Procedure for Evaluating Fuel Composition Effects on Combustor Life

Howard L. Foltz* and Milton J. Kenworthy†
General Electric Company, Evendale, Ohio

A generalized method is presented for estimating the effects of fuel composition on liner life. This method avoids the detailed temperature and stress distribution calculations required when using conventional cyclic material property charts. The simplified approach became possible when it was found that cyclic life ratios due to fuel change were very similar when correlated with a convenient temperature parameter that had already been used in the past to correlate fuel composition with metal temperature change. This life ratio was found to be relatively independent of 1) the peak temperature existing with the base fuel, 2) the coolant temperature, and 3) the actual detailed stress calculation. A trend of increased life ratio effect at longer cyclic lives for crack initiation was found. This trend can be incorporated into life ratio estimates from the prepared curves by using the actual observed service life without the need for a calculated absolute life.

Nomenclature

$T_{coolant}$ = coolant temperature
T_L = combustor liner metal temperature
$T_{L_{base}}$ = combustor liner metal temperature with base fuel

Introduction

THE approach described in this article provides a more general methodology for estimating the effects of flame radiation on service life than was used in the past at General Electric. This generalized approach does not involve detailed heat transfer and stress calculations. While the absolute estimates provided in this simplified and more general approach are not as accurate or sophisticated as those provided by more detailed analyses, similar estimates of the relative effects of fuel property changes on combustor life are provided by the generalized approach. The method directs attention specfically to the actual service life and the particular nature of service failures as basic inputs to the procedure. Life estimates can be made from these generally available facts without utilizing the detailed information familiar only to the combustor designer. It also permits estimates to be made for combustors for which detailed analyses are not available.

Fuel Effects

The primary effect of fuel property changes on combustor life is due to the change in flame radiation and the resulting change in combustor liner metal temperature. It is generally assumed that for first approximation, the internal flowfield, fuel air distribution, and local combustion efficiencies remain relatively unchanged with changes in fuel type causing no change in convective heating of the walls. The flame radiation changes are due, therefore, only to changes in flame luminosity/emissivity characteristics of the flame. Some combustors will, however, have additional effects. In a very highly loaded combustor dome, the location of the flame zone may move axially with changes in fuel type. The combustor in the General Electric J85 engine is believed to exhibit this flame zone movement. Another General Electric combustor, the low smoke J79-10B, may be unusually sensitive to the exact reattachment point of the swirl cup flows to the conical dome that may be fuel sensitive. Low pressure ratio, low inlet temperature combustors may exhibit some changes in fuel distribution due to fuel droplets penetrating to different depths with different fuels, resulting in changes in the early fuel distribution. Combustors that can develop large carbon deposits will be fuel sensitive to this feature and the carbon deposits will, in turn, affect fuel distribution. Although there are some effects of fuel on the basic gas temperature pattern within some combustors, most of the data can still be interpreted in terms of flame luminosity changes in an unchanging temperature field. The discussions and analyses indicated below assume that only flame radiation changes need be considered.

Several studies, including Ref. 1, have shown that flame radiation levels in a given combustor correlate well with the carbon/hydrogen ratio of the fuel composition. Other fuel characteristics are of much less importance. However, individual combustors will have somewhat different luminosity characteristics which will further differentiate the combustor liner metal temperatures since metal temperatures are influenced both by flame radiation and the convection heating and cooling of the liner.

High combustor liner metal temperatures and gradients result in high stresses, and these high stresses result in life-limiting low-cycle fatigue cracking, crack propagation, and warping/buckling failures. High-temperature metal oxidation and metal burnout may also be involved, but usually these occur only after warping or buckling occur in a way which further aggravates the metal temperature.

Predictions or correlations of combustor liner life can be made from stress calculations using metal temperatures and low cycle fatigue material property data. Machined ring liners with circumferential continuous cooling slots have generally been analyzed with much greater sophistication than punched louver designs. The temperature distribution within the machined ring structures (with the guidance of a few measured temperatures) are more predictable from calculations than are punched louver structures and are therefore more amenable to accurate stress prediction. The machined ring liners are generally newer designs used in the higher pressure ratio, higher inlet temperature engine applications where more sophisticated designs are needed to achieve the same life. These designs generally have signif-

Received Dec. 20, 1985; revision received Feb. 6, 1986. This paper is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

*Senior Engineer, Augmentor Aero Design.
†Manager, Augmentor Aero Design.

icantly longer lives than the older punched-louver designs. The failure mode predicted by these analyses is generally confined to low cycle fatigue crack initiation. Final failure involves subsequent crack propagation which may be a longer portion of the life than time-to-crack initiation. Crack propagation proceeds through regions of varying temperatures and stresses, and the stresses may be subsequently relieved by the presence of the crack itself. For machined ring liners, time-to-failure has been sometimes assumed as a factor from experience multiplied by the calculated or measured time-to-crack initiation, but this factor is not identical for every combustor or for every crack location.

Punched louver designs, when new, have cracks initiated or crack-type stress concentrations at the end of each louver. The life is a function only of crack propagation. As with the machined ring design, the cracks propagate through regions of varying temperature and stress. Material property data on crack propagation rates show trends vs stress level that are somewhat similar in character to data for crack initiation.

Warpage in a punched louver design or warpage of the lip forming the cooling slot in a machined-ring design can greatly shorten the remaining life by changing the internal flow field, resulting in increased convective heating of the downstream portion of the liner. Machined ring liners are designed to avoid this cooling slot warpage or buckling problem; where it has occurred in practice, changes are introduced to prevent the buckling. The life calculations indicated below concentrate on crack initiation and crack propagation without providing any specific modification to account for warpage.

Life Calculation

Before life data on an engine become available, the combustor designer estimates life by the following calculation procedure. First, metal temperature distribution within the structure is calculated based on detailed heat transfer inputs established partly from available metal temperature measurements. Next the stresses within this structure are calculated. Last, the cyclic life is calculated from material property data on low cycle fatigue. The stresses within the structure are first calculated as pseudo-elastic stresses which are the stresses that would occur if there were no creep or yield. Sometimes life is estimated directly from this result and material property data near the peak metal temperature where stresses are high. The method provided below does not go beyond this sophistication. A further refinement would estimate the stress relaxation that should occur due to the creep or yield that would take place in one cycle and the hysteresis loop of the subsequent cycles. Further, it would use property data based on this stress level. In addition, more sophisticated life calculations recognize that the actual part goes through a temperature change in every cycle, while the cyclic material property data have generally been obtained by cycling at constant temperature.

The method provided below circumvents the detail of calculating stress from temperature distribution as indicated above by doing a perturbation calculation on a cyclic life already established from service. The method also has been structured to permit direct utilization of the correlation relationships selected for presenting flame radiation effects on metal temperature.

Correlation of Fuel Type vs Liner Temperature

Figure 1 shows a correlation presented by Blazowski and Jackson in Ref. 2. The effects of fuel type are correlated in terms of the change in peak liner metal temperature due to one fuel ratioed to the peak metal temperature above the coolant temperature for a base fuel. These correlation parameters are also adopted in the method described below.

Material Property Data for Crack Initiation

Material property data on low cycle fatigue crack initiation for Hastelloy X are presented in Fig. 2, as used at General Electric in some design procedures. Hastelloy X is the material typically selected for General Electric's machined ring combustors. Above 1400°F (1034 K), the curves are influenced more and more by the creep behavior of the material. The pseudo-elastic stress (in the simplest calculation) is essentially proportional to the thermal gradient. Changes in the thermal gradient are proportional to changes in $(T_L - T_{\text{coolant}})$, the peak liner metal temperature level above the coolant temperature. These relationships permit the material property data to be transposed from the form

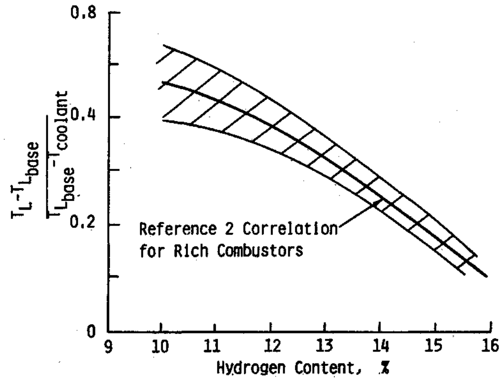

Fig. 1 Liner temperature rise correlation.

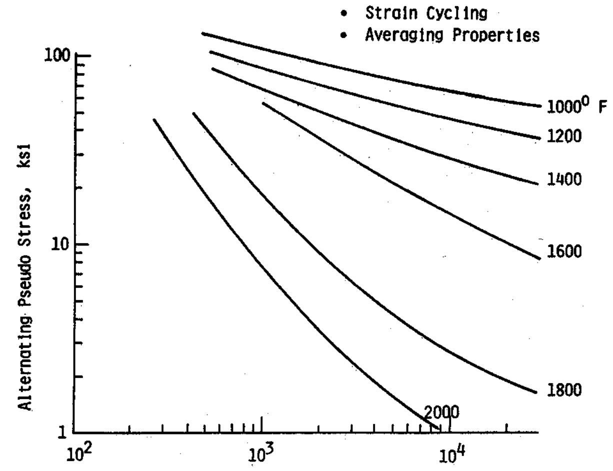

Fig. 2 Fatigue diagram, Hastelloy-X sheet stock.

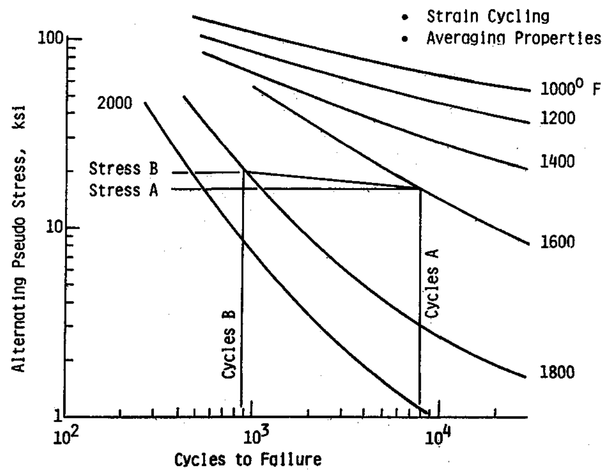

Fig. 3 Fatigue diagram, Hastelloy-X sheet stock.

above, in which they are usually used, into a form which presents the changes in cyclic life for a change in peak liner temperature ($T_L - T_{coolant}$), which is also proportional to a change in the pseudo-elastic stress.

This transformation is illustrated in Fig. 3 for a 1600°F (1145 K) base design and a 200°F (110 K) increase in metal temperature due to fuel type. The fatigue diagram is entered at some arbitrary point (cycles A) and the corresponding 1600°F stress level (stress A) is read from the curve. The stress level (stress B) for a 200°F increase in metal temperature is obtained from

$$\text{stress B} = \text{stress A } (1800 - T_{coolant}/1600 - T_{coolant}) \quad (1)$$

The resulting cycles (cycles B) are read from the 1800°F (1255 K) curve at the stress B level. The life ratio is calculated as

$$\text{life ratio} = (\text{cycles B}/\text{cycles A}) \quad (2)$$

A typical transformed curve is shown in Fig. 4 for a 1600°F base design for two coolant temperatures [700°F and 900°F (644 K and 756 K)]. These curves are for a 100°F (56 K) fuels effect. As seen in the figure, only a small change in life ratio is obtained for the 200°F change in coolant temperature.

Figure 5 shows transformed material property data at three different peak metal temperature levels. The resulting life ratios are very similar. Thus, parameters of cyclic life and the quotient of $(T_L - T_{L_{base}})/(T_{L_{base}} - T_{coolant})$ are significant in the life ratio predicted by the materials property data curves, while the actual metal and actual coolant temperature levels are parameters that to a first approximation can be neglected in this type of transformation.

Data at 1600°F metal temperature with 700°F inlet temperature are presented in Fig. 6 and can be used in a reasonably general way. These curves give a life ratio directly from a knowledge of the metal temperature change. They show an increasing effect on life for longer cyclic life conditions. If the refinement of relaxation, etc., were considered, the effects of a temperature increase at long life might be greater, but this refinement seems to be far beyond what could be accomplished as a simple transformation of the materials properties curves.

With these new curves (Fig. 6) as a calculating tool, it is possible to go from predicted fuel effects on the metal temperature, such as Fig. 1, and the knowledge of cyclic life in service, directly to relative effects on life.

Material Property Data for Crack Propagation

Crack propagation data obtained at General Electric, specifically on Hastelloy X, J79 type punched louvers are shown in Fig. 7. The similarity to the curves in Fig. 6 is apparent. Initial treatment of crack propagation data for HS188 combustor material were found to give life ratio results similar to those found with the low-cycle fatigue data for crack initiation. Figure 6 was, therefore, adopted in this procedure for both crack initiation and crack propagation.

Some additional treatment of existing crack propagation data was conducted, showing somewhat different trends than Fig. 6. Reference 3 contains crack propagation data on both HS188 and Hastelloy X. These data were treated by the same approach indicated by Fig. 3, resulting in the curves shown in Fig. 8. Notice that the life ratios are close to a constant, with no definite trend and changing crack growth rates. However, as indicated above, the trends indicated by Fig. 6 were utilized in the subsequent analysis, rather than the relatively constant value suggested by Fig. 8. Use of Fig. 8 values would result in less effect of fuel type on life.

Recent Metal Temperature Data

In addition to the correlation from Ref. 2 in Fig. 1, Fig. 9 shows correlation lines for recently tested combustors at General Electric.[4,5,6] The correlation band from Ref. 2 compared combustors at cruise operating conditions and included the J79-10A type of combustor. However, at takeoff conditions which have a much stronger effect on combustor life than cruise, the J79-10A trends fall below the correlation band as indicated. The liner of the type in the J79-10B engine exhibits a very small effect of fuel changes in the conical dome even though this is a region exposed to very high convective heating; and, hence, the designers have provided for intensive cooling in this region. A given increase in flame radiation makes a much smaller increase in metal temperature than in regions with conventional cooling levels.

The actual failure modes encountered in service on many combustors are near the aft end of the liners well away from the high flame radiation dome region and are, therefore, not affected as much by flame radiation effects as are combustors with primary failure modes near the dome region. For most combustors, failure modes that limit service life are confined heavily to a single mode or axial location for any

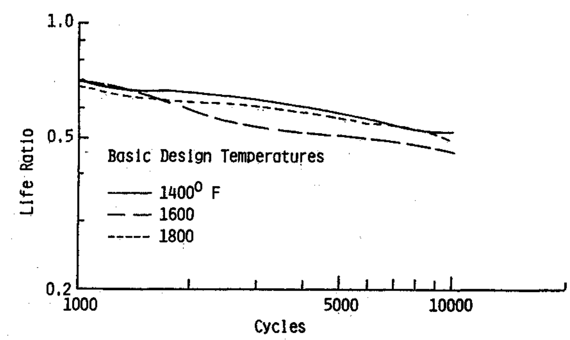

Fig. 5 Liner life ratios at three design temperatures for low cycle fatigue.

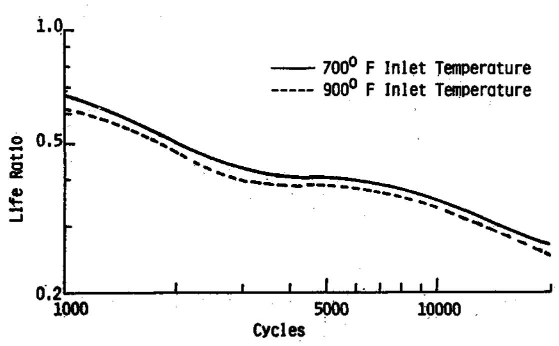

Fig. 4 Liner life ratio at 1600°F base design for a 100°F change in metal temperature.

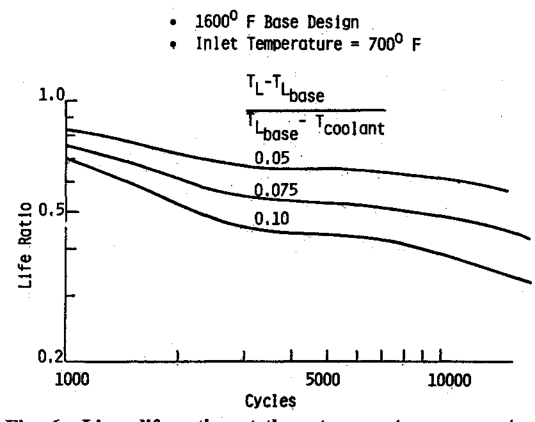

Fig. 6 Liner life ratios at three temperature parameters.

one combustor type. Thus, the axial locations of actual service failures affect the correlation curve selected from Fig. 9. Figure 10 shows data from a TF39 combustor.[4] The correlation for the aft portion of the TF39 liner is suggested as applicable to combustors encountering failure primarily in their aft portion. In engine combustors where fuel effects data are not available, but where service experience indicates failures in the high radiation dome region, the basic correlation curve B in Ref. 2 from Fig. 9 is perhaps appropriate for estimating life. This curve is very close to the data correlation for the forward portion of the TF39 combustor. This correlation has been used for General Electric T58 and T64 combustors for which specific data are not available. The failure mode for the General Electric TF34 combustor is near the aft end of the combustor; therefore, curve C is recommended. This curve is also recommended for other combustors with failure modes near the aft end of the liners.

Cyclic Life in Service

The combustor service life is available from Air Force and Navy maintenance records and procedures. For many engines, the established engine overhaul times are strongly influenced by combustor life, and this becomes one convenient measure of life. For other engines, the maintenance and repair schedules are somewhat more flexible. However, the combustor service life in hours needed to repair, or a replacement is generally available for each combustor application.

The service life information most readily available is in terms of hours of service, but thermal cycles on the combustor are also needed for life estimation. The thermal cycles per hour of service are not always available and frequently must be estimated from knowledge of the general flight mission. Furthermore, life can be significantly affected by the exact mission mix or usage of the engine. If a small but significant number of missions include very extreme conditions, such as supersonic dash, the controlling factor on life would tend to be these extreme cycles, and the other lesser cycles could most be ignored. Under such a mission mix, the curves in Fig. 6 would be entered at a much lower number of thermal cycles than the true number for an average mission, and the predicted effects of fuel changes on life ratio would be less. Also, the relative effect of an on-off cycle which occurs about once per hour vs an idle to maximum cycle (not so severe) which may occur six to fifteen times an hour in a fighter application is not well established, but a value of six is a reasonable average for the two types of cycles when better information is not available. A value of three thermal cycles per hour of flight is more appropriate for helicopter missions.

Life Ratio Estimates

The effect of fuel type on metal temperature is determined as discussed in the above sections. Where specific metal

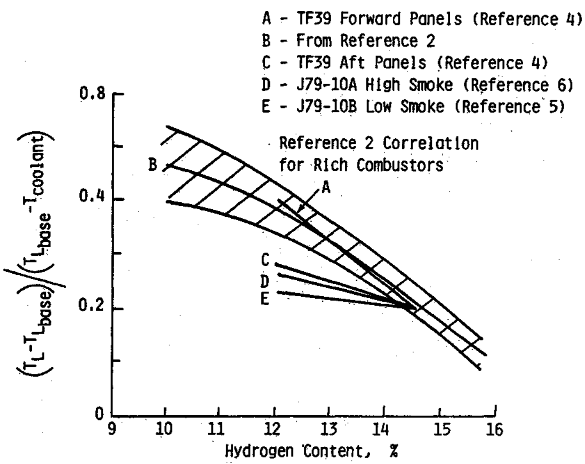

Fig. 9 Liner temperature rise correlation.

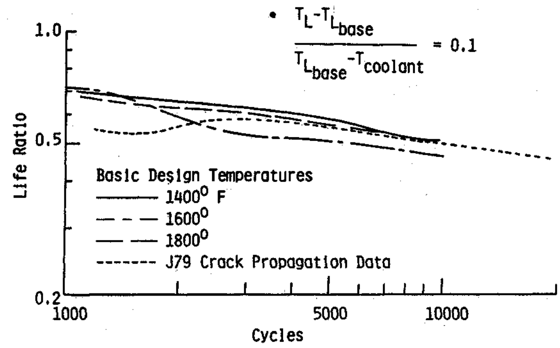

Fig. 7 Liner life ratios at three design temperatures for low cycle fatigue and crack propagation.

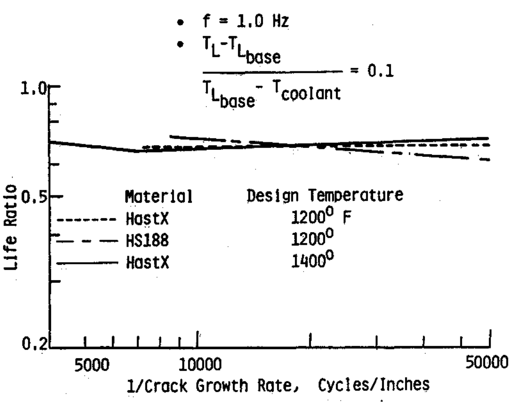

Fig. 8 Crack propagation data—liner life ratio.

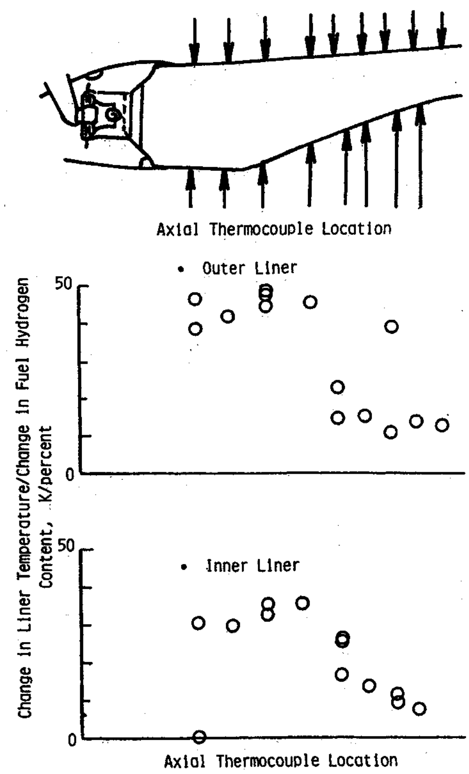

Fig. 10 Spatial variation in rate of change of liner temperature to fuel hydrogen at takeoff.[4]

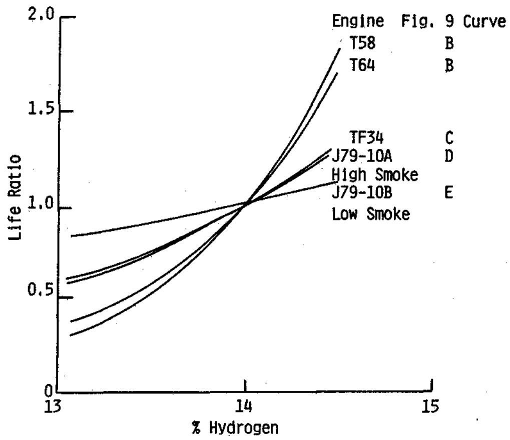

Fig. 11 Effect of fuel content on liner life.

temperature vs fuel type information is known in the region of the combustor where the failures limiting service life occur, the data can be correlated as in Fig. 9. Where data on fuel effects are not available, curve B of Fig. 9 can be assumed for combustors with failure modes in regions exposed to typical dome luminosity modes and curve C for combustors where the failure modes are near the aft end of the combustor. With the temperature effect, due to fuel hydrogen content selected, together with service life available from maintenance records, and the considerations discussed in the previous section, the life ratio can be determined from Fig. 6.

Using the indicated method, the predicted effect of hydrogen content of the fuel on life ratio for five General Electric combustors, consistent with service in U.S. Navy applications, is shown in Fig. 11. For each engine, the curve selected for the metal temperature effect from Fig. 9 is indicated.

As an example, for the J79-10A combustor curve D was selected from Fig. 9. It is based on data recently obtained on this particular combustor in the region where combustor failures occur. The service life is well established at 600 h. In a fighter application, the cyclic life is estimated at six times the service life of 3600 thermal cycles. Figure 6 was then entered at 3600 cycles, and the life ratio showed several values of the temperature parameter, each value corresponding to a specific fuel hydrogen content on curve D of Fig. 9. This permits the curves in Fig. 11 to be constructed.

Conclusions

A generalized method is presented for estimating the effects of fuel composition on liner life. This method avoids the detailed temperature parameter and stress distribution calculations required when using conventional cyclic material property charts. Cyclic life ratios due to fuel changes were found to be similar when correlated with a temperature parameter used in the past to correlate fuel character effects on liner temperatures. This life ratio was found to be relatively independent of the peak temperature existing with base fuel, coolant temperature, and the actual detailed stress calculation.

Acknowledgments

The development of this method was funded partly by Southwest Research Institute in support of their Contract N00140-80-C-2269 with the Navy.

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