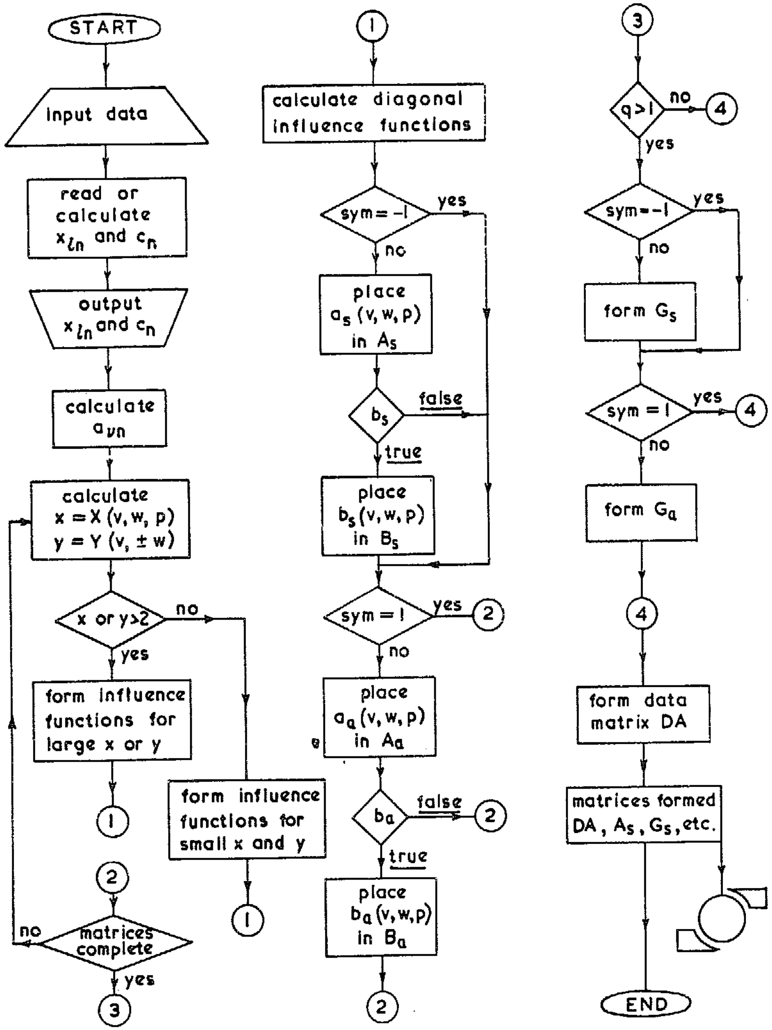

FIG. 1. General flow diagram for Part I.

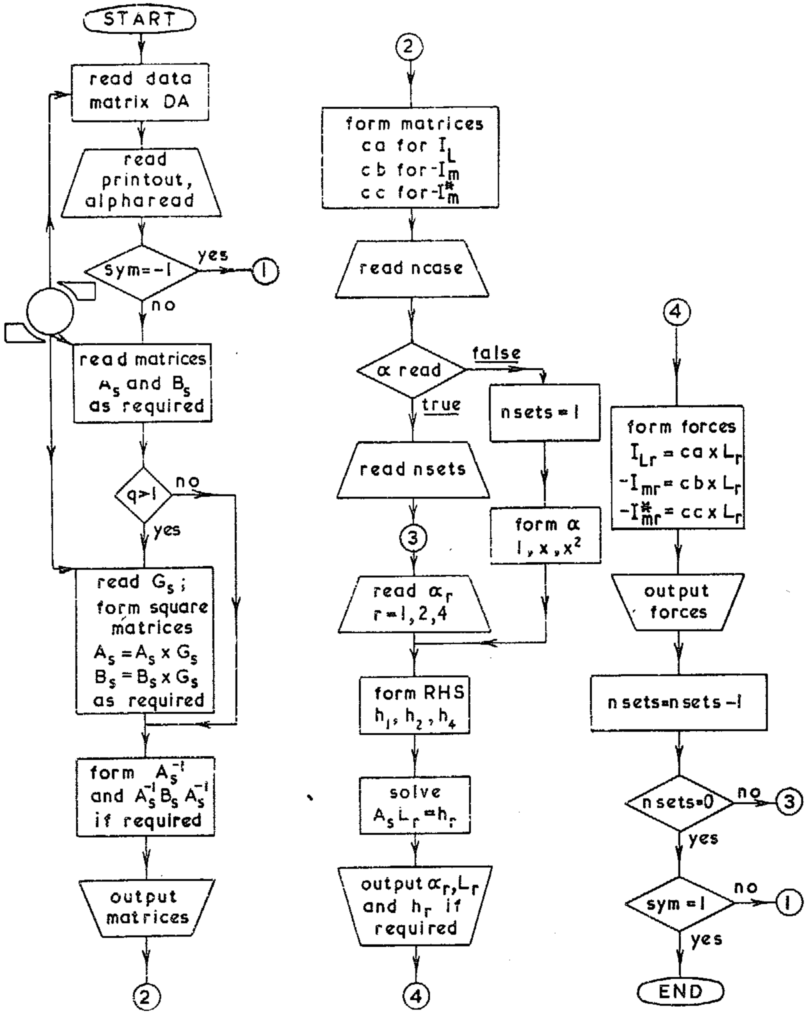

FIG. 2a. General flow diagram for Part II.

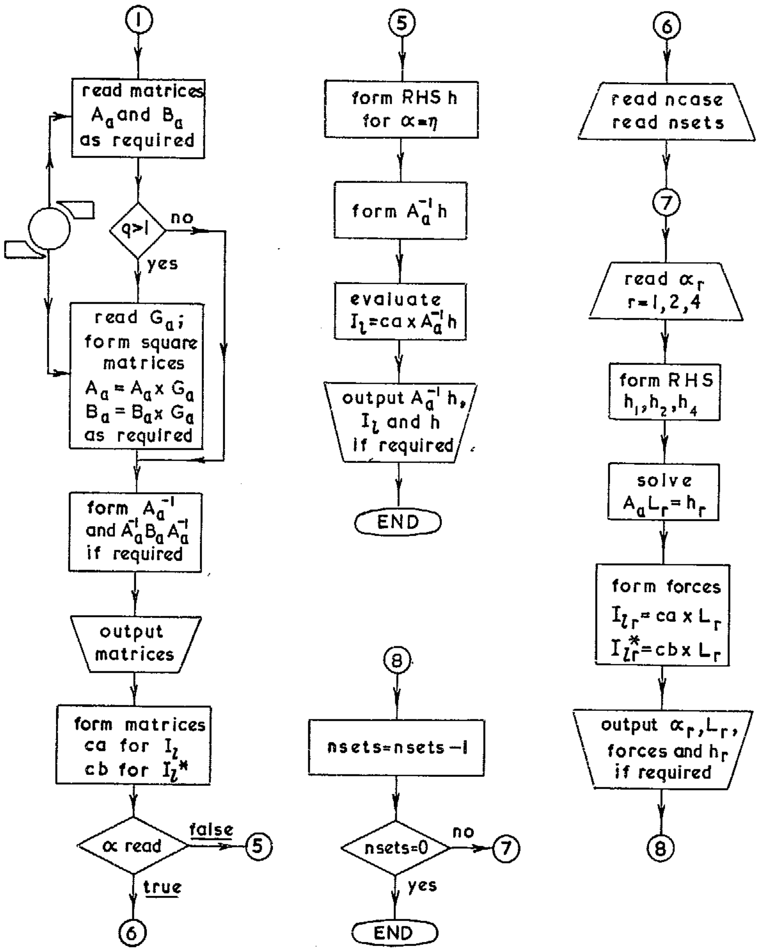

FIG. 2b. General flow diagram for Part II. (contd.)

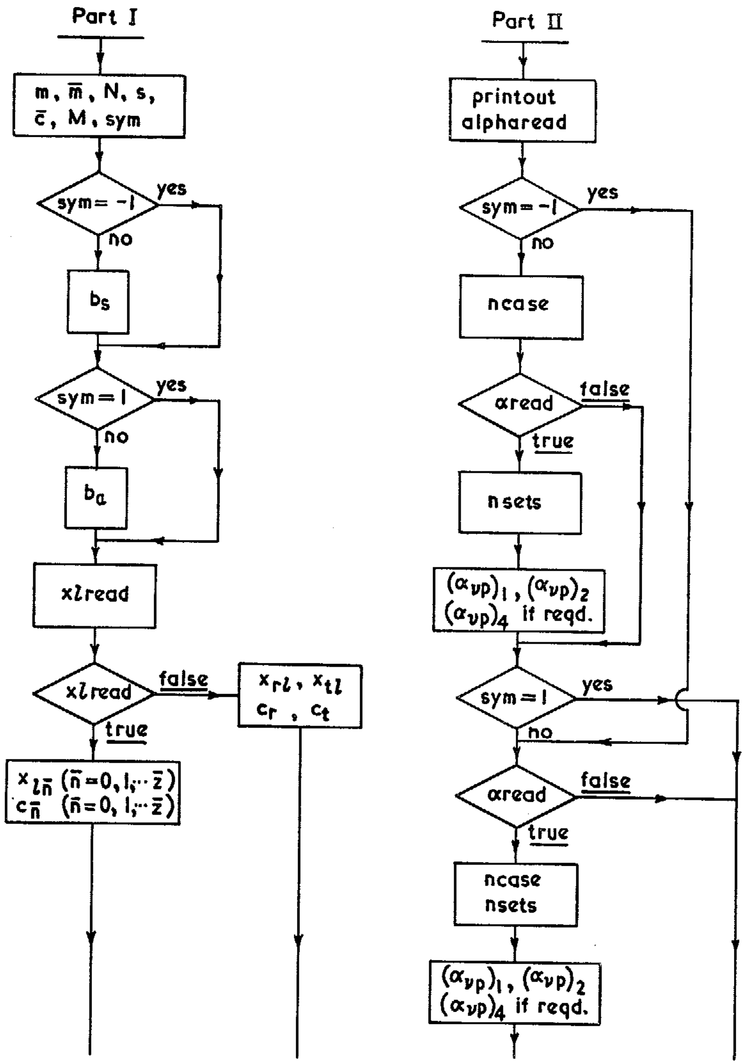

FIG. 3. Flow diagrams for input data.