STRESS AND VIBRATION

Regardless of the theoretical potentialities of any engine, the engine is of little value, practically, if the various parts do not "hang together" and perform their intended purpose during the necessary life of the engine. For this reason, careful attention must be directed towards the stresses and strains induced in the various parts during operation. The stress problem is particularly severe in the rotating members. Consider this highly schematic sketch of a typical jet engine. Figure 37 . Air enters at this end and is compressed by the rotating compressor blades. The air flow is not as smooth, however, as we should like it to be, and the buffeting of air over the blades tends to induce in them vibrations that have been the source of many an engine failure. After compression, the air passes through the combustion chambers where fuel is injected and burned. Hot gas leaves the combustion chamber and passes through the turbine. The turbine blades are, therefore, subjected not only to gas buffeting, but also to intense heat; and the stress problem in the turbine blade is also severe. By instrumenting the turbine and compressor blades with strain gages, we have learned much about stress characteristics of these components. In this discussion, I should like to focus attention, however, on the problems associated with the turbine disk shown here. Its primary function is to carry the blades and to transmit torque from the blades to the shaft. The unusual stress problems associated with it, the difficulty of learning much about its problems from research on the engine itself, and the importance of a sound stress analysis on this component makes research on stresses in disks an extremely important problem.

The disk is an inherently heavy component and the weight of other components also are affected by the weight of the disk. The designer is, therefore, not in a position to apply heavy factors of safety to the disk because of the possibility of tremendously increasing the weight of the engine. Yet, he dare not design too light a disk for fear of bursting in the engine. Fragments of burst disks have been known to penetrate 8 or more inches of solid steel and the danger to pilot and aircraft of a burst in flight is obvious. What is necessary is a method for achieving an optimum design not too light and not too heavy, but such an achievement awaits much research.

Let us consider some questions that must be answered. First, the relative importance of centrifugal and thermal stresses. In the next chart, figure 38 , we show the important stress systems in gas turbine disks. Here is a half-section of a typical disk. The disk rotates at high speeds and is, therefore, subjected to centrifugal stresses. For the sake of defining our terminology, the disk is shown to reduce scale in this sketch. At any location, the stresses that act on a small element are the radial stress in a direction along a disk radius, and tangential stress in a direction tangent to a circle through the element. Because the distinction regarding centrifugal and thermal stresses that I wish to emphasize lies largely in the tangential stresses, we shall omit future discussion of radial stresses and concentrate on tangential stresses. Now consider the centrifugal stresses. If we imagine the disk divided into two halves, then the centrifugal pull of rotation of each of the halves must be resisted by a stress system such as shown here. In a plot of stress against radius, the centrifugal stress distribution looks like this. Now let us consider the thermal stresses. We have noted in this figure the extremes of the temperature to which the disk is subjected during engine operation. The rim which is near the hot gases is at a "hot" 1200° F. while the center which is remote from the hot gases is at a relatively cool 360° F. It is a well-known property of metals that they tend to expand when heated. The rim would like to expand a large amount corresponding to its high temperature. The remainder of the disk attempt to expand lessor amounts in accordance with their lower temperature. Because of the conflict of relative expansions of the various parts, a system of pushing and pulling is established in the disk. To prevent the rim from expanding as much as it would like to, compressive stresses are induced init. To make the central region expand more than it would like to, tension stresses are induced in this region. This thermal stress system is depicted in this sketch which shows compression at the rim and tension at the center. In this plot of stress along the radius, we have shown the thermal stress. The high negative values at the rim indicate compression and the positive values toward the center indicate tangent.

The dilemma of the designer is how to assign the proper significance to each of these types of stresses. Theoretical considerations indicate that they should not merely be added. No information exists at this time as to how to assign the proper weight to each of these stresses.

Among other questions over which the designer puzzles is that of determining just how much importance to assign to ductility. Ductility, as you all know, is the ability of the material to stretch before breaking. A material that is not ductile is said to be brittle and it is a well-accepted fact that a brittle material, while inherently strong, may fail due to impact, to stress concentrations such as holes and scratches, or even due to rough handling. Completely brittle materials are, of course, not desirable but how much ductility is necessary is not known. It is an unfortunate circumstance that strength and ductility are inverse to each other. The higher the ductility, the lower the strength even though the resistances to stress concentration may be improved. Many potentially good disk materials are by-passed at the present time because they are not believed to have sufficient ductility for use in gas-turbine disks. Perhaps we could make disks stronger and use more suitable materials if the importance of ductility could be properly evaluated.

To answer these and other questions affecting optimum design, we are making use of spin pits rather than engine tests. In a spin pit, the test can be conducted under ideal conditions without endangering personnel or surrounding equipment and without destroying an engine for each disk test. A schematic sketch of our pit is shown in the next chart. See figure 39 . Here is the disk which is driven at any desired speed by an air turbine. Surrounding the rim of the disk is a series of coils connected to an induction-heating unit. Eddy currents are induced in the rim by the induction-heating coil and heat this rim to any desired temperature. Note the advantage of induction heating over other possible methods - we can get highly localized heating at the rim and keep the center cool, thereby simulating air conditions. With the air turbine and induction-heating unit, we can simulate any desired speed and temperature gradient. Lining the pit to make bursting safe is about a foot of soft steel followed by a foot of armor plate, followed by 2 feet of concrete. The actual equipment is shown at your right. The cover has been removed from the pit and suspended on a stand. You may note the air turbine, the disk, the induction-heating coils around the disk and this 75,000-watt unit supplying power. We should have liked to start up the induction-heating unit to show you how temperature conditions in the engine are simulated. Because of the amount of time involved in heating the disk however, we have painted the rim with a fluorescent paint that causes the disk to glow approximately as it does five or so minutes after starting of the induction-heating unit. As you see, the rim is glowing hot while the center remains relatively cool.

We have burst a number of disks in this pit, some cold and some under temperature gradient. In the pit is a disk that has been tested under temperature gradient. For the sake of identify, we have painted it white. As you see, it is quite indistinguishable from the rubble produced by the bursting of a disk. In this case, as a matter of fact, the disk did not quite burst. The shaft failed, but the energy released is obvious from the havoc. It might be interesting to note that when the shaft failed, the disk was turning at a speed 60 percent higher than its rated speed or at a stress two and one-half times its value at the rated speed, an indication of the safety insurance that the designer is forced to incorporate in a disk because of lack of complete information regarding optimum design.

One of the disks burst in the pit has been mounted on the front panel. Many tests are as yet to be conducted in this pit. I should like to present some data that we have obtained, not in this pit but in a smaller pit and not on actual turbine wheels, but on small parallel-sided disks that were designed especially to yield some light on the question of the relative importance of ductility and tensile strength. Some of the disks burst are in the next chart, figure 40 where we have a plot of the strength of a series of disks as a function of the strength of the material. Along the horizontal axis is the tensile strength of the material as determined from a tension test on a specimen of material similar to that which the disk was made. Along the vertical axis, we have plotted the strength of the disk as computed at the speed of bursting. The strength of the disk is directly proportional to the strength of the material. In the next chart, figure 41 we have made a plot of the ratio of the disk strength to the tensile strength of the material as a function of ductility. If ductility is an important factor in disk strength, then we would expect appreciable variation in this ratio with ductility. We see, however, that regardless of ductility this ratio is constant and very close to unity. These tests cover the range of ductility that would normally be of interest in disk design. The lower limit of ductility shown here is 3 percent elongation of a two-inch gage length. We are as yet investigating lower ductility.

liquid is removed at the top of the column. The high boiling red liquid concentrates at the bottom so we have separated the mixture.

Our problem is to separate just a few components from a petroleum stock which may contain 10,000 hydrocarbons. Such a separation requires a very efficient distillation column. To increase distillation efficiency the column height must be as tall as possible and to increase the quantity of product the column diameter must be made larger. In the next room we have some distillation columns 30 feet tall and of sufficient diameter to give small experimental quantities of fuels. In the next building you visit you will see some columns 100 feet tall with diameters up to 8 inches which will allow us to isolate fuels in sufficient quantities for testing in jet engines.

In summary -- we are evaluating the performance characteristics of a wide variety of hydrocarbon fuels so that in the very near future it will be possible to increase the supply of turbojet fuels and (2) we are conducting research that will allow extended flight range for aircraft.

We also ran a number of tests in which very small holes were drilled at the center of parallel-sided disks. These tests were conducted for two reasons. First, to learn how detrimental small holes really are. As you know, the stress at the center of the disk is nominally doubled by the presence of a small hole, yet it is frequently necessary to incorporate small holes at the center of the disks. Do these holes reduce the strength of the disk in half? Another reason for these tests was to evaluate this factor of ductility as affecting a stress concentrated area. The high ductility frequently specified for disk materials is intended for overcoming stress concentrations by conducting tests with small holes and we would be able to evaluate ductility directly in a region of stress concentrations. The results are shown in the next chart. Figure 42. We have plotted the ratio of the bursting speed of the disk with a hole to the bursting speed of a solid disk as a function of ductility. If a small hole weakens the disk, we would expect the disk with the hole to burst at a much lower speed than a solid disk or for this ratio to be less than unity. If ductility has an important bearing on the strength of disks with small holes, we would expect the effect to reflect itself in such a plot. As you see, however, this ratio is constant, independent of ductility and this constant is very close to unity.

We deduce from this chart first that in the range of ductility above 3 percent elongation, a small hole is of little detriment to the strength of the disk and second, that very little ductility is necessary to overcome the effects of stress concentration in disks of sound materials. On the basis of these results, it is felt that disk strengths can be increased by accepting lower ductility, thereby making possible the attainment of higher tensile strength.

Our spin pits will be used to investigate other disk problems as for example shape determinations and slide-carrying ability of various designs. These tests, supplementing those we have already conducted, will, we hope, provide the data so urgently necessary to make engines lighter, stronger, and more efficient.

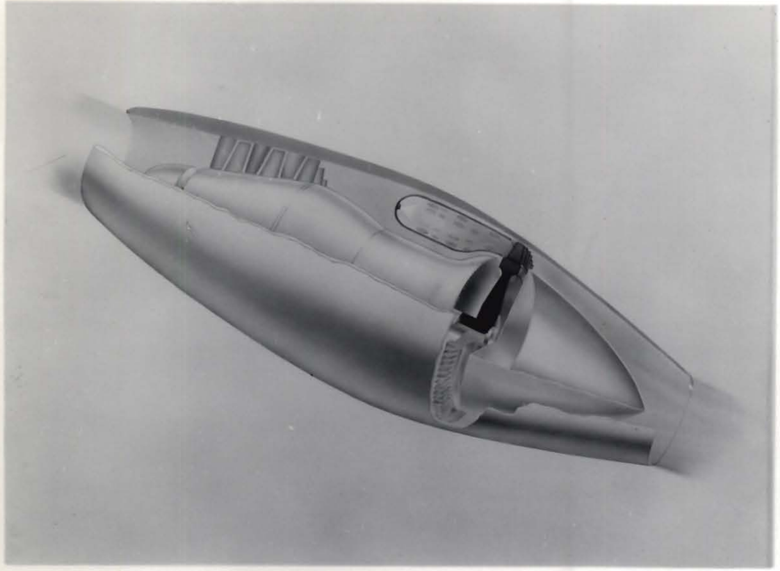

Figure 37.

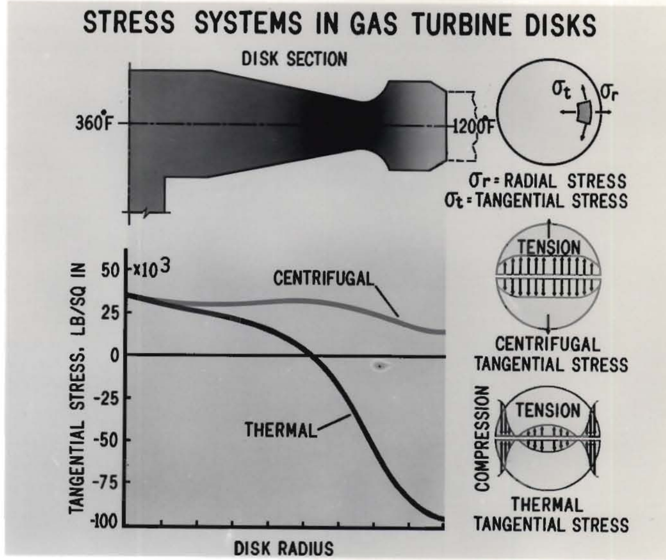

Figure 38.

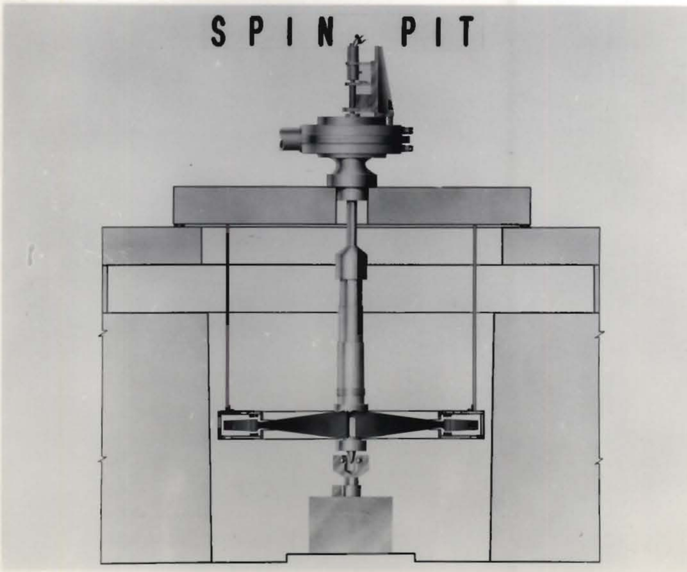

Figure 39.

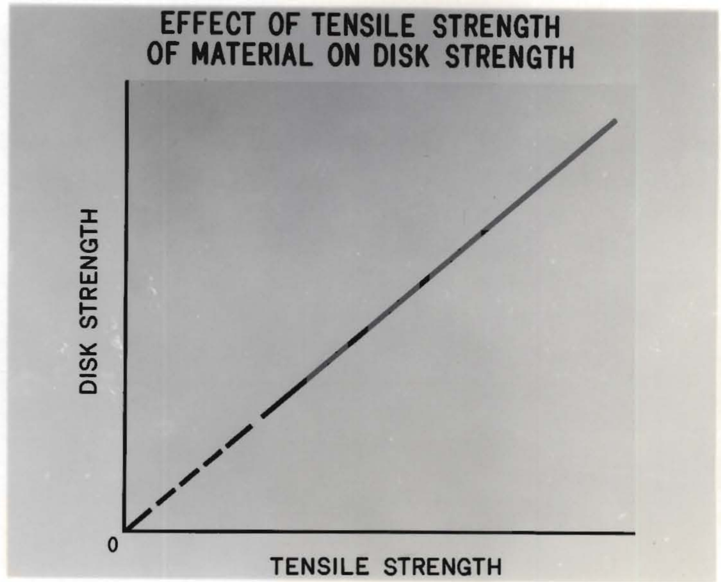

Figure 40.

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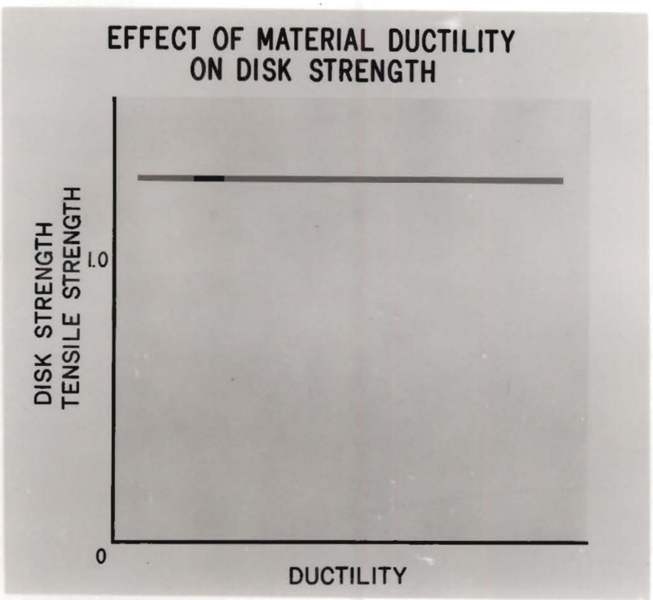

Figure 41.

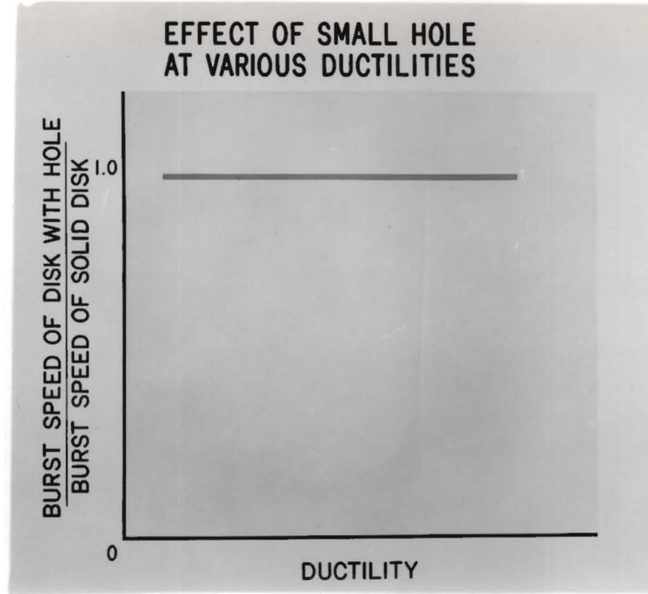

Figure 42.

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MATERIALS DEMONSTRATION

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
Lewis Flight Propulsion Laboratory

Second Annual Inspection

September 28, 29, and 30, 1948

An increase of 500° F in the operating temperatures of the turbojet engine over present practice would mean an increase of approximately 34 percent in the power output of the engine. The same temperature increase in the turbopropeller engine means a 20 percent decrease in fuel consumption when the engine is operated at optimum conditions. These increases in performance mean that at higher operating temperatures a lighter engine can be used for the same power output. For turbopropeller engines of equal weight the higher available power output can mean higher flight velocities, or longer range, or the extra power reserve that is so essential for military aircraft.

Operating temperatures of engines can be raised either by cooling those parts that operate at high temperature or by the use of materials that will withstand the higher temperatures. The high-temperature alloys in use today have a top operating temperature in the neighborhood of 1500° F. Their current utilization as turbine-blade materials at blade temperatures of about 1450°F involves frequent unscheduled engine shut-downs for blade replacement. A part of the research on high-temperature materials by the NACA is directed towards a better understanding of these materials with a view to extending their life. As engine service life may be the time required for the first turbine blade to fail, an intensive study is being conducted on the mechanisms of these first failures and particularly on some method of inspection that will detect these inferior blades prior to engine installation. For temperatures of operation above the range of existing alloys more refractory alloy systems are under consideration. Most promising of these are the chromium-iron-molybdenum alloys and the molybdenum-base alloys. It is felt that these still experimental alloys will be useable in the temperature range between 1500° and 1900° F. Most of the super alloys use large quantities of such strategically critical materials as cobalt and columbium. Investigations are underway to permit the substitution of domestically plentiful materials for these scarce materials.

For use at operating temperatures above 2000° F we are forced to turn to those materials having the very highest melting points. The materials in this category with which we are working are the oxides and carbides of metals and are called ceramics. Although some ceramics have been run in experimental turbines at present ceramics are too fragile to withstand normal engine operation. In order to eliminate this fragility, studies are being made of the effects on ceramics of fabricating and composition variables and of heat treatment, and on the latent possibilities of structure stabilization.

A very promising approach that offers much promise for the early minimizing of the problem of fragility of ceramics is in the use of small addition of metals. Bodies so formed, which consist of a metal and a ceramic, we have chosen to call ceramals. Because of time limitations, only the work on these composite bodies, ceramals, will be presented.

Figure 43 lists the properties of some ceramic materials (Boron Carbide, Aluminum Oxide, etc) of Vitallium, a typical super alloy, and of a ceramal body composed of a mixture of 80 percent titanium carbide and 20 percent cobalt.

Also shown in figure 43 are the strength-to-weight ratios of these materials. As the materials are being considered for turbine blades, in which the stress is essentially centrifugal and is dependent on the weight or density of the body, the significant figure is not the absolute tensile strength but rather the strength-to-weight ratio. It should be noted that the two bodies having the highest strength-to-weight ratios (boron carbide and aluminum oxide) are ceramics. Next to these in strength-to-weight ratio is the ceramal body (80 percent titanium carbide plus 20 percent cobalt). The high-temperature alloy has, at 1800° F, a strength-to-weight ratio approximately one-third that of the best ceramic and one-half that of the ceramal.

Figure 44 shows trends for strength-to-weight ratios and the resistance to thermal shock of metals, ceramics, and ceramals at temperatures above 2000° F. Thermal-shock resistance is defined as the ability of a body to undergo adrupt changes in temperature without fracturing. It is the ability to resist thermal shock while maintaining high strength at elevated temperature that indicates the superiority of ceramals over both metals and ceramics.

To demonstrate the relative thermal shock resistance of a ceramal and a ceramic we have a unit capable of rapidly heating the test specimen, a small disk, to 1800° F and rapidly quenching it in cold air. A disk made from one of the better ceramic materials is to be heated and quenched, together with a disk of the previously mentioned ceramal. The apparatus consists of a conventional combustion chamber liner inside a glass cylinder. Fuel, kerosene, is admitted into the apparatus at the dome and air through the bottom; a spark plug at the rear of the unit ignites the fuel-air mixture. After thermal shocking it can be noted that the ceramic disk has fractured.

The ceramal disk has only a very minor amount of surface oxidation and is apparently undamaged.

Figure 45 shows the United States' consumption and production of two metals, cobalt and chromium, that are the basis for the high-temperature alloy, Vitallium, and of titanium dioxide, a ceramic that is the principal ingredient of the previously mentioned ceramal. It can be seen that the United States produces only 12 percent of the cobalt and only 15 percent of the chromium that it consumes. The United States has large economically feasible reserves of neither of the materials. On the other hand, the United States produces 97 percent or practically all of the titanium dioxide that it uses and has tremendous reserves that can readily be developed. In the event of a national emergency, a very large part of existing titanium dioxide production could be readily diverted to essential turbine use. In the case of the metallic elements which are already used for essential metallurgical purposes, this diversion could not readily be accomplished.

The remaining demonstrations illustrate some of the problems involved in the preparation and use of ceramals. Such problems as well as the more fundamental investigation of determining promising combinations of metals and ceramics, constitute a large part of the NACA research on high-temperature materials.

Ceramals are made from powders and their preparation involves blending of the powdered constituents, compacting the blended powders, and the sintering of the compact. In order to obtain a uniform body of high density it is essential that the powders flow freely during the compacting operation. As the constituents are crystalline and have distinct cleavage characteristics, the crushed particles are angular and tend to interlock, producing such compacting defects as bridging cavities and density variations. A commercial spray drier is used at the laboratory to agglomerate these jagged particles into small spheres and thereby improve their ability to flow. In these hour-glasses are ceramic powders of the same particle size, one of which has been agglomerated in the spray drier while the other is as-blended. As I invert the hour-glasses it is very apparent that the agglomerated powder flows freely and continues to do so. The unagglomerated powder, on the other hand, flows sporadically and soon bridges over the orifice in the hourglass.

Another problem encountered in the use of some ceramals is the lack of structural stability of some of the ceramic constituent. If the ceramic constituent undergoes phase changes that are accompanied by volume changes, stresses are set up and the thermal-shock properties of the body are seriously impaired. One method of eliminating this serious defect employs minor additions of stabilizing elements. In order to study these transformations or inversions, X-ray diffraction apparatus such as can be seen here is employed. This apparatus consists essentially of an X-ray source (the tube) which causes a beam of X-rays to impinge on the specimen. The X-ray beam is diffracted by the atomic network of the specimen and is picked up by the Geiger counter. A feature of this apparatus is that the specimen is so mounted on a small resistance furnace that structure of the specimen can be studied both at room temperature and at elevated temperature. Vacuum apparatus has also been hooked up to this unit so that the elevated temperature structure could be studied without the interference of oxides. As I move the Gieger-Counter into the path of the diffracted beam, you can observe the large number of impulses that are registered by both the loud speaker and the small neon light. These impulses register on the chart as a peak in the diffraction pattern. An illustration of the type of stabilization possible is shown in the next figures. Figure 46 shows the room temperature and the 1900° F patterns of zirconium dioxide. On heating to 1900° F the body is subject to a phase change as indicated by the change in location of the peaks of the diffraction pattern. If small amounts of basic oxides are added this body is stabilized as shown in figure 47 It can be noted that this body has diffraction patterns indicating the same structure at both room temperature and at 1900° F. This body undergoes no inversions and the thermal-shock characteristics are superior to those of the unstabilized zirconium dioxide.

Here in a small furnace we have a high-temperature alloy, a ceramal, and a ceramic bar partially immersed in molten salt at 2000° F. On each of these bars are thermocouples, positioned so that they indicate, on the potientiometers on the panel, the temperature of the bars at equal heights above the liquid salt. It can be noted that the temperature of the ceramal is considerably higher than the temperature of either the alloy or the ceramic. This means that the thermal-conductivity of the ceramal is higher than that of either the high-temperature alloy or the ceramic. This high thermal conductivity of ceramals is advantageous in that heat is rapidly dissipated and the body operates cooler than would either the metal or the ceramic in a fixed-temperature gas stream. However, the fact that large quantities of heat are poured into the turbine-wheel rims when ceramal blades are used poses some problems in wheel design.

In conclusion, it appears that while research on metallic alloys is important, it can at best provide for relatively slight gains in maximum operating temperatures. Ceramals offer much promise for utility at temperatures as much as 1500° above current practice. Research progress to date indicates that useable ceramals will be attained in the near future.

George Deutsch

PHYSICAL PROPERTIES OF MATERIALS

MATERIAL	TENSILE STRENGTH 1800 °F	DENSITY	STRENGTH-TO-WEIGHT RATIO 1800 °F
B_4C	22,500	2.5	9,000
AL_2O_3	32,000	4.0	8,000
80% TiC-20% Co	33,000	5.6	5,900
TiC	15,700	4.25	3,690
SiC, B_4C	10,000	3.0	3,333
VITALLIUM	25,000	8.3	3,015
BcO	6,200	3.0	2,066
Zr SiO_4	8,700	4.5	1,925
Zr C	11,700	6.3	1,858
MgO	3,100	3.5	885

Figure 43.

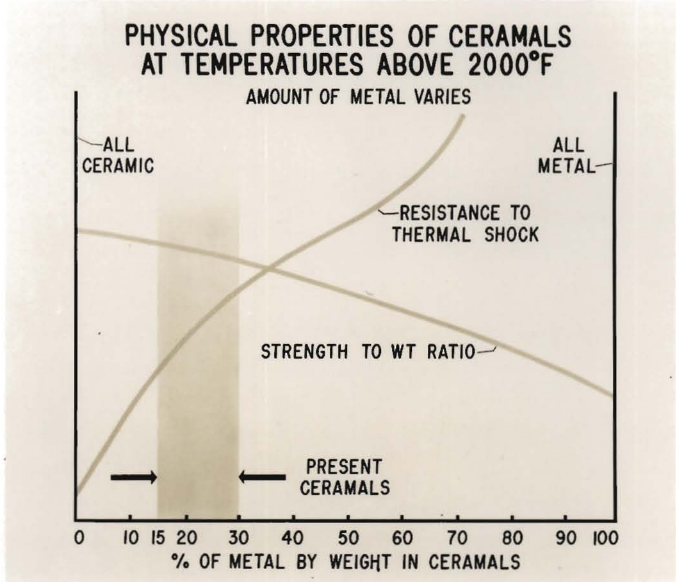

Figure 44.

UNITED STATES CONSUMPTION AND PRODUCTION OF CRITICAL MATERIALS

MATERIAL	CONSUMPTION (TONS)	DOMESTIC PRODUCTION (TONS)	PERCENT DOMESTICALLY PRODUCED
COBALT	3,000	346	12
CHROMIUM	965,000	145,000	15
TITANIUM DIOXIDE	324,000	315,000	97

Figure 45.

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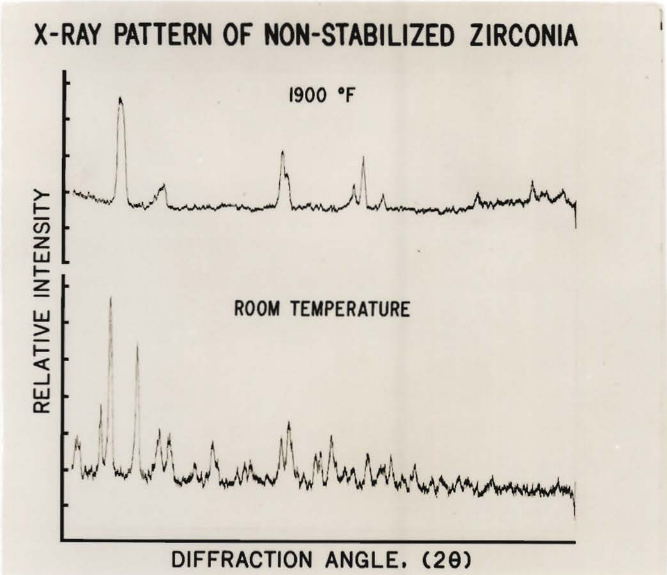

Figure 46.

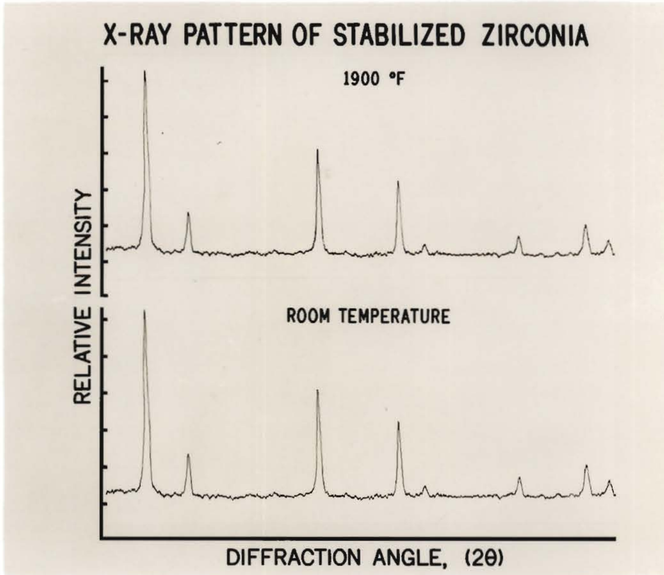

Figure 47.

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MATERIALS & STRESSES
PHYSICAL PROPERTIES OF CERAMALS
AT TEMPERATURES ABOVE 2000°F
AMOUNT OF METAL VARIES
ALL CERAMIC
ALL METAL
RESISTANCE TO THERMAL SHOCK
PRESENT CERAMALS
% OF METAL BY WEIGHT IN CERAMALS
CERAMAL
CERAMIC
ALLOY
C-22334
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