# Application of Thermal Barriers to High-Temperature Engine Components

R. L. NEWMAN,* K. R. CROSS,† AND W. C. SPICER†
*Detroit Diesel Allison Division, General Motors Corporation, Indianapolis, Ind.*
AND
H. D. SHEETS‡ AND T. D. DRISKELL§
*Battelle Memorial Institute, Columbus, Ohio*

## Theme

THE present trend to more severe operating conditions in turbine engines will require fairly sophisticated cooling schemes. The thermal barrier, a low conductivity coating, is a means of reducing the cooling requirements. The chief benefit of a thermal barrier is a saving in cooling air and thus less loss in engine performance. Compared with other cooling methods, thermal barriers are most beneficial in engines with large heat-transfer coefficients—i.e., high-pressure ratios. Results of a test program to match or exceed engine burner liner or vane leading edge requirements with selected ceramic thermal barriers are presented. The materials tested were alumina (high thermal shock resistance), zirconia (low thermal conductivity), and zircon foam (very low conductivity).

## Contents

At the start of this program, the basic ground rule of not carrying on a materials development program was set. The aim was to evaluate current—off the shelf—materials; drawing on Allison's experience with nickel base alloys and the ceramic industry's experience with refractories. The thermal barrier employed is a ceramic high-temperature, low thermal conductivity structure, applied to turbine engine components to reduce the heat flux from hot gases.

These consisted of thick ceramic layers, supported by Hastelloy-X(R)¶ honeycomb brazed to Hastelloy-X(R) substrates. The honeycomb cells are filled with ceramic and oversprayed with a dense ceramic coating for erosion protection. Dense ceramic fillers and low-conductivity ceramic foams were examined.

The low-conductivity ceramic foam was considered only for combustor liner applications. The more dense, and thus stronger, ceramics were evaluated both for liner applications and for vane leading edges. This Synoptic summarizes the experimental evaluation of these reinforced ceramics, both high and low density.

The chief means of material screening and evaluation is a thermal shock test which is described elsewhere.[1] Materials are ranked by the number of thermal shocks to failure. A thermal shock cycle consists of a sudden cooling transient (2400-2500°F/sec) from the initial gas temperature to a level about 600°–1000° cooler, and, after stabilization, a heating transient at the same rate to the original gas temperature. The initial gas temperature is 2000°F. After twenty shocks, and every ten thereafter, the gas temperature is raised 200°F until the maximum burner temperature (3000°F for leading-edge specimens; 2600°F for burner liner specimens) is reached.

The specimens were tested with gas conditions corresponding to the proposed use in an engine. The test conditions were for vane leading edge specimens—normal flow, $h_G = 300$ Btu/ft$^2$-hr-°F; and for combustor liner specimens—parallel to flow, $h_G = 100$ Btu/ft$^2$-hr-°F. The vane leading edges had a radius of 0.125 in., while the liner specimens were 3 in. × 4 in. plates. Photographs are shown in the original paper.

The specimens were evaluated in terms of the number of accumulated thermal shocks and the temperature level at failure. Structural damage to the specimens after testing was determined by visual observation of coating separation, cracks, spalling, and erosion.

One of the potential problems with the use of ceramic coating in turbine engines will be foreign object damage. In particular, dust erosion may be critical. Materials can be compared by noting the time to erode a given thickness.

The Allison erosion test rig used a calibrated abrader. Calculations were performed to equate a standard test on this rig with a 10 hr whole-engine test.[2] These correlate the test conditions (20° impact angle, 0.03 $lb_{dust}/lb_{air}$, $V = 680$ fps) to the whole engine test, assuming equal distribution of dust throughout the engine and a linear effect of dust concentration. Our test criteria is no erosion through the outermost layer of the thermal barrier with an exposure substantially equivalent to the whole-engine test.

The ballistic impact criterion for liner application is less than 25% decrease in the number of thermal shocks to failure after a standard impact on a 1-in. disk screening specimen. The standard impact is a 0.175-in.-diam., 0.35-g sphere (Daisy Xtra Special BB Shot) with ¼ ft lb kinetic energy, impacting at a 20° angle to surface.

Thick nickel backing for impact specimens increases the severity of the crater. Based on qualitative inspection of craters, these impacts are the same as 8-12 in.-lb impacts on a burner liner section which has only a 0.030 in. Hastelloy X backing.

The test criteria are summarized as follows: thermal shocks—able to survive thermal shocks at temperatures equivalent to 2500°F in an engine,** in a configuration similar to the intended use; erosion—no erosion through coating for an exposure equivalent to 10 hr in a dusty engine environment; and ballistic impact—75% of thermal shock strength after impact.

One of the objectives of this program was the estimation of the cooling air savings in an engine. The cooling air requirement is

$$\dot{m}_{COOL} = A(T_{GAS} - T_{COOLANT})/(R_{GAS} + R_{TB} + R_{COOL})C_{PAIR}T_{COOL}$$

Received December 22, 1971; revision received May 30, 1972. Originally prepared as Paper 21-C-71 F Ceramic-Metal Division, American Ceramic Society, St. Louis, Mo., September 1971. Full paper (authors Report RN 71-55) is available from the National Technical Information Service, Springfield, Va., 22151, as 74-24822 at the standard price (available upon request).

Index categories: Structural Composite Materials (Including Coatings); Thermal Modeling and Experimental Thermal Simulation.

* Senior Research Engineer. Member AIAA.
† Senior Research Engineer.
‡ Associate Chief.
§ Senior Research Scientist.
¶ Trademark of Stellite Division, Cabot Corp.

** 2600°F for liner specimens, 3000°F for leading-edge specimens.

In addition to cooling air requirements, a maximum gas temperature—limited by cooling—can be calculated. This maximum gas temperature is

$$T_{GAS(MAX)} = \frac{R_{GAS} + R_{TB} + R_{COOL}}{R_{COOL}}(T_{METAL} - T_{COOL}) + T_{COOL}$$

It is clear that thermal barriers will be most effective for small values of gas film resistances, $R_{GAS}$, or large values of heat transfer coefficients, $h_{GAS}$. As an example, let us consider a hypothetical engine, which has the following environment: burner – $h_{GAS} = 300$ and $h_{COOL} = 100$ Btu/ft²hr°F; and vane leading edges – $h_{GAS} = 900$ and $h_{COOL} = 300$ Btu/ft²hr°F. The burner liner is a cylinder 20 in. diam × 12 in. long and there are fifty 3 in. vanes with a leading-edge radius of 0.1275 in. The results are shown in Table 1.

**Table 1 Cooling air requirements using various thermal barriers**

| Thermal barrier | Cooling air required, lb/sec: Burner liner | Vane leading edge | Total |
|---|---|---|---|
| Unprotected | 1.15 | 0.21[a] | 1.36 |
| 0.020 in. alumina | 1.06 | 0.16 | 1.22 |
| Honeycomb-$ZrO_2$ | 0.98 | 0.12 | 1.10 |
| Honeycomb-$Al_2O_3$ | 1.04 | [b] | 1.25 |
| Honeycomb-foam | 0.77 | [b] | 0.98 |
| Best combination | 0.77 | 0.12 | 0.89 |

[a] Very marginal—$T_G$ (MAX) ≈ 2000°F.
[b] Cannot be used $T_G$ (MAX) < 2000°F.

Keeping the ultimate goal of the testing program in mind —selection of a best material—the testing results are shown in Table 2 for the best specimens of each type of thermal barrier. From this table and the test criteria, both the hot pressed zirconia and the ceramic foam thermal barriers are suitable for burner liners. No material passed the test criteria for use as a leading edge.

The mode of failure during these tests agrees with the stress analysis. The predicted failure mode, tensile cracking above the cell walls, agreed with the frequent failure mode; a mosaic crack pattern following the honeycomb pattern. The analysis predicts that this should occur during the cooling thermal shock; however, the testing cannot verify this.

The other possible failure mode, compressive spalling during heating, is less likely as a result of the high compressive strengths of ceramics. Nevertheless, this failure might explain the "catastrophic" failure of two flat foam specimens. The ceramic foam would be expected to be weaker in compression, and thus more susceptible to this type of failure. An alternative explanation would have the coating cracking in the typical mosaic pattern, becoming detached, and the gas then eroding the foam. This requires that "mosaic-crack failures" happen during the final cool-down of a series, and "catastrophic failures" happen during a series. Unfortunately, it is not possible to tell exactly when failure occurs during an experiment.

The heat transfer through various thermal barriers has been studied. The chief benefit of a thermal barrier will be a saving in cooling air, not an increase in allowable temperatures. In some cases, the maximum gas temperature may be lowered, but the cooling load will always be less. Compared with other cooling methods, thermal barriers are promising for engines with large heat-transfer rates, i.e., high-pressure ratio engines.

For very small leading edges, monolithic coatings are suitable, but for larger radii leading edges and burner liners a honeycomb structure is much better. There is a potential use for both monolithic and reinforced ceramic. At a gas temperature of 2000°, an 0.020 in. monolithic alumina coating saves about 10% in cooling air for both leading edges and burner liner. A zirconia filled honeycomb saves 23%; and a foam filled honeycomb on the burner liner produces a 39% saving.

The transient thermal stress in the honeycomb has also been evaluated for the points of probable failure. While the absolute values of the stresses are uncertain, we can compare the calculated levels at different conditions. The chief results are that our thermal shock test burner matches an engine vane leading-edge stress level (although at a higher temperature) and can exceed an engine burner liner condition at the same temperature. These stresses are comparable to the strength of the ceramics currently being considered.

## References

[1] W. C. Spicer, Ross, P. T., and Newman, R. L. "A Well-Defined Thermal Shock Transient Test Burner," *Review of Scientific Instruments.*, Vol. 43, No. 2, Feb. 1972, pp. 236–244.

[2] "Engine, Aircraft, Turbojet and Turbofan, General Specification for," Military Specification MIL-E-5007C, Oct. 1966.

[3] Cavanagh, J. R. et al., "The Graded Thermal Barrier—A New Approach to Turbine Engine Cooling," AIAA Paper 72-361, San Antonio, Texas, 1972.

**Table 2 Median test results**

| Type of thermal barrier | Thermal shock testing — Number of shocks to failure-median values (best value in parentheses): Thickness, in. | Burner liner No. | Burner liner Shocks | Leading edge No. | Leading edge Shocks | Erosion testing — Equiv. hours of engine operation | Ballistic impact testing — % degradation in thermal shock testing after impact: Impact energy ft lb | degradation |
|---|---|---|---|---|---|---|---|---|
| Cast zirconia | 0.065 | | | 4 | 20(40) | 16.7 | | |
| Hot press zirconia | 0.065 | 1 | 60 | 5 | 35(60) | [a] | 0.25 | 30% |
| Ceramic foam + PS coating | 0.065 | 10 | 12(40) | | | 11 | | |
| Ceramic foam + bonded coating | 0.065 | 3 | 50 + (50+) | | | 68 | 0.125 | 33% |
| Plasma sprayed zirconia | 0.015 | | | 1 | 50 | 59.5 | | |
| Graded plasma sprayed coating[b] | 0.015 | | | 4 | 45(50) | | | |
| | 0.030 | 3 | 80 + (100+) | 9 | 35(50) | | 0.25 | none |
| Zirconia brick[c] | | | | 1 | 40 | 308.6[d] | [e] | |
| Test criteria | | | 50 | | 100 | 10 | 0.25 | 25% |

[a] Not tested, should match or exceed cast zirconia.
[b] From Ref. 3, listed for comparison.
[c] Listed for comparison.
[d] No measurable wear.
[e] No measurable damage after 4 ft lb impact.