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MINISTRY OF SUPPLY

**NATIONAL GAS TURBINE ESTABLISHMENT
PYESTOCK, HANTS.**

MEMORANDUM No. M.257

**A LABORATORY
THERMAL SHOCK TEST
BASED ON THE USE OF
A FLUIDISED BED**

by

J. NORTHWOOD and S.W.K.SHAU

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NATIONAL GAS TURBINE ESTABLISHMENT

A laboratory thermal shock test based on the use
of a fluidised bed

- by -

J. E. Northwood and S. W. K. Shaw

SUMMARY

A laboratory test for studying the thermal shock behaviour and assessing the thermal shock resistance of gas turbine blade materials has been developed using a fluidised bed as the cooling medium. The heat transfer characteristics of fluidised solids have been measured, using different bed materials. The most important factors governing the heat transfer to a fluidised bed appear to be the gas flow rate, the particle size and the thermal properties of the fluidising gas. Heat transfer coefficients of a similar order to those calculated for current gas turbine blading are obtainable. Preliminary thermal shock tests from 900°C to 1000°C have been made on a number of ceramic and cermet compositions and a creep resistant alloy using a symmetrically tapered disc test-piece.

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1.0 Introduction

In uncooled gas turbine designs for aircraft, the current trend is towards the use of higher blade temperatures in order to obtain greater engine thrusts. Blade materials that have adequate resistance to steady and fluctuating stresses at higher operating temperatures than is possible with existing metallic materials, are being considered. However, with increase in blade temperature, the transient stresses arising from temperature gradients generated by rapid heating (e.g. during starting and acceleration), and by rapid cooling (e.g. during shut-down or in the event of an accidental fuel cut) become more severe. The subjection of the material to these transient thermal stresses is termed thermal shock. The effect on the blade material will depend on the magnitude and number of repetitions of the transient thermal stresses and the temperature at which these are developed. If the value of the maximum thermal stress exceeds the maximum breaking stress of the material, then failure will occur. In ductile materials, e.g. metals, the capacity for relieving the stress by plastic deformation is all important, and therefore repeated cycles of heating and cooling are usually necessary to cause failure by cracking or to make replacement of the blades necessary due to an unacceptable degree of distortion.

The use of ceramics has been suggested¹ for turbine blading because of their attractive high strength properties at temperatures for which current blading alloys are inapplicable. However the major deterrent to the application of most ceramics is their relatively poor thermal shock resistance. In order to provide some degree of ductility and therefore to improve thermal shock resistance, the introduction of a metal phase to the ceramic giving a ceramic/metal mixture or cermet has been considered.

It was therefore essential to develop a method of studying the thermal shock behaviour i.e. the factors involved and the effects produced by thermal shock, and of assessing the thermal shock performance of such materials, and also of both existing and potentially useful metallic materials. This Memorandum is concerned with the development of a laboratory thermal shock test and of the results of preliminary tests on ceramic and cermet compositions.

2.0 Methods of studying thermal shock behaviour

Both theoretical and experimental approaches have been made to the study of the thermal shock behaviour of materials.

2.1 Theoretical methods

The magnitude of the thermal stresses produced by thermal shock in elastic materials is dependent on the transient thermal strains developed and the Young's Modulus of the material. The transient thermal strains are dependent on the temperature differences produced in the material, and the thermal coefficient of expansion. The temperature difference is governed by the geometry of the shape (e.g. thin sections will cool more rapidly than massive sections), the rate of heating or cooling, and the thermal conductivity of the material. A thermal shock resistance index:-

$$\frac{k_s \cdot \sigma}{E \cdot \alpha}$$

[See Appendix I for List of Symbols]

has been suggested by several investigators^{1,2,3} as a means of assessing the approximate relative thermal shock resistance of elastic materials of similar shape and size, and heated or cooled rapidly under the same conditions. However, thermal conductivity (k_s) of the material is of less importance at high values of the non-dimensional parameter $\frac{a \cdot h}{k_s}$ (i.e. for large sized specimens of half thickness a , and high heat transfer coefficient, h) and therefore the index:-

$$\frac{\sigma}{E \cdot a}$$

is often also used. Indices of the above types are applicable only to brittle i.e. non-ductile materials.

Theoretical investigations are being made to determine the temperature and stress distributions in turbine blade shapes during rapid heating and cooling and, if possible, to derive formulae for the correlation of thermal shock behaviour with material properties, dimensional factors and heat transfer rates. For such complex shapes it was considered that mathematical solutions were more likely to be obtained in successive stages, commencing with a simple shape such as a circular cylinder. The theoretical investigations have been initially confined to brittle materials where failure occurs in one cycle. Preliminary experiments have established⁴ the validity of the theory for the calculation of these transient thermal stresses developed in rapidly cooled alumina cylinders. The theoretical approach has limitations to its usefulness for ductile materials owing to the complex nature of the problem and the number of variables involved.

2.2 Experimental methods

For the experimental study of thermal shock phenomena it is necessary to heat and cool specimens under controlled conditions of heat transfer, preferably similar to those at the blades of a gas turbine. Manson⁵ has pointed out the importance of heat transfer rate by showing that with air cooling (i.e. low rate of heat transfer), beryllia had superior thermal shock resistance to alumina, but on water quenching (i.e. high rate of heat transfer) the order of merit was reversed, the thermal shock resistances being expressed as the minimum temperature differential to cause failure. Although the local heat transfer coefficient (h) may vary over the surface of an aircraft gas turbine blade by a factor approaching 8, the mean values of heat transfer coefficient at a turbine blade for applications representing the extremes of engine size and operating conditions may lie between 0.02 and 0.10 c.h.u./ft² s^{0.5}. A useful laboratory thermal shock test should therefore be capable of attaining mean heat transfer coefficients within this range, preferably by forced convection, in order to simulate engine conditions.

It is generally accepted that for most brittle materials, the thermal shock arising from rapid cooling is more detrimental than that arising from rapid heating, mainly because, in the former case, the surface stresses are tensile. The tensile strengths of ceramic and cermet materials are generally considerably lower than the compressive strengths. It was therefore desirable to concentrate on methods of rapidly cooling specimens, with a view to selecting the preferred method for a laboratory thermal shock test.

In the choice of a suitable test, consideration must be given to the mode of heat transfer. Liquid metal baths are unsuitable, since, while they may give heat transfer coefficients of the right order, the mode of heat transfer is initially by conduction, due to the high conductivity of the liquid metals relative to air. As shown in the diagrams in Figure 1, this results in a different temperature gradient and consequently a different stress pattern in the material from that produced by forced convective cooling. Where repeated heating and cooling cycles are to be carried out, liquid metal adhering to the test-piece would be difficult to remove and possibly involve corrosion problems on reheating the test-piece after the quenching cycle. Quenching into oil or water has the disadvantage that at a certain specimen temperature, dependent on the temperature and degree of agitation of the liquid during quenching, the heat transfer is appreciably increased due to the breakdown of the vapour phase around the specimen and subsequent direct cooling by the liquid. Figure 2 shows typical cooling curves for water at room temperature and near boiling point with both stationary and rotating test-pieces. The change in slope of the curves is readily apparent in the tests on a stationary specimen in cold water while for the corresponding test-piece rotated in a circle at a peripheral speed of 1 ft/s, a very high heat transfer is obtained soon after the test-piece has started to cool. Water spray cooling has the disadvantage that the test-piece is alternately cooled by water and air as each water droplet hits the surface and is evaporated, causing a succession of local thermal shocks. Such non-uniform heat transfer rates were considered undesirable.

Thermal shock tests can be carried out by heating local areas of the test-piece such that the unheated portion restrains the thermal expansion of the heated zone, followed by rapid cooling (e.g. by an air blast). Alternatively, continuous cooling of the unheated portion of the test-piece can be effected while a zone or edge of the test-piece is intermittently heated.

Rapid heating in high velocity, high temperature gases, followed by rapid cooling in high velocity air at controlled rates and pressure could be used, as for rig tests on a cascade of blade shapes. Such rigs involve the use of large quantities of air and fuel, are costly to install and operate and are therefore undesirable for a laboratory test. Heat transfer conditions similar to those occurring in an engine would be possible by rotating a test-piece in hot or cold gases preferably at high pressure (e.g. 10 to 20 atmospheres), so that relatively low rotational speeds (i.e. 3,000 rev/min) could be used. The design of such apparatus presents practical difficulties, particularly for repeated tests using both heating and cooling shock cycles.

From the work of previous investigators⁶⁻¹¹ it was evident that fluidised beds had heat transfer properties of the same order as that required for a laboratory thermal shock test. Fluidisation of a bed of powdered solids is achieved by supporting the material on a porous plate through which gas is blown. At a critical mass flow rate (G_0) of the fluidising gas, the particles disperse and are supported by the gas, such that the bed of powder has a similar appearance to a liquid. The mechanism of heat transfer in a fluidised bed is not fully understood. The most convincing explanation is that heat is transferred from the surface of a relatively hot object placed in the fluidised bed, through the surface gas film and the particle gas film, to the particle surface; the heat is then mainly carried away by the particles and transferred to the walls of the container. The fluidising gas should therefore have a high thermal conductivity, high specific heat and low viscosity in order to promote high rates of heat transfer to the particles. Bed materials of high specific heat,

high density and small particle size would be expected to give high heat transfer coefficients, on account of their high thermal capacity and high surface area per unit volume. Materials of high bulk density should give high heat transfer rates by virtue of the greater gas flow required to fluidise them.

Using a small air mass flow relative to a rig test a fluidised bed can be readily used as a medium for rapidly cooling heated specimens. Flexibility of operation and control of the heat transfer coefficient (h) is possible, and the design of thermal shock test-piece is subject to few limitations. A study of the separate and combined effects of cycles of rapid heating and cooling is important. For the heating cycle a hot fluidised bed is being developed.

3.0 The heat transfer characteristics of experimental fluidised beds

While it was undesirable for the development of the laboratory thermal shock test to make a complete investigation of the factors governing heat transfer rates in fluidised beds, it was evident that there was only sufficient agreement amongst previous investigators to give qualitative guidance on the relative importance of those factors which would promote the maximum heat transfer rates and also uniform fluidisation. A range of metal and refractory powders viz. chromium, wolfram, stainless steel, silica and silicon carbide were chosen as bed materials for this work, several closely sized fractions of powder being used for the last three of these materials. Values of the heat transfer coefficient (h) were obtained for each closely sized fraction of bed material at air flow rates ranging from that required to just fluidise the bed (G_0) to the point where part of the bed material was entrained in the air stream. In a few experiments, a 90 per cent nitrogen 10 per cent hydrogen gas mixture was used as the fluidising gas. Further details of this work are given in Appendix II.

The work on heat transfer in fluidised beds agrees with most previous workers that small sized bed materials give higher heat transfer coefficients than large sized material, although there appears to be a lower limit to the particle size that will give the maximum (h) value. The effects of individual physical properties of the powder on the heat transfer to a fluidised bed have not been established, although such effects appear to be small. Heat transfer to the bed is influenced predominantly by the mass flow of air passing through the bed material.

The results indicate that reproducible heat transfer coefficients within the range 0.02 to 0.04 c.h.u./ft² s °C can be obtained by using a number of different bed materials, some of which viz. 150 to 170 and 170 to 200 mesh silicon carbide, 240 to 300 mesh stainless steel and 150 to 170 mesh Chelford silica sand will give (h) values over the whole range by suitable control of the air mass flow (G) through the bed.

4.0 The design of thermal shock test

4.1 Apparatus

The experimental work confirmed that heat transfer coefficients of the same order as those occurring under engine conditions could be obtained using a fluidised bed for the rapid cooling of heated specimens. The construction of a thermal shock test apparatus based on a fluidised bed was therefore completed, the apparatus being shown schematically in Figure 3. This consists of a fluidised bed A surmounted by a vertical electric resistance tube furnace B with a "Kanthal A.1" element, capable of reaching

temperatures up to 1,300°C. The bed, 6 in. diameter, and 6 in. deep rests on a sintered bronze filter (grade C Porosint) having a mean pore size of 12.5 μ . This part of the container is water-cooled, the flow rate of water being maintained constant. Another water jacket surrounds the top of the container which is surmounted by the furnace. Between the filter and the air inlet, a diffusion chamber is interposed so that the air reaching the filter is at a uniform flow rate and pressure over the cross-section of the container. The main air stream from the fluidised bed passes through an exit duct, G. A door, H, is provided in the container to permit attachment and removal of test pieces. These are held in a carrier, C, mounted on the end of a rod, which, at its upper end, is attached to a ram, D. This is held vertically in a steel framework which also supports the furnace and fluidised bed. The rod passes through an aperture at the top of the furnace, the annulus being kept as small as possible to reduce any upward flow of air from the fluidised bed through the furnace. A water jacket, E, surrounds this opening, with a sighting window, F, at one side of the jacket. The ram is pneumatically operated to ensure that the time taken to transfer a test-piece from the furnace to the bed is kept to a minimum i.e. less than 1 second. Electro-magnetically operated air valves, I, are used to operate the ram, in conjunction with a suitable timer, J. This is adjusted to keep the ram in the "up" position during the heating period, and in the "down" position during the cooling period. A counter K is fixed to the framework and records the movement of the ram and hence the number of thermal shock cycles.

Ancillary equipment for the thermal shock test comprises a rotameter for measuring the air flow rate through the fluidised bed, air valves and pressure gauges, an air drier and an air filter. Air is supplied at a pressure of 80 lb/in² from a stabilised compressor.

4.2 Test-piece design

The test-piece normally used is a symmetrically tapered disc the shape and dimensions being as shown in Figure 4. This shape was preferred to that of a plain cylinder or disc, because it was considered that the thickness should vary, as in an aerofoil section. The maximum stress is developed at the periphery of the disc and will vary with the edge radius. The edge radius is similar to that of the trailing edge radius of current turbine rotor blading i.e. 0.010 to 0.020 in. Being of small size, the ceramic and cermet specimens were easily manufactured in the form of plain discs, and subsequent machining, using either carbide or diamond grinding, presented no difficulty.

5.0 Experimental procedure

All test-pieces were checked for surface defects before thermal shock testing. Three test-pieces were fixed in the carrier shown in Figure 5. They were mounted on a horizontal rod passing through the central hole of each test-piece and held loosely between wires inserted through holes in the rod. Inspection of test-pieces was carried out initially after every cycle, but for tests of long duration, this was reduced to an examination after every ten cycles.

5.1 Test conditions

The test-pieces were slowly heated in the furnace for eight minutes (mean heat transfer co-efficient of 0.005 c.h.u./ft² s °C) and then immersed in the fluidised bed for two minutes. For a given bed material the required heat transfer coefficient was obtained by control of the air mass flow through

the bed. The bed material used for these tests was 150 to 170 mesh silicon carbide. The amount of air required to obtain heat transfer coefficients between 0.02 to 0.04 c.h.u./ft² s °C ranged from 6 to 320 lb/hr ft².

5.2 Criterion of failure

In the absence of fracture, the criterion of failure was taken as the appearance under examination with a binocular microscope at x 60 magnification of a crack in the test-piece surface. As an aid to the examination for cracks, two techniques have been used. The first consists of immersing the test-piece in a solution of coloured wax in benzene. The solution penetrates the cracks and after the test-piece has been cleaned with benzene, the cracks are made more readily visible by the presence of the coloured wax. Another method was to paint the test-piece with a red penetrant dye, wash in water and allow the dye remaining in the crack to seep out and outline the crack. This latter method has proved very successful in revealing fine "crazing" cracks on ceramic and cermet test-pieces.

6.0 Preliminary thermal shock test results

Approximately sixty thermal shock tests have been completed using the $\frac{1}{8}$ in. diameter tapered disc test-piece shown in Figure 4 and the fluidised bed as the cooling medium. These tests were intended to assess the relative thermal shock resistances of materials which included metal/oxide mixtures, metal bonded carbides, a silicon carbide composition, molybdenum disilicide, and Nimonic 95 as a reference material. The nominal compositions and suppliers of these materials are given in Table I.

The results of the multi-cycle thermal shock tests carried out initially from 1,000°C and 900°C (and later from 1,020°C) into a fluidised bed at 20°C, are given in Table II.

The criterion of failure (i.e. examination for cracks with a binocular microscope at x 60 magnification) has obvious limitations when examining oxidised i.e. scaled surfaces. It has been found that when a crack is visible in a ceramic or cermet specimen, the crack usually extends radially from the edge of the specimen to at least three-quarters of the way up the tapered section. Experience has shown that within the frequency of examination a crack is either not visible or is of considerable length. On the other hand, with metallic specimens, relatively small cracks, which are revealed after a greater number of cycles and propagate slowly, are usually found.

It will be recalled that a metal phase is added to a ceramic (forming a cermet) to introduce some ductility and increase the thermal shock resistance. It is thought that until sufficient metal is added to form a continuous metallic network (approximately 40 per cent chromium in the chromium-alumina compositions prepared by Flessey Co. Ltd.) little change in thermal shock resistance will be obtained. Further increase in metal content would be expected to produce corresponding increase in thermal shock resistance. Contrary to expectations, the thermal shock properties of the Flessey 70 per cent chromium-alumina composition are no better than the 20 per cent chromium-alumina material. Five 0.020 in. edge radius test-pieces in the 70 per cent chromium-alumina material failed after one cycle from 1020°C ($\Delta T = 1,000^\circ\text{C}$) with a mean (h) value of 0.04 c.h.u./ft² s °C. The Haynes-Stellite 79 per cent chromium-alumina test-piece with 0.020 in. edge radius withstood without failure 430 cycles with a temperature difference of 1,000°C and similar (h) value, while under similar testing conditions with an 0.010 in. edge radius, three test-pieces failed after

70, 130 and 730 cycles respectively. It is readily apparent that this chromium-alumina material is considerably superior in thermal shock resistance to the other chromium-alumina cermets. This difference may possibly be due to the different methods of manufacture and to differences in structure. The Haynes-Stellite composition is made by direct mixing of chromium and alumina followed by cold pressing and sintering, and has a coarse-grained structure. The Plessey materials are prepared by mixing chromic oxide, carbon and alumina, followed by reduction of the chromic oxide by the carbon prior to pressing and sintering, and have a much finer grained structure.

The two metal-bonded titanium carbide types of cermet appear to have similar thermal shock resistances, the 40 N (Hard Metal Tools Ltd.) composition being slightly superior. Both materials are somewhat inferior to the Haynes-Stellite 79 per cent chromium-alumina. Two ceramics, molybdenum disilicide and silicon carbide, have been tested. The former appears to have a slightly greater thermal shock resistance than the Plessey chromium-alumina materials. Tests on the "Niafrax" silicon carbide were carried out with a temperature difference of 1,000°C and a mean (h) value of 0.04 c.h.u./ft² s °C on test-pieces with 0.010 in. edge radius. Failure of three test-pieces occurred after 45, 120 and 180 cycles respectively. These results indicate that this material has thermal shock properties intermediate between those of the Haynes-Stellite material and the titanium carbide base cermets.

A few tests at different edge radii have been completed on the reference alloy Nimonic 95. A test-piece of edge thickness approximately 0.001 in. failed in 70 cycles, and an 0.005 in. edge radius test-piece in 140 cycles, the test conditions being a temperature difference of 1,000°C and an (h) value of 0.04 c.h.u./ft² s °C. Under similar test conditions three 0.010 in. edge radius test-pieces failed by cracking after 490, 690 and 750 cycles respectively. As expected, Nimonic 95 is generally superior in thermal shock resistance to the ceramics and cermets, but by comparison, one test-piece of the 79 per cent chromium-alumina (tested simultaneously with Nimonic 95) showed a surprisingly high endurance. In those tests on Nimonic 95 where endurances of the order of 400 cycles and above were obtained, it is probable that excessive oxidation (aggravated by spalling of the oxide during successive heating and cooling cycles) contributed to the failure of the specimens.

Typical thermal shock failures of the disc test-piece are shown in Figure 6, together with a microsection showing intercrystalline thermal shock cracks in one of the Nimonic 95 test-pieces.

Insufficient thermal shock tests have been made to indicate whether any close relationship exists between the thermal shock indices for the experimental materials (see Table III) and the test results. Also, insufficient data is available to compile an index for 20 per cent and 40 per cent chromium-alumina, "Niafrax" silicon carbide, "Carbometal" and molybdenum disilicide.

From the $\frac{\sigma}{\alpha E}$ indices for the 30 per cent chromium-alumina (which has not been tested in thermal shock but should be intermediate in performance to the 20 per cent and 40 per cent chromium-alumina and 79 per cent chromium-alumina, similar performance could be expected. Comparing the $\frac{k_s \sigma}{\alpha E}$ indices, the superiority of the 79 per cent chromium-alumina is evident and is borne out by the test results. However, for cermets the thermal shock index is not a true indication of thermal shock resistance since the slight ductility introduced by the metal phase has a considerable effect on thermal shock resistance, a factor which is not included in the index.

7.0 Appraisal of thermal shock test

The interim results obtained with this test serve to show that the testing method based on the use of a fluidised bed for rapid cooling determines the relative thermal shock resistances of brittle and ductile materials. In its present form, the thermal shock test is not a rapid test, mainly due to the fact that the heating rates are slow and that the entire specimen (not just the region at the edge) is heated to the desired temperature prior to the cooling cycle. High frequency heating of the specimen is being considered but a method which more closely simulates engine conditions e.g. using a hot fluidised bed is considered preferable and is being investigated. If successful, a two minute or even a 90 second heating and cooling cycle respectively is possible, using the same shape and size of specimen. The merits of the present test are that controlled, reproducible and uniform heat transfer rates can be readily employed and can be maintained or varied over a limited range of values, which are of the same order as those estimated for engine conditions. The test can therefore be used to study the effect of variation in the cooling conditions (i.e. varying heat transfer coefficient and temperature differential) and of specimen size, shape, composition and structure on thermal shock phenomena. Although it may not define exactly how a new material will behave in an actual engine, it makes possible comparison of the thermal shock resistances of new high temperature materials under controlled cooling conditions.

8.0 Conclusions

8.1 A laboratory thermal shock test based on the use of a fluidised bed for the cooling cycle has been developed.

8.2 Experiments on heat transfer in fluidised beds have shown that for a given bed material, the most important factor controlling the heat transfer to a fluidised bed is the rate of gas flow through the bed. Although, in general, fine particles give higher heat transfer coefficients, there appears to be a lower limit to the particle size for maximum heat transfer coefficient.

8.3 Controlled and reproducible heat transfer rates of a similar order to those estimated for current gas turbine blading, and capable of being varied over a small range of values (i.e. heat transfer coefficients of 0.02 to 0.04 c.h.u./ft² s °C) have been obtained.

8.4 Preliminary thermal shock tests indicate that the 20 and 40 per cent chromium-alumina compositions and molybdenum disilicide have poor thermal shock resistance. One oxide cermet (79 per cent chromium-alumina), silicon carbide and the carbide cermets tested have reasonably good thermal shock resistance, although none are as good as the reference alloy, Nimonic 95.

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TABLE I
Nominal compositions and suppliers of materials tested

Material designation	Supplier	% Nominal chemical composition by weight					
		Al ₂ O ₃	TiC	Cr ₂ O ₃	Ni	Cr	Others
20% chromium-alumina	Flessey Co. Ltd., Towcester, Northants	80	-	-	-	20	4% Cr ₂ O ₃ in solid solution
40% chromium-alumina	Flessey Co. Ltd., Towcester, Northants	60	-	-	-	40	4% Cr ₂ O ₃ in solid solution
70% chromium-alumina	Flessey Co. Ltd., Towcester, Northants	30	-	-	-	70	9/10% Cr ₂ O ₃ in solid solution
7% chromium-alumina	Haynes-Stellite Divi- sion of Union Carbide & Carbon Co., U.S.A.	21	-	-	-	79	9/10% Cr ₂ O ₃ in solid solution
40N	Hard Metal Tools Ltd., Coventry.	-	54	6	40	-	-
"Carbometal"	Carbometals Ltd., St. John's Wood, London	-	TiC-based cermet with TiC/NbC/TaC in solid solution and Ni/Cr binder				-
Molybdenum disilicide, MoSi ₂	Flessey Co. Ltd., Towcester, Northants	-	-	-	-	-	-
"Miafrax" silicon carbide	Carborundum Co. Ltd., Manchester.	-	-	not known	-	-	-
Nimonic 95	Henry Wiggin & Co. Ltd.	-	-	-	bal.	18/21	15/21 Co. 2.3/ 3.5 Ti, 1.4/2.5 Al

TABLE II

Thermal shock test results

Material	Manufacturer	Edge radius	Heat transfer coefficient (h) c.h.u./ft ² s°C	Temperature differential (ΔT)°C	No. of cycles to failure
20 per cent chromium-alumina, cold pressed and sintered	Flessey Co. Ltd.	0.020"	0.04	980	3; 3; 3
40 per cent chromium-alumina, hot pressed	Flessey Co. Ltd.	0.020"	0.04	980	1*; 2*
			0.04	1000	1*; 1*; 2
			0.03	1000	1*; 1*
40 per cent chromium-alumina, cold pressed and sintered	Flessey Co. Ltd.	0.020"	0.04	1000	1; 1; 1; 2
70 per cent chromium-alumina, cold pressed and sintered	Flessey Co. Ltd.	0.010"	0.04	1000	1
			0.03	1000	1
			0.02	1000	1; 1; 1
			0.04	1000	1; 1; 1; 1
			0.03	1000	2
79 per cent chromium-alumina, cold pressed and sintered	Haynes-Stellite Co.	0.010"	0.04	1000	70; 130; 730
			0.04	1000	430 (U.C)

* Fractured
 U.C Uncracked
 (Continued overleaf)

TABLE II (cont'd)

Material	Manufacturer	Edge radius	Heat transfer coefficient (h) c.h.u./ft ² s°C	Temperature differential (ΔT)°C	No. of cycles to failure
54 per cent titanium carbide 6 per cent chromium carbide 40 per cent nickel (4CN) cold pressed and sintered	Hard Metal Tools Ltd.	0.010"	0.04	1000	40; 45; 60
		0.010"	0.04	880	50; 120; 400 (U.C)
Ni/Cr bonded TiC containing NbC/TaC (in solid solution) cold pressed and sintered	Carbometal Ltd.	0.010"	0.04	880	130; 330
		0.010"	0.04	1000	10*
Molybdenum disilicide, hot pressed	Flessey Co. Ltd.	0.020"	0.04	1000	1; 2; 2*; 2*; 7*
			0.03	1000	1*; 8*; 10
"Miafrax" silica carbide	Carborundum Co. Ltd.	0.010"	0.04	1000	45; 120; 180
Nimonic 95	H. Wiggin & Co. Ltd.	0.001"	0.04	1000	70
		0.005"	0.04	1000	140
		0.010"	0.04	1000	490; 690; 750

U.C - Uncracked

* Fractured

TABLE III

Thermal shock indices for ceramics and cermets

Material	Tensile strength (σ)		Thermal conductivity (k_g)		Mean coefficient of expansion (α)		Young's modulus (E)		$\frac{\sigma}{\alpha E}$ °C	$\frac{\sigma k_g}{\alpha E}$ cal/cm	Material
	Kg/cm ²	Temperature °C	o.g.s. units	Temperature °C	per 10 ³ °C	Temperature °C	Temperature °C	Temperature °C			
Nickel-bonded titanium-chromium carbide (40N)	2882	982	0.052	25	9.5	20/800	3.34	20	91.0	4.80	Nickel-bonded titanium-chromium carbide (40N)
30% chromium-alumina	1406	982	0.012	25	8.65	20/800	3.68	20	43.8	0.53	30% chromium-alumina
7% chromium-alumina	1230	982	0.12	20/265	8.4	20/1000	3.32	20	48.7	5.81	7% chromium-alumina

TABLE IVPhysical properties of experimental bed materials

Material	Melting point °C	Specific gravity	Mean specific heat 0/100°C c.h.u./lb°C	Mean thermal conductivity 0/100°C c.h.u./ft s°C
Chromium	1,920	7.00	0.104	0.0111
Wolfram	3,382	18.80	0.034	0.0255
Stainless Steel (18/8 type)	1,426/ 1,399	7.90	0.12	0.0025
Silicon carbide	decom- poses 2,200	3.22	0.165	0.0029
Silica sand	1,710	2.65	0.20	-

TABLE V

Heat transfer data on experimental bed materials

Bed material	Particle size of fraction		Bulk density* lb/ft ³	Air flow required to just fluidise bed (G ₀) lb/s ft ²	G/G ₀ for† (h _{max})	Maximum heat transfer co- efficient (h _{max}) obtained c.h.u./ft ² s°C	
	B.S. Mesh No.	diameter					
		ft					microns
Chelford silica sand	60/85	0.00069	212	91.8	0.00530	6	0.0305
	100/120	0.00046	138	91.1	0.00282	7	0.0325
	150/170	0.00032	97	88.6	0.00178	25	0.0390
Stainless steel	60/85	0.00069	212	251.0	0.03940	3.5	0.0310
	100/120	0.00046	138	256.0	0.01580	7	0.0355
	150/170	0.00032	97	247.0	0.00860	9	0.0385
	240/300	0.00020	60	248.0	0.00289	35/40	0.0430
Silicon carbide	60/85	0.00069	212	101.0	0.01460	6	0.0295
	150/170	0.00032	97	102.2	0.00178	45/50	0.0395
	170/200 (R.A. 500 grade)	0.00027 0.000049	83 15	99.2 65.6	0.00145 0.00039	45/50 approx. 50	0.0400 0.0195

* The bulk density used is the density of the bed after fluidisation, i.e. with open packing of particles

† G/G₀ = Ratio of air flow through bed to air flow required to just fluidise the bed

TABLE V (cont'd)

Bed material	Particle size of fraction		Bulk density* lb/ft ³	Air flow required to just fluidise bed (G ₀) lb/s ft ²	G/G ₀ for* (h _{max})	Maximum heat transfer co- efficient (h _{max}) obtained c.h.u./ft ² s°C
	B.S. Mesh No.	diameter ft microns				
Wolfram	170/200	0.00027 83	526.0	0.02280	5	0.0300
Chromium	150/200	0.000295 90	206.0	0.00510	15	0.0385

* The bulk density used is the density of the bed after fluidisation, i.e. with open packing of particles

*G/G₀ = Ratio of air flow through bed to air flow required to just fluidise the bed

TABLE VI

Physical properties of gases

Gas (25°C) (by volume)	Viscosity $\times 10^5$ lb/ft s	Thermal conductivity $\times 10^6$ c.h.u./ft s°C	Density $\times 10^6$ lb/ft ³	Specific heat at constant pressure c.h.u./lb°C
Air	1.25	0.42	7.40	0.242
Hydrogen	0.59	3.01	0.52	3.50
Nitrogen	1.18	0.43	7.23	0.250
10% H ₂ + 90% N ₂	1.17	0.55	6.55	0.270

values estimated by interpolation

APPENDIX I

List of symbols

A	Surface area of sphere	ft ²
a	Half thickness of test-piece	ft
c _s	Specific heat of solid	{ c.h.u./lb ^o C cal/gm ^o C
E	Young's modulus of elasticity	Kg/cm ²
G	Mass flow rate	lb/s ft ²
G ₀	Minimum fluidising mass flow rate	lb/s ft ²
h	Heat transfer coefficient	c.h.u./ft ² s ^o C
h _{max}	Maximum heat transfer coefficient	c.h.u./ft ² s ^o C
k _s	Thermal conductivity of solid	{ c.h.u./ft s ^o C c.g.s. units
r	Radius of sphere	ft
ΔT	Temperature difference	oC
$\frac{dT}{dt}$	Cooling rate	oC/s
V	Volume of sphere	ft ³
W	Weight of sphere	lb
α	Coefficient of linear expansion	in/in ^o C
ρ _s	Density of solid	lb/ft ³
σ	Tensile strength	Kg/cm ²

APPENDIX II

Heat transfer characteristics of fluidised solids

Experimental work was carried out to determine the important factors governing heat transfer in fluidised solids, particularly to establish the conditions which gave the maximum possible heat transfer rates from heated shapes quenched into fluidised beds. Bed materials possessing high melting points (in order to avoid local fusion or sintering to shapes quenched in the beds) and high density or high specific heat were selected (see Table IV). Closely-sized fractions of each material were prepared in order to determine the effect of particle size. Throughout the tests, the bed diameter (6 in.), depth (6 in.) and bed filter (Grade C 'Porosint', mean pore size 12.5μ) were maintained constant, the container being water-cooled. Air was used as the fluidising gas, with the exception of a few tests with a 90 per cent nitrogen, 10 per cent hydrogen mixture.

The heat transfer characteristics of the experimental fluidised beds were derived from the cooling rates of 20 mm diameter 30 per cent chromium-iron spheres heated to 1200°C and quenched in the beds. The following relation, based on Newton's Law of cooling, was used:-

$$h = \frac{W \cdot c_s}{A \cdot \Delta T} \cdot \frac{dT}{dt} \dots\dots\dots(1)$$

i.e.

$$h = \frac{V \cdot \rho_s \cdot c_s}{A \cdot \Delta T} \cdot \frac{dT}{dt} = \frac{r}{3} \cdot \frac{\rho_s \cdot c_s}{\Delta T} \cdot \frac{dT}{dt} \dots\dots\dots(2)$$

The cooling rates were measured using a platinum/13 per cent rhodium-platinum thermocouple, with its junction located at the geometric centre of the sphere, and connected to a Tinsley amplifier and high speed recording galvanometer (response 0.2 sec). From the recorded millivolts (temperature)/time curve, the average heat transfer coefficient over the temperature range 1040°C to 640°C was obtained using Equation 2. The mean value of specific heat (0.157 cal/gm°C) over this range was determined experimentally. Due to sudden large changes in specific heat below 640°C (i.e. at the Curie Pt.) for 30 per cent chromium-iron, mean (h) values below this temperature were not employed.

The results of the heat transfer tests are given in Table V. It was found that uniform and reproducible (h) values were obtainable over the range of temperatures studied. For each bed material there is a minimum air mass flow rate (G₀) below which fluidisation will not occur. It was found that, with increasing air mass flow rate (G), the heat transfer coefficient increased to a maximum value, and thereafter remained virtually constant. The generalised curves in Figure 7 show that finely divided bed materials give higher (h) values than coarse material, and that the maximum (h) value is attained at higher G/G₀ ratios. Very fine powders, e.g. the 10/20μ silicon carbide tended to agglomerate and therefore behaved essentially as a coarse powder. Thus there was an optimum size range which varied with the material. With the exception of wolfram, no pronounced differences in (h) value were obtained

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with different materials of similar particle size e.g. 150/200 mesh. The individual importance of bulk density and material density, and specific heat could not be derived from the results, although it is probable that the effects of these properties on the (h) value are inter-related to one another and to the particle size. Using a 90 per cent nitrogen/10 per cent hydrogen mixture instead of air, a definite increase in heat transfer coefficient resulted. This is probably due to the favourable physical properties of hydrogen (see Table VI). It was estimated that the use of 100 per cent hydrogen would result in an (h) value approximately 50 per cent greater than the maximum value obtained with air as the fluidising gas. Difficulties in the use of hydrogen due to explosion risks and provisions for burning the gas are, however, a serious deterrent to its use.

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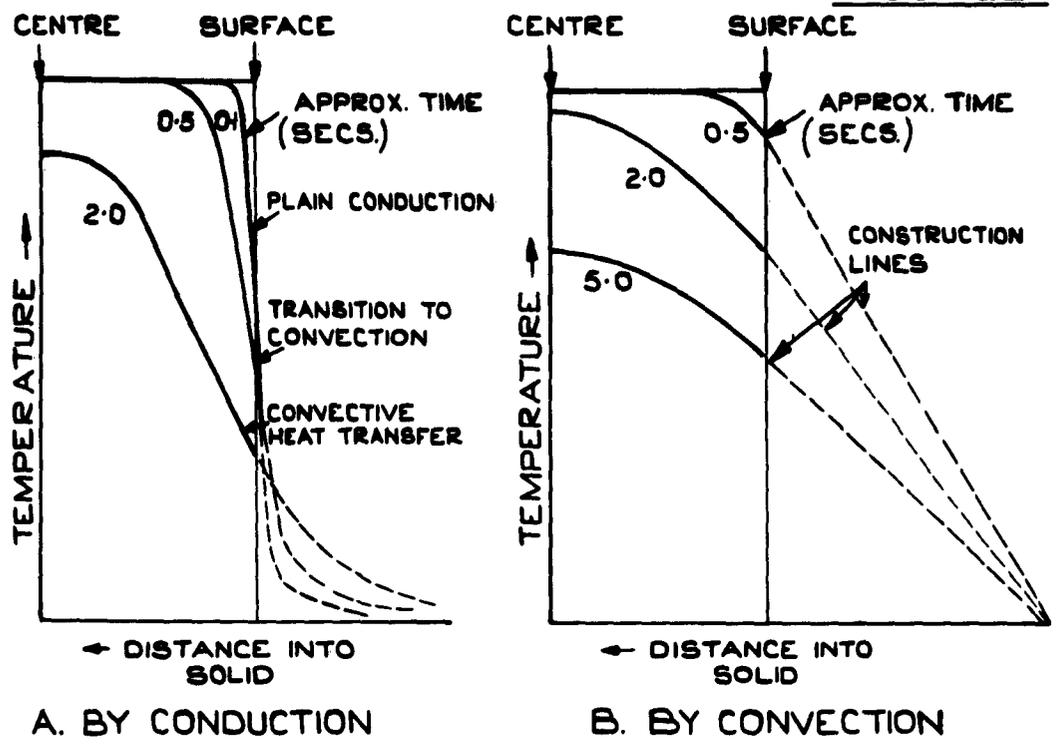
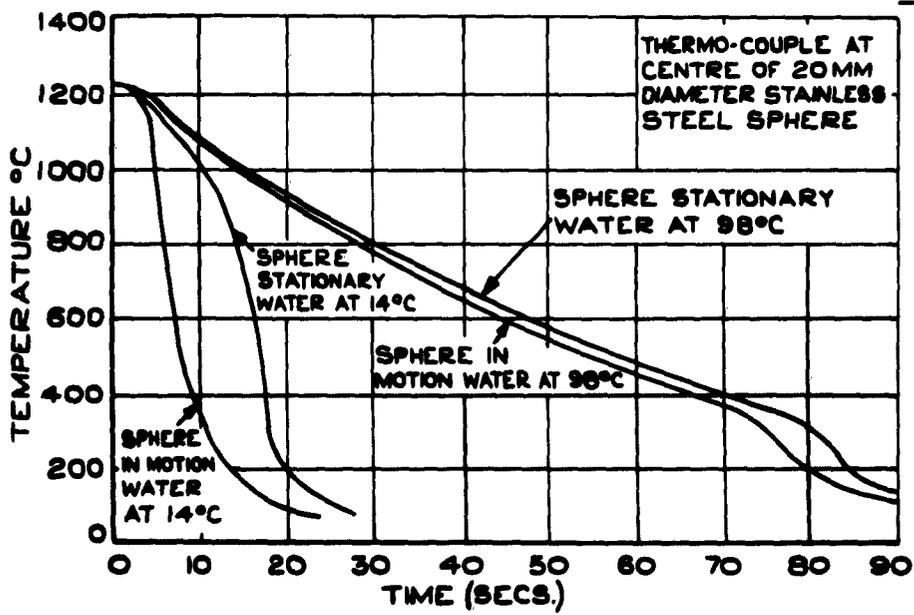


FIG. 1. MODES OF HEAT TRANSFER ON RAPID COOLING

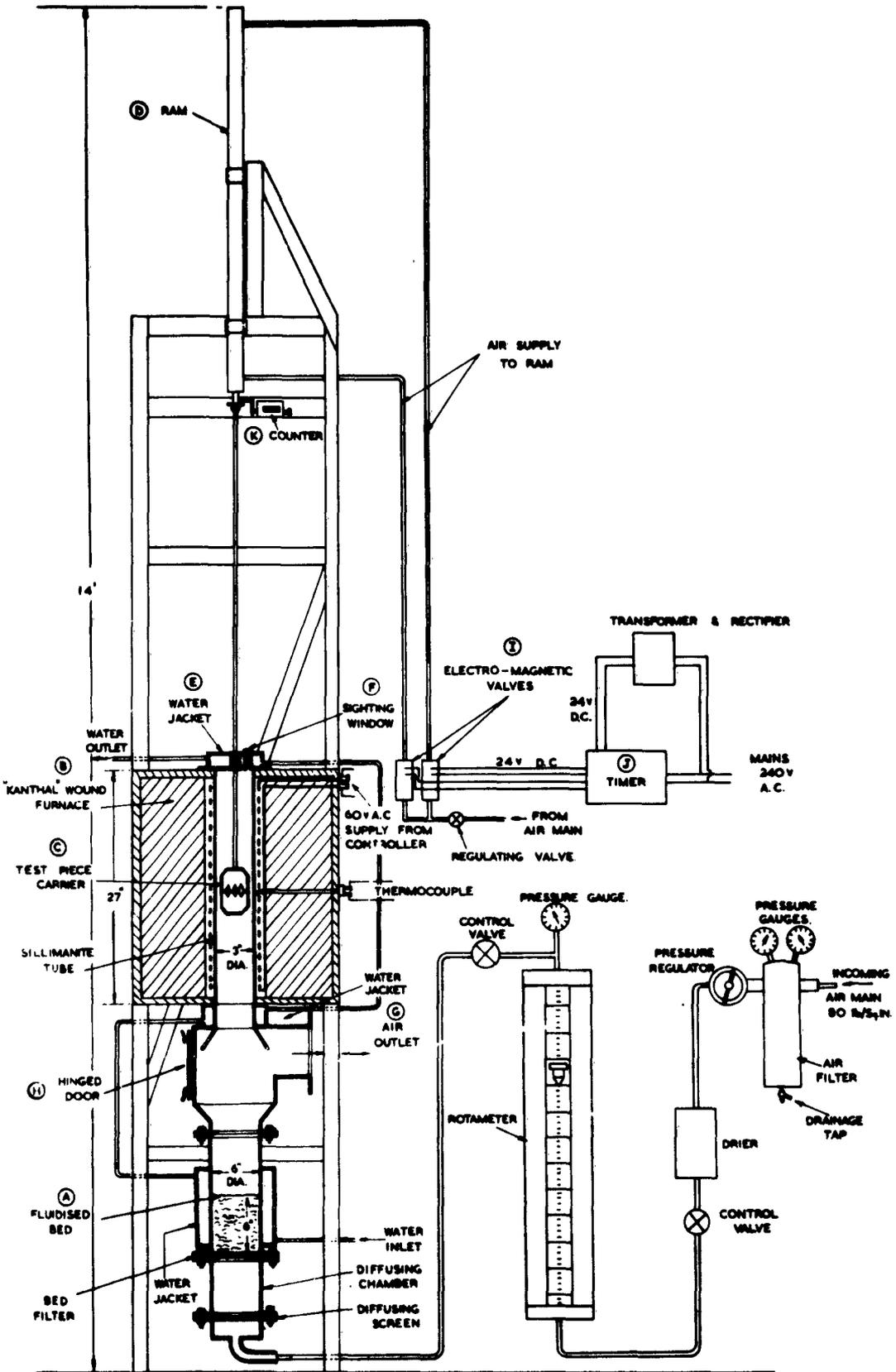
FIG. 2



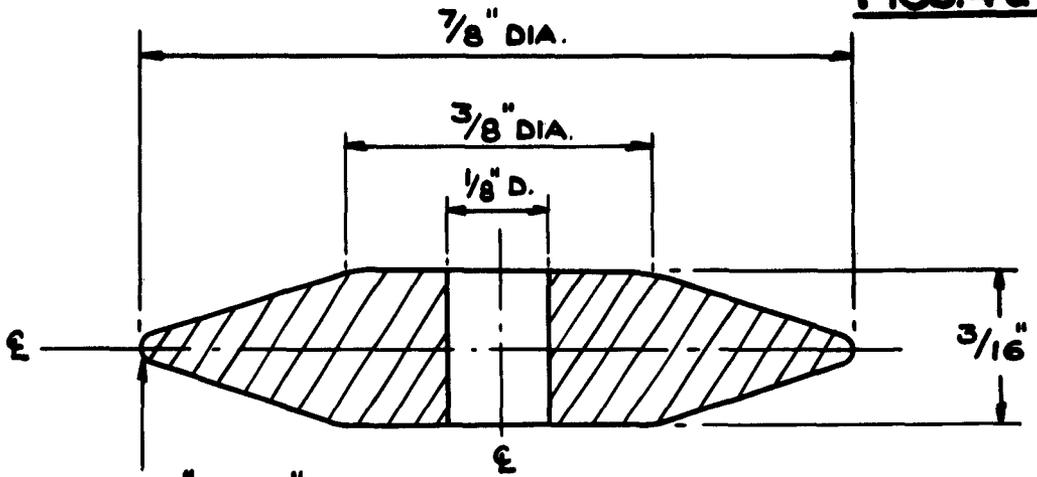
COOLING RATES OBTAINED BY WATER QUENCHING

FIG. 3.

SK. 21137.



LABORATORY THERMAL SHOCK TEST APPARATUS



RADIUS 0.020," 0.010,"
0.005" OR KNIFE EDGE

FIG. 4. THERMAL SHOCK TEST PIECE

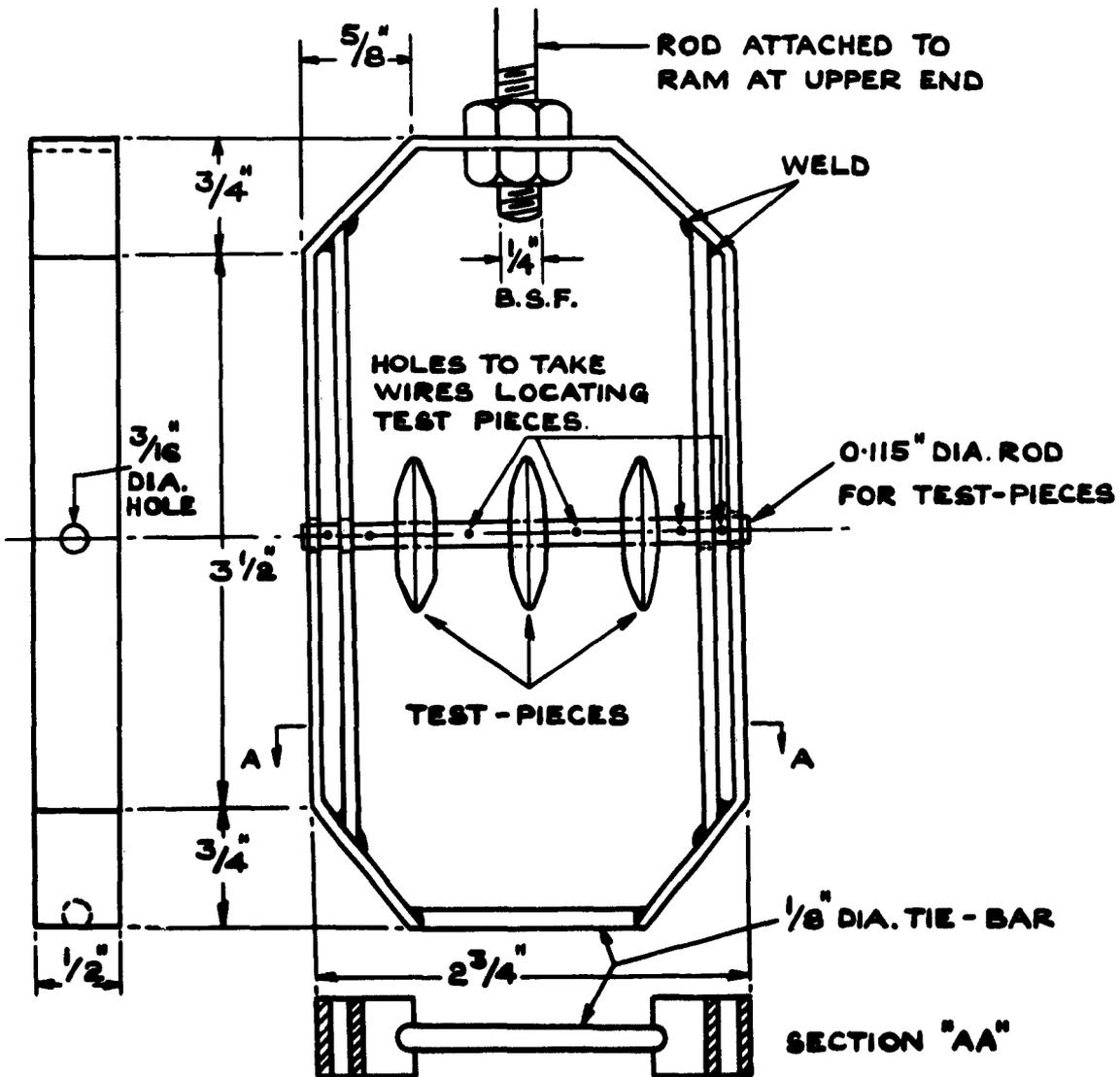
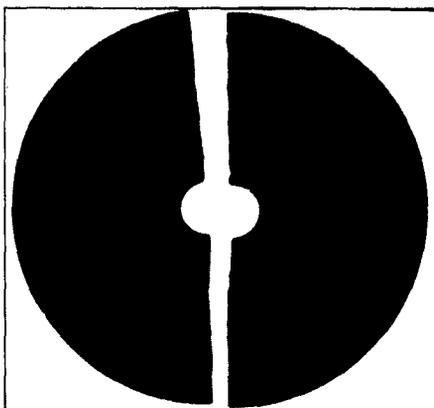


FIG. 5 TEST PIECE CARRIER.

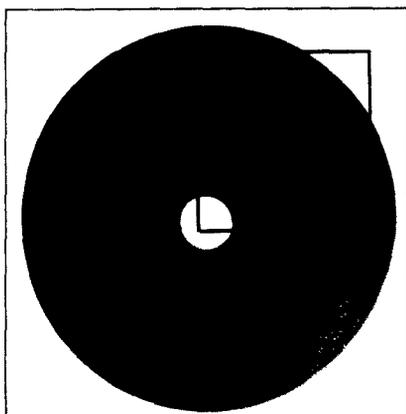
FIG. 6.



MOLYBDENUM DISILICIDE (PLESSEY)^{x3}
 $\Delta T=1000^{\circ}\text{C}$ $h=0.04 \text{ chu./ft}^2\text{s}^{\circ}\text{C}$
2 CYCLES.



NI/CR BONDED TIC (CARBOMETAL)^{x3}
 $\Delta T=1000^{\circ}\text{C}$ $h=0.04 \text{ chu./ft}^2\text{s}^{\circ}\text{C}$
10 CYCLES.



NI/CR BONDED TIC (CARBOMETAL)^{x3}
 $\Delta T=880^{\circ}\text{C}$ $h=0.04 \text{ chu./ft}^2\text{s}^{\circ}\text{C}$
330 CYCLES.



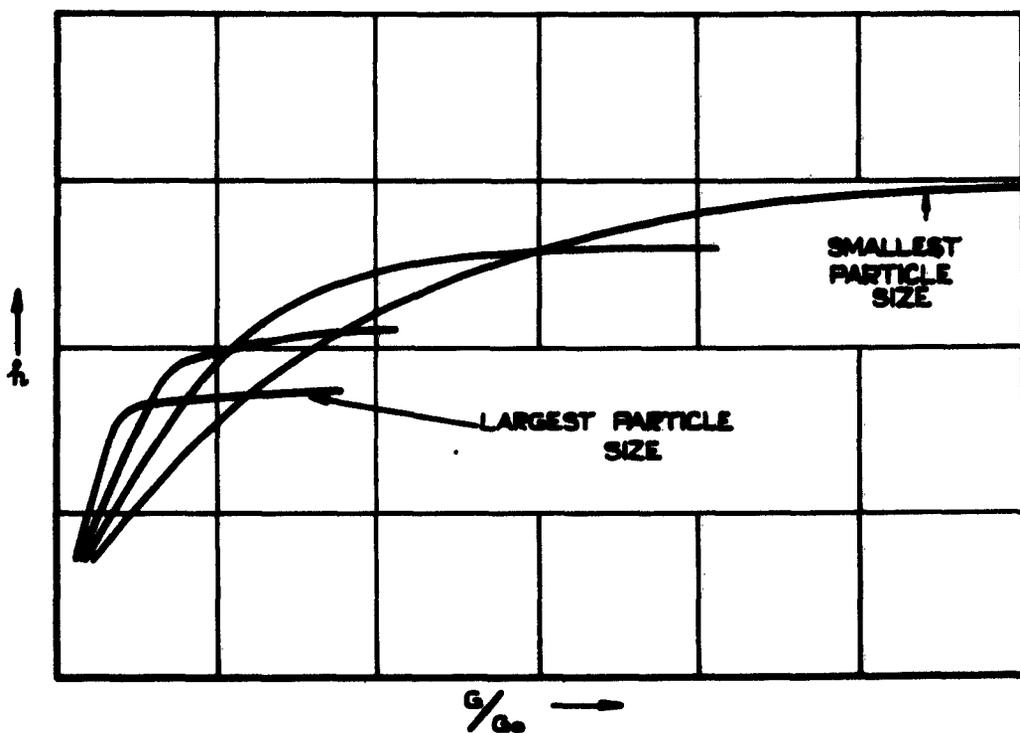
x7



NIMONIC 95 (0.005" EDGE RADIUS)^{x75}
 $\Delta T=1000^{\circ}\text{C}$ $h=0.04 \text{ chu./ft}^2\text{s}^{\circ}\text{C}$
140 CYCLES.

THERMAL SHOCK FAILURES OF A CERAMIC, CERMET,
AND CREEP RESISTANT ALLOY.

FIG. 7.



GENERALISED CURVES FOR
NON DIMENSIONAL GAS FLOW (G/G_0)
AGAINST HEAT TRANSFER COEFFICIENT (h)

DETACHABLE ABSTRACT CARDS

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Northwood J. E. and Shaw S. W. K.
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