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ANALYTICAL STUDY OF COOLED TURBINE BLADES CONSIDERING COMBINED STEADY-STATE AND TRANSIENT CONDITIONS

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16. Abstract

A stress analysis considering both creep and fatigue damage was made for three turbine blade cooling configurations for hypothetical advanced airbreathing engine missions each consisting of a fast acceleration, a 2-hour cruise at Mach 3 and 75 000 feet (22.86 km), and a fast deceleration. The best design was a film-convection cooled configuration followed by a multiple small hole design. A liquid metal cooled blade showed the poorest life largely because of severe fatigue damage.

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SUMMARY

An analysis was made of section lives of three turbine blade cooling configurations for hypothetical advanced airbreathing engine missions each consisting of a fast acceleration, a 2-hour cruise at Mach 3 and 75 000 feet (22.86 km), and a fast deceleration. The configurations evaluated were a film-convection cooled, a multiple small hole, and a liquid metal cooled design. The blades were analyzed mainly for airfoil sections 70 percent of the span distance from the hub using transient and steady-state temperature distributions previously computed. Stress distributions and creep, plastic, and total strains for each of 250 cycles or missions were calculated from a stress analysis computer program which considered both transient and steady-state effects. Times to failure under combined creep and fatigue damage were determined using IN 100 creep and isothermal strain cycling data. The film-convection cooled blade which was superior to the other designs was limited in life predominantly by creep damage for the design conditions. The liquid metal cooled blade had the poorest life because of the severity of the fatigue damage which considerably overshadowed the creep damage. The superiority of the film-convection cooled blade over the multiple small hole blade was largely due to the greatest total strain changes occurring away from any holes in the former design and adjacent to holes in the latter.

INTRODUCTION

An analysis is made of section lives of three turbine blade cooling designs for a hypothetical advanced airbreathing engine having repeated missions consisting of a fast acceleration from idle, a 2-hour cruise at Mach 3 and 75 000 feet (22.86 km), and a fast deceleration to idle.

Turbine blade life is mainly dependent on the combined effects of creep and fatigue damage. During engine acceleration, the metal temperatures at the leading and trailing edges of turbine blades tend to increase more rapidly than at the midchord or interior regions. During deceleration, the edges tend to cool more rapidly than the midchord or interior of the blade. These transient temperature gradients result in large thermal strains and strain changes and may cause local plastic flow to occur. If these strain changes during engine cycling are large enough, there will be progressive fatigue damage with each repetition of the mission. If creep and fatigue damage are of the same order of magnitude, blade life is less than if each damage effect were considered isolated from the other.

Reference 1 presents a steady-state stress relaxation analysis of five turbine blade cooling configurations based on the times to 1 percent local creep strain and using temperature distributions obtained from references 2 to 4 for a typical supersonic cruise condition and a constant coolant flow rate. The five designs in descending order of their steady-state creep lives are (1) a transpiration cooled blade with a porous shell supported on a strut, (2) a multiple small hole blade which depended primarily on film cooling, (3) a strut insert blade using impingement cooling at the leading edge and horizontal fins to cool the midchord region convectively, (4) a film-convection cooled blade with both film and convection cooling at the leading and trailing edges, and (5) a liquid metal cooled blade.

Transient temperature distributions have been calculated for these designs for fast and slow engine cycling as part of the overall program of references 2 to 4. Cyclic lives for the slow acceleration-deceleration condition are presented in reference 5 for the multiple small hole, strut insert, and film-convection cooled blade designs using a proprietary analytical method of which the assumptions and details are not reported.

The purpose of this study is (1) to demonstrate how blade life can be predicted from combined steady-state and transient temperature data, and (2) to evaluate qualitatively and compare the film-convection, multiple small hole, and liquid metal cooled configurations for a typical series of missions. Each mission consisted of a fast acceleration, 2-hour cruise at Mach 3 and 75 000 feet (22.86 km), and a fast deceleration. Steady-state and transient temperature distributions calculated for the program reported in references 2 to 4 are employed.

The section lives are determined from a stress analysis program which is essentially a combination of the stress relaxation program used in reference 1 and the transient stress analysis program described in reference 6. Isothermal strain cycling test results for IN 100 specimens with and without holes from reference 6 are used in conjunction with this method to estimate the degree of fatigue damage.

The blades are compared mainly on the basis of the lives at an airfoil section 70 percent of the span distance from the hub, since transient temperatures for the multiple small hole and liquid metal cooled blades are only available at this span location. The variation in the section life of the film-convection cooled blade as well as its susceptibility to creep and fatigue damage with span distance is explored. Some general conclusions are drawn about the effects of transient conditions on blade lives.

ANALYTICAL CONDITIONS

Blade Cooling Configurations

The three cooling designs that are studied are illustrated in figures 1 to 3.

In the film-convection cooled design shown in figure 1, the cooling air enters the airfoil through an inlet near the leading edge and two central inlets. At the midchord region of the blade, the air circulates up and down spanwise channels. Part of this air impinges on the leading edge internal surface from crossover slots in the adjacent channel wall. All the air used to cool the leading edge is discharged through film cooling holes. The trailing edge is mainly convectively cooled by air discharging through slots although there is a small contribution due to film cooling.

The multiple small hole blade configuration of figure 2 has rows of closely spaced holes distributed over the airfoil shell. Air is ejected through these holes and forms an insulating film around the blade surface. The trailing edge is cooled through a combination of film cooling and convection cooling by air flowing through slots.

In the liquid metal design, shown in figure 3, the compressor discharge air is used to cool heat exchanger tubes instead of cooling the blade directly. The liquid metal used in this design is potassium. Boiling of the potassium occurs as it flows through radial passages and absorbs heat from the leading edge and midchord regions of the airfoil. Vapor then forms around the metal surface of each passage. This vapor is forced back to the base of the blade by the liquid metal pressure. Condensation occurs in the cooled tubes below the blade platform. The trailing edge is convectively cooled with air since space limitations make it impracticable to use liquid metal cooling.

All three blade configurations are assumed to be integrally cast structures.

Engine Operating Conditions and Blade Geometry

The transient and steady-state heat transfer claculations are based on a cruise flight at Mach 3 and 75 000 feet (22.86 km) altitude. Under these conditions, the gas turbine inlet temperature is 2270° F (1517 K) with a 1270° F (961 K) blade coolant inlet temperature. The turbine blades have a tip speed of 1700 feet per second (518 m/sec) and a hub-

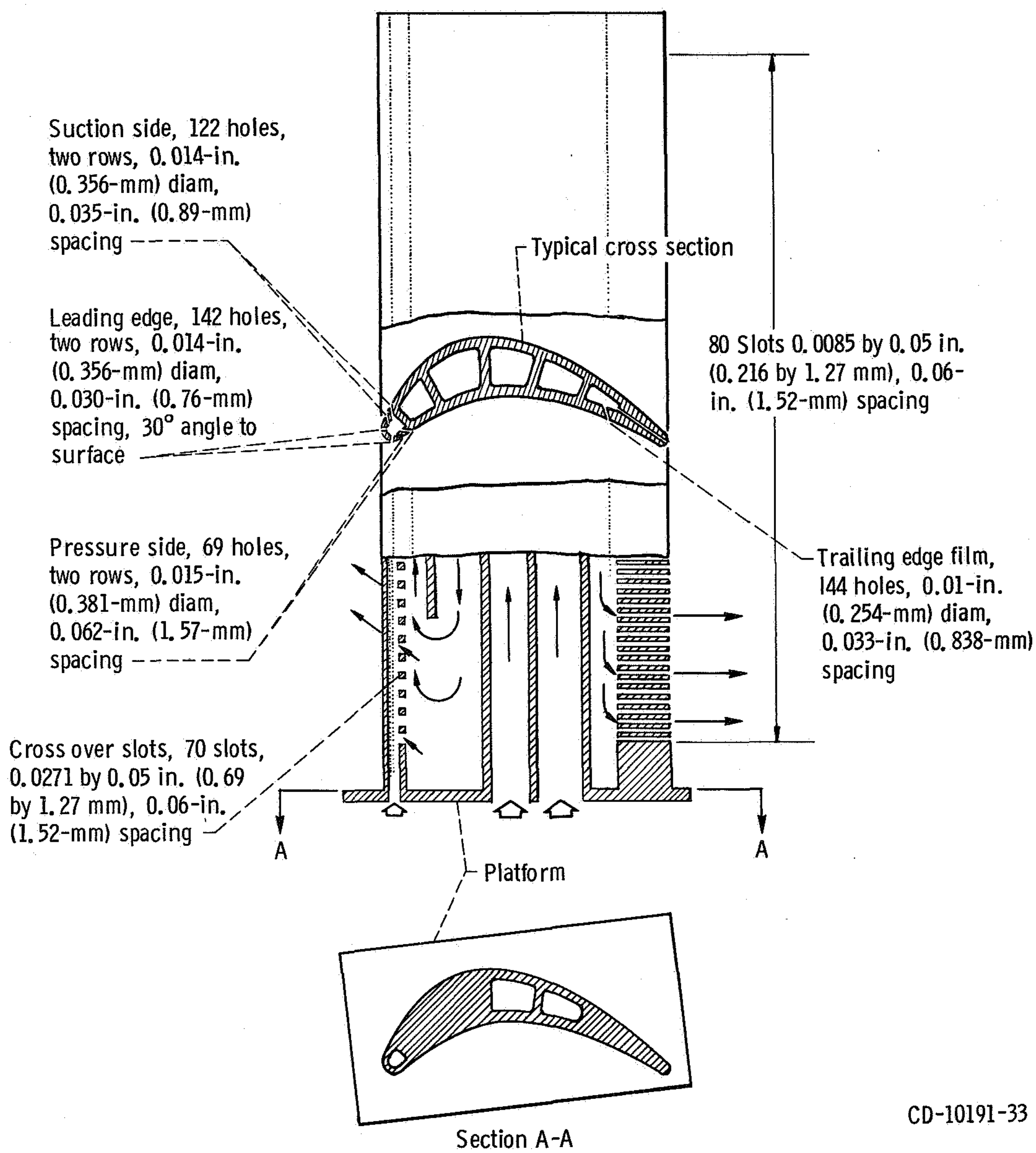

Figure 1. - Film-convection cooled design.

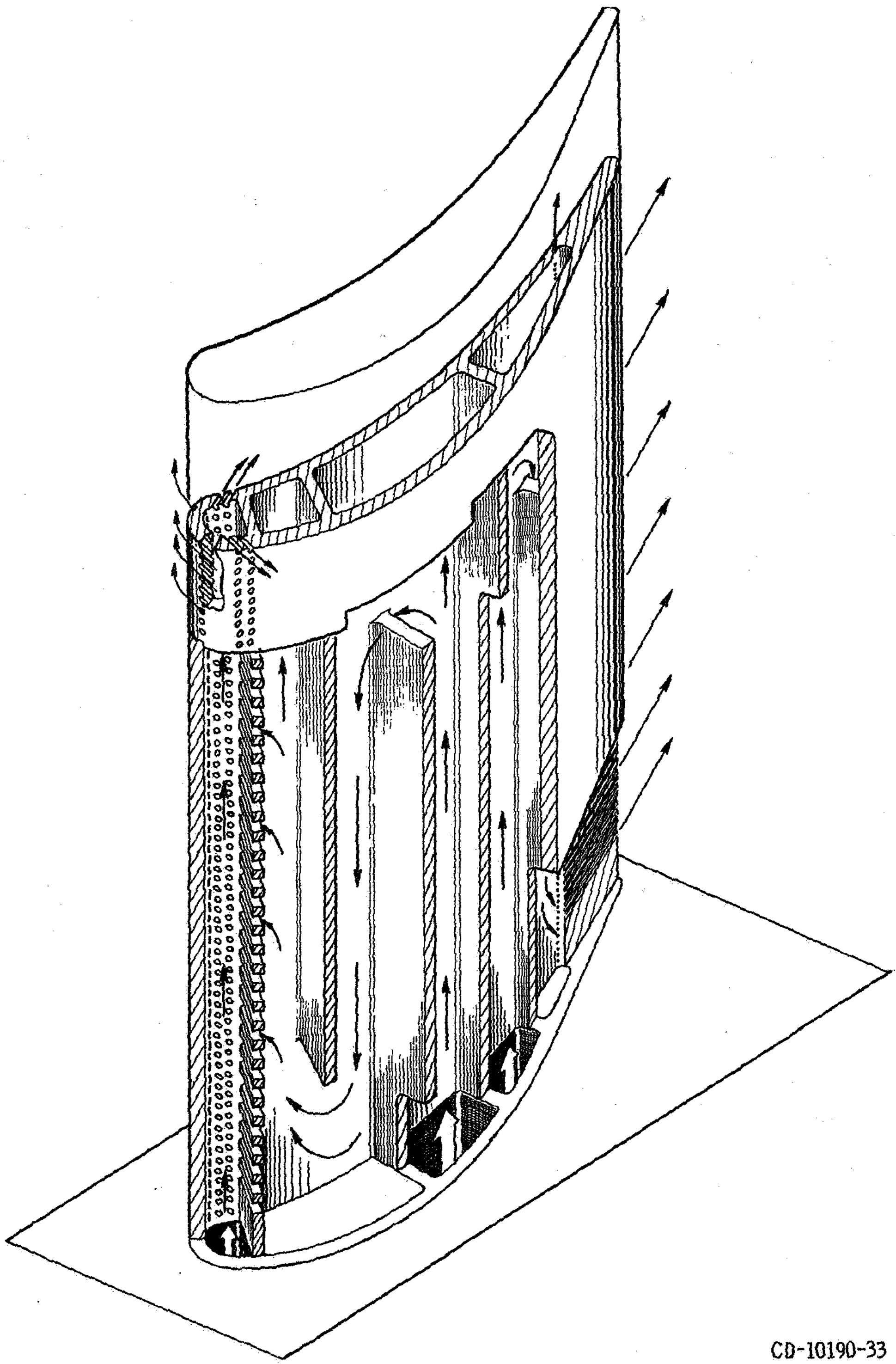

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Figure 1. - Concluded.

Row	Hole configuration
1 to 3 and 8	A
4 and 9	B
5 to 7 and 10 to 13	C

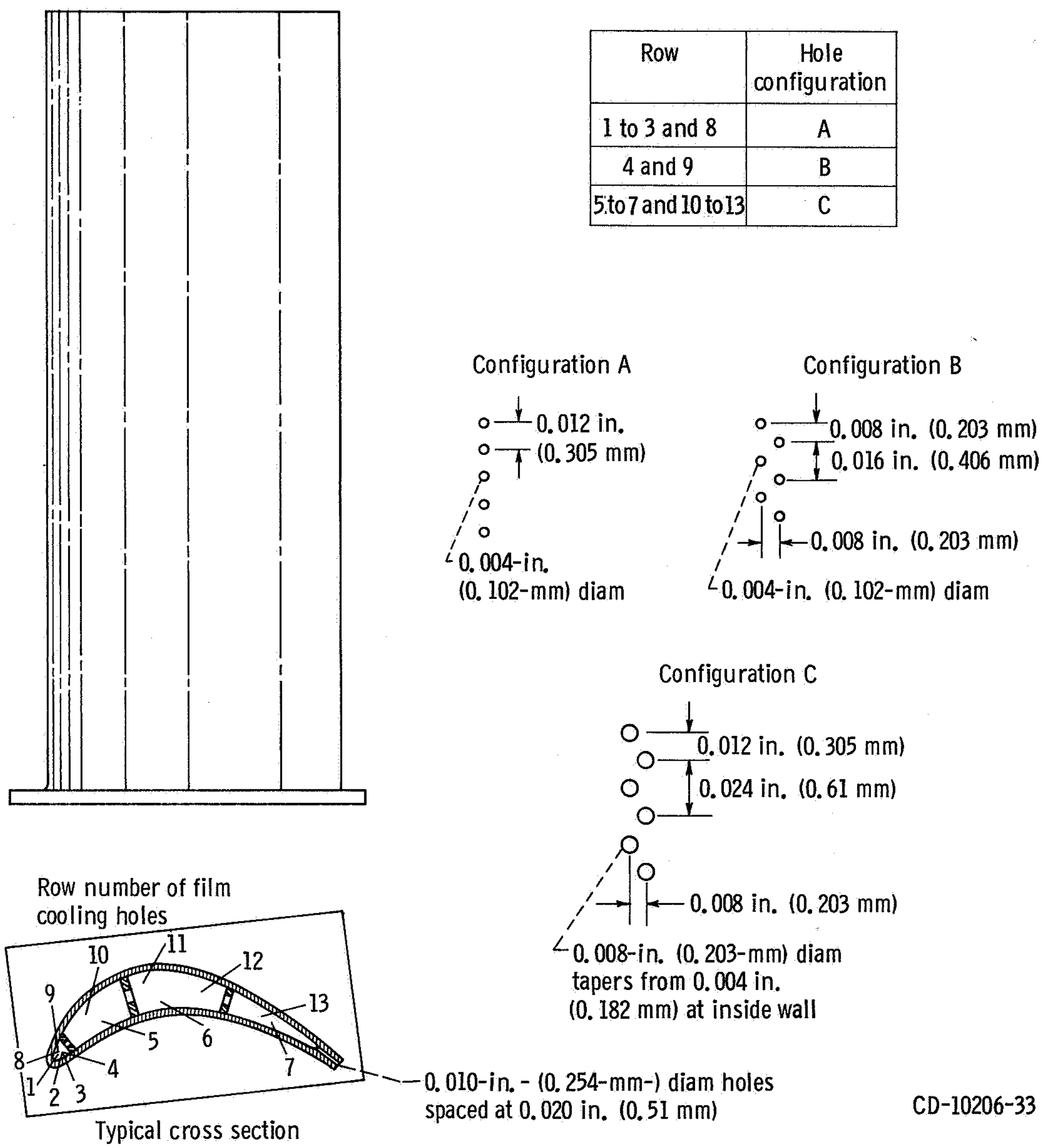

Figure 2. - Multiple small hole design.

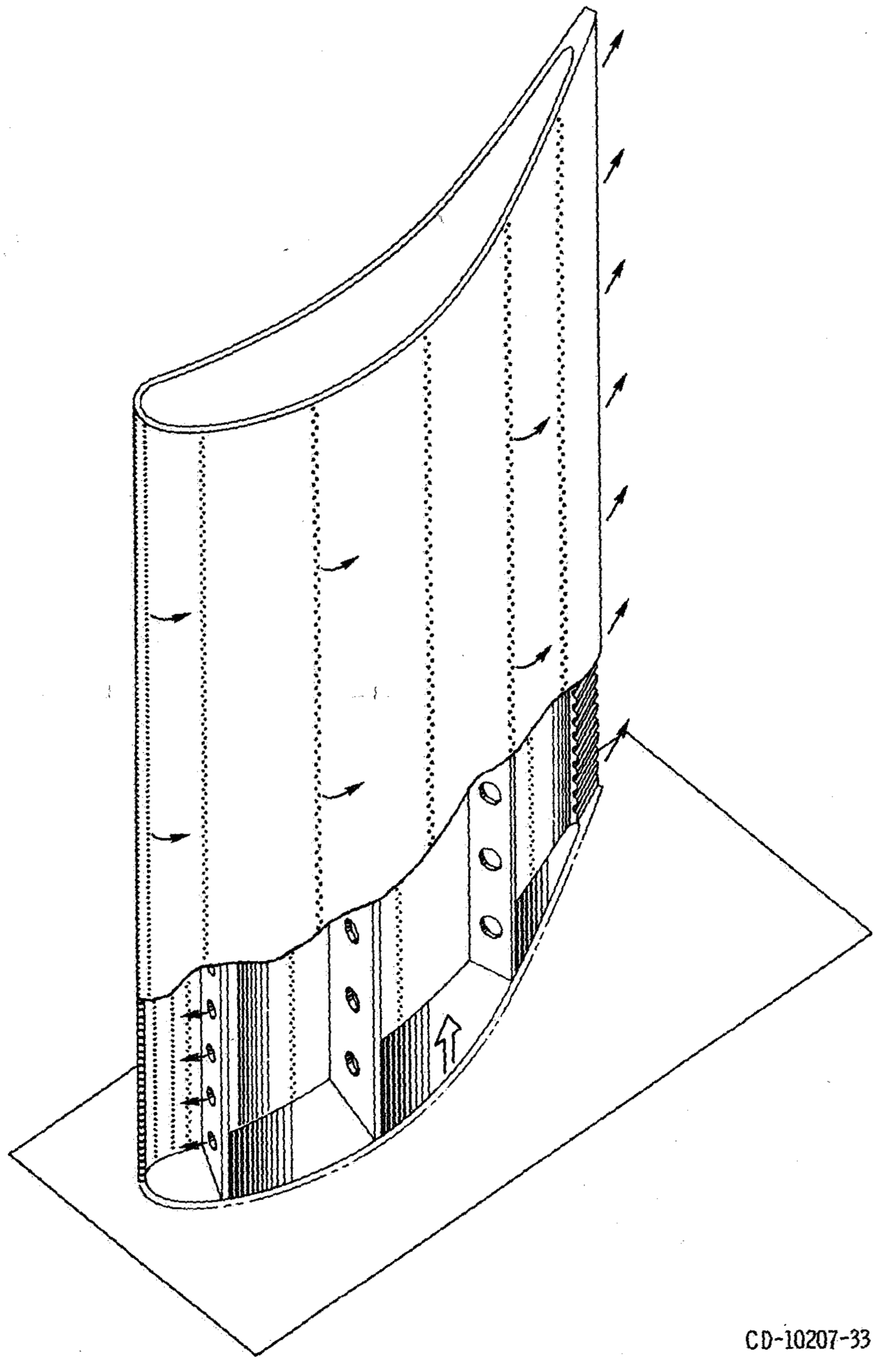

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Figure 2. - Concluded.

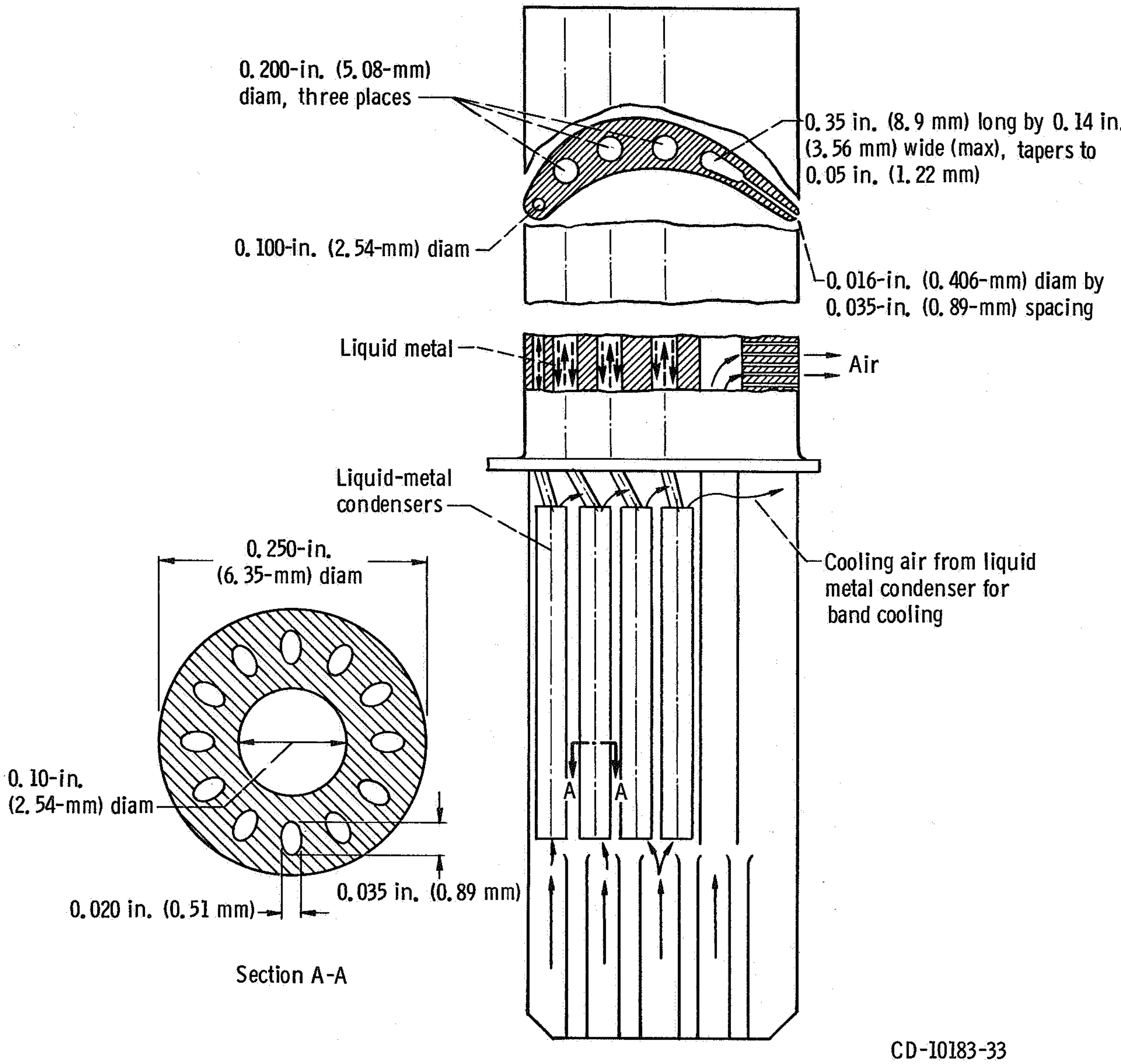


Figure 3. - Liquid metal and convection cooled design.

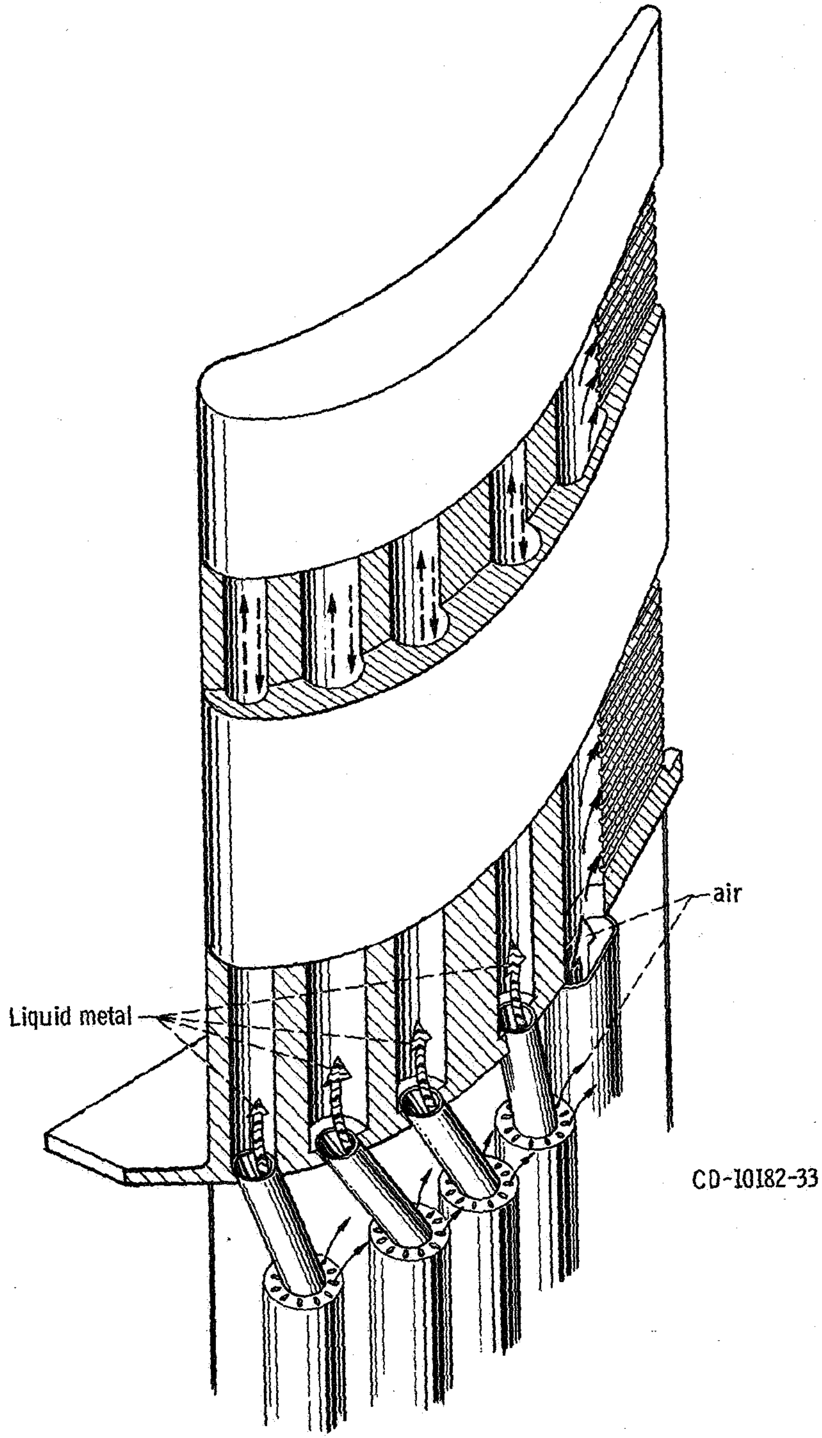


Figure 3. - Concluded.

tip diameter ratio of 0.81. The blades have a chord width of approximately 2 inches (5.1 cm) and an airfoil span length of 5.3 inches (13.46 cm). The airfoils are considered to be tilted to cancel out bending moments due to the gas loads at the cruise condition. At other engine conditions, between idle and sea level static, the gas loads are minor and are neglected.

The engine is assumed to undergo repeated missions each consisting of a fast acceleration from idle to sea level static conditions, a 2-hour cruise flight, and a fast deceleration from sea level static to idle conditions.

The film-convection, multiple small hole, and liquid metal cooling configurations have coolant to total gas flows of 3.54, 3.82, and 3.17 percent, respectively, at the sea level static condition and 2.89, 2.86, and 2.68 percent, respectively, at the Mach 3 cruise condition.

Blade Transient Temperatures

The turbine inlet gas characteristics for the fast engine acceleration and deceleration are reproduced in figure 4 from references 2 to 4. During acceleration, the turbine inlet gas temperature rises from 900° F (755 K) at idle to 2400° F (1589 K) at sea level static conditions in 4 seconds. On deceleration, the gas temperature drops back to a minimum at idle in 2.5 seconds.

Transient temperature distributions were computed as part of the heat-transfer analyses of references 2 to 4 for the fast acceleration and fast deceleration cycles for all three

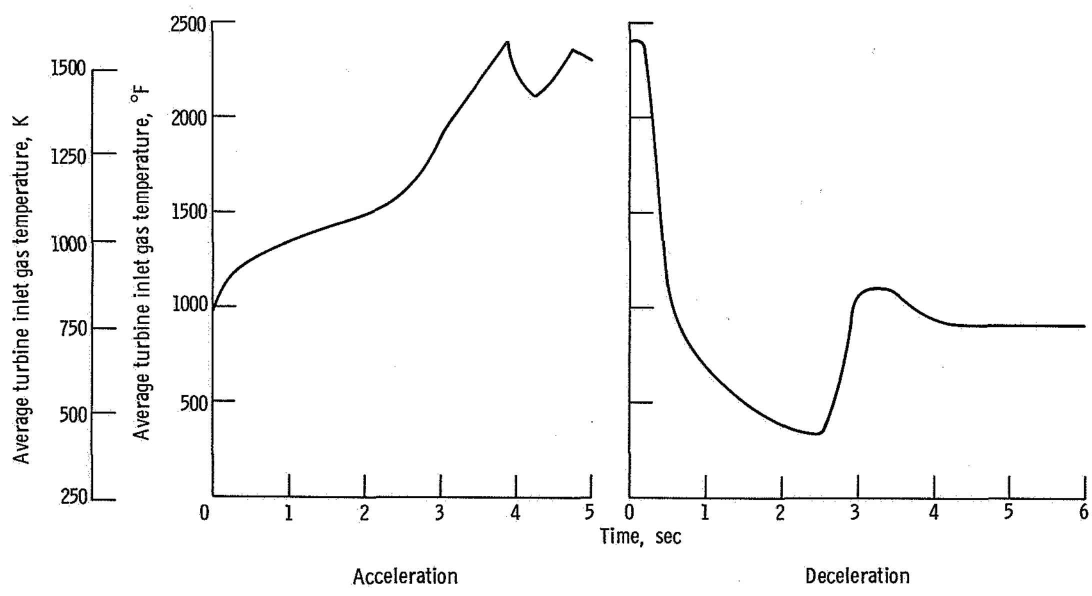
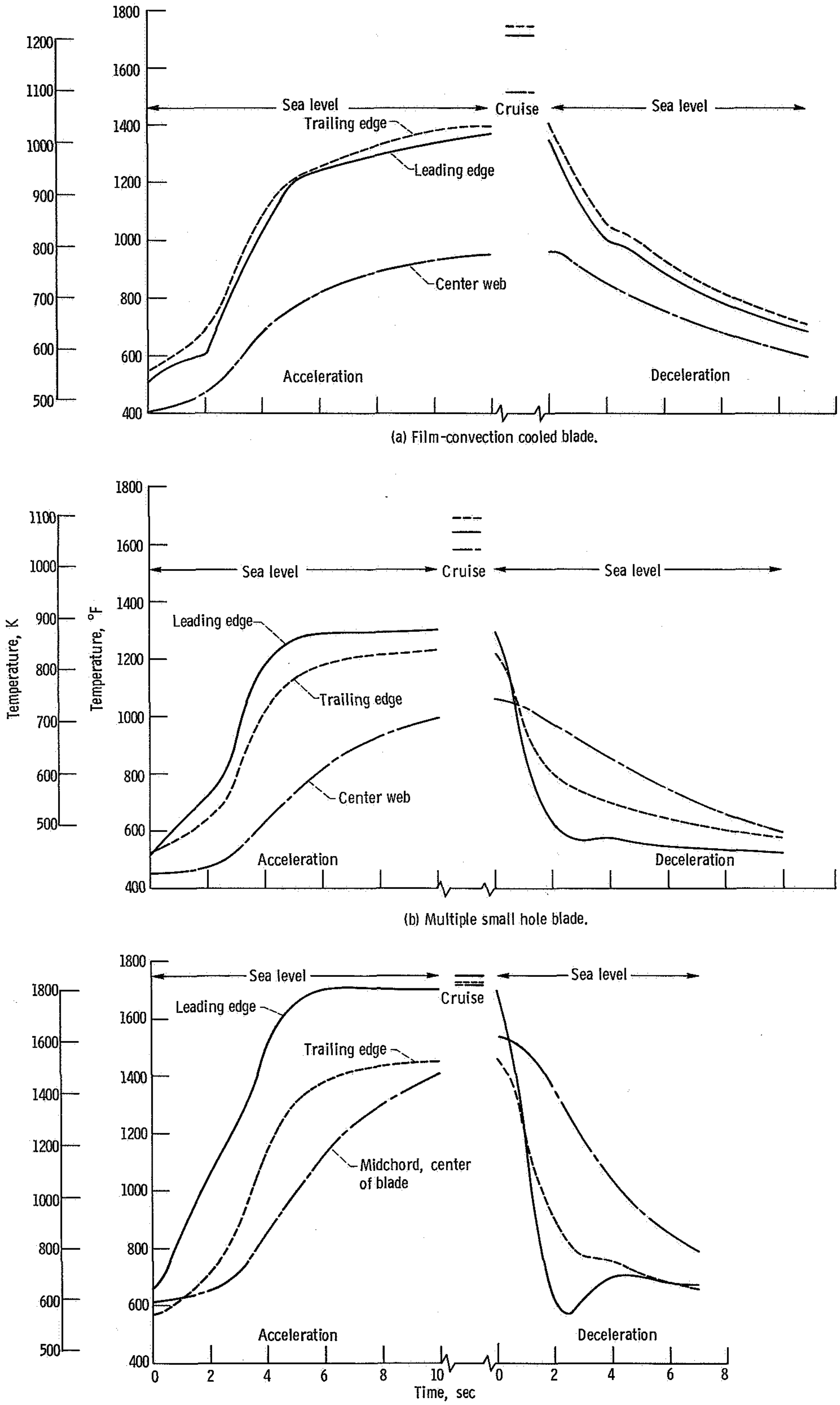


Figure 4. - Turbine inlet gas temperature from idle to sea level static conditions (refs. 2 to 4).



(a) Film-convection cooled blade.

(b) Multiple small hole blade.

(c) Liquid metal cooled blade.

Figure 5. - Blade temperature response during engine cycle (70 percent span location).

cooling configurations at a section 70 percent of the span distance from the airfoil hub. In addition, transient temperature distributions were computed for the film-convection blade at sections 10, 30, and 50 percent of the span distance from the hub.

The blade metal temperature responses for the cooling configurations are shown by figure 5 for positions at the leading and trailing edges and near the center of the 70 percent span sections. In all three cases, either the leading or trailing edge is the hottest part and the center the coolest part of the blade during acceleration. This is also true during deceleration for the film-convection cooled blade (fig. 5(a)). However, the center of the blade tends to be hotter for most of the deceleration part of the cycle for the multiple small hole (fig. 5(b)) and the liquid metal cooled blade (fig. 5(c)). To reach the maximum metal temperature on accelerating from idle to sea level static requires about 11 seconds for the film-convection cooled blade and 6 seconds for the other configurations. The metal temperature at which the temperature gradient first levels out or reverses itself on decelerating from sea level static to idle is reached in somewhat over 9 seconds for the film-convection cooled blade and in about $2\frac{1}{2}$ to 3 seconds for the multiple small hole and liquid metal cooled blades.

In figure 5, even though the metal temperatures at cruise are of about the same order for all three configurations, the liquid metal design shows considerably higher transient and sea level static metal temperatures. The hottest part of the liquid metal blade at sea level static at the 70 percent span location (fig. 5(c)) is about 1700° F (1200 K) compared with 1400° F (1033 K) for the film-convection cooled blade (fig. 5(a)) and 1300° F (978 K) for the multiple small hole blade (fig. 5(b)).

The most significant effect of the transient condition is in causing thermal lags between the midchord and edge regions during deceleration. At the start of deceleration, the leading edge is the hottest part of the multiple small hole (fig. 5(b)), and liquid metal cooled (fig. 5(c)) blades. However, after $2\frac{1}{2}$ seconds, the midchord or center web is hotter by 370° F (461 K) and 700° F (644 K) for the multiple small hole and liquid metal cooled configurations, respectively. No such thermal lag is evidenced by the film-convection cooled blade where the trailing edge is the hottest and the center web the coolest parts of the airfoil throughout the cycle.

ANALYTICAL PROCEDURE

Stress Analysis Method and Assumptions

The stress analysis program used to determine the blade lives is a combination of the stress relaxation program described in reference 1 and the transient stress analysis program described in reference 6 with some minor modifications to make them compatible with each other. The program considers the effects of the centrifugal and gas loads on the blades, thermal stresses, creep under steady-state operation, plastic flow under both transient and steady-state operation, and Bauschinger effects. The usual assumption of strain compatibility is made that plane sections remain plane. Effects of restoring moments arising from the line of action of the centrifugal force being offset from the section centroid because of distortion of the blade due to plasticity or creep can also be considered. End effects are neglected but should not be important, provided the section under examination is a reasonable distance from the blade tip. The effects of spanwise temperature gradients are also not considered. However, the analysis should be valid as long as the spanwise temperature gradients are fairly linear, which they are in reference 2 at cruise except for the film-convection cooled blade near the tip.

Steady-State Creep Damage

Creep data for IN 100 from reference 7 was correlated in Larson-Miller form and applied with a strain hardening rule to calculate the stresses and creep strains as a function of time at the cruise condition. This procedure is explained in detail in reference 1. Because of the excessive amount of computing time that would be required to run the cases under examination to failure, the program was stopped after 500 to 1000 hours of total cruise flight after which there are only slight further changes in stresses with time. The time to stress rupture at cruise was calculated using the stress rupture data of reference 7 for the final stress level when the program stopped. However, this stress rupture time does not take into account the higher stresses that were experienced before relaxation was completed. During this period the blade suffered greater creep damage than would be predicted by the use of the final stress level. In order to compensate for this, an equivalent time to reach the creep strain when the program stopped was determined using the final stress. The difference between this equivalent time and the time at which the program stopped was subtracted from the stress rupture time previously calculated to give the life.

Fatigue Damage

Cyclic lives are based on the total strain range and maximum temperature during the cycle and related to isothermal low cycle fatigue tests. Experimentally derived curves from strain cycling tests to fracture at 1700° F (1200 K) of IN 100 bar specimens with and without holes are reproduced in figure 6 from reference 6. Stress concentration effects

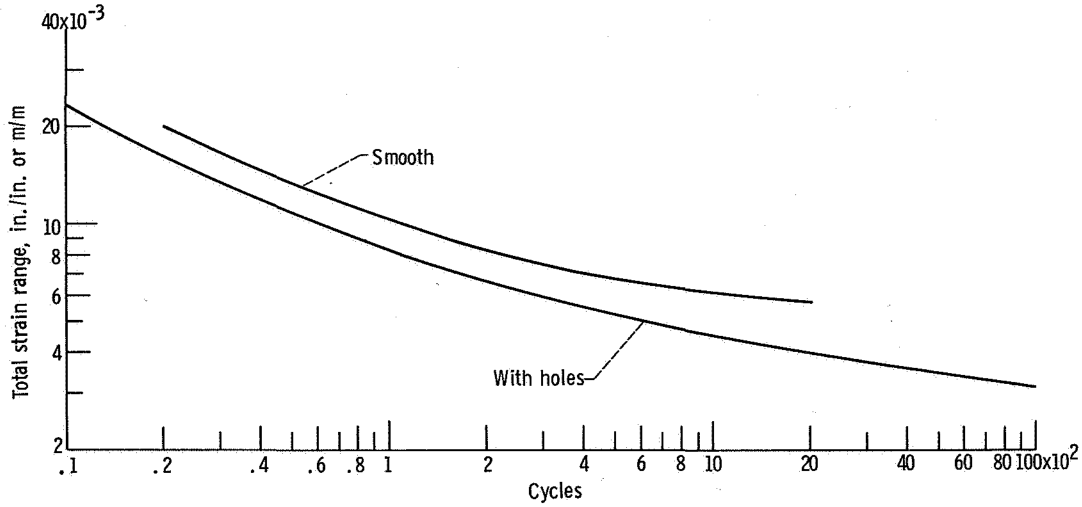


Figure 6. - Effect of total strain range on cycles to fracture for IN 100 at 1700° F (1200 K) (ref. 6).

due to film cooling or other holes are taken into account by using the fatigue results from specimens with holes. The cyclic lives of the blade configurations are based on the 1700° F (1200 K) results because the maximum temperatures during the missions are about 1700° F (1200 K), as shown in figure 5. However, it is noted that the strain cycling results in reference 4 are relatively insensitive to test temperatures from 1000° F (801 K) to 2000° F (1367 K).

Combined Creep and Fatigue Damage

Steady-state creep rupture and fatigue failure times are determined for the nodes which show the most serious creep and fatigue damage at the airfoil sections under examination. The time to failure under combined creep and fatigue damage is determined by the method of reference 8 which assumes that the percent damage due to both failure mechanisms must add up to 100 percent or

$$\frac{t_r'}{t_r} 100 + \frac{N_f'}{N_f} 100 = 100 \tag{1}$$

where t_r' and N_f' are the times and cycles, respectively, to failure under combined creep and fatigue, t_r and N_f are the times to creep rupture and the cycles to fatigue fracture, respectively, and a cycle is equivalent to 2 hours for the mission being considered. The 1700° F (1200 K) curve for specimens with holes in figure 6 was used to determine the fatigue cyclic lives for nodes where holes occur and the curve for smooth specimens for nodes where no holes are present.

RESULTS AND DISCUSSION

Film-Convection Cooled Blade

Effect of span location. - The results from stress analyses at the 10, 30, 50, and 70 percent span locations of the film-convection cooled blade are shown in figure 7.

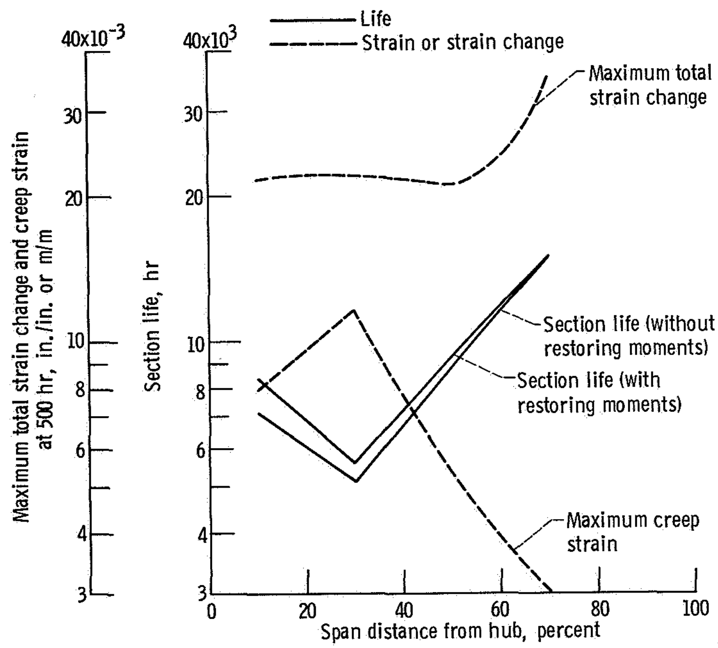
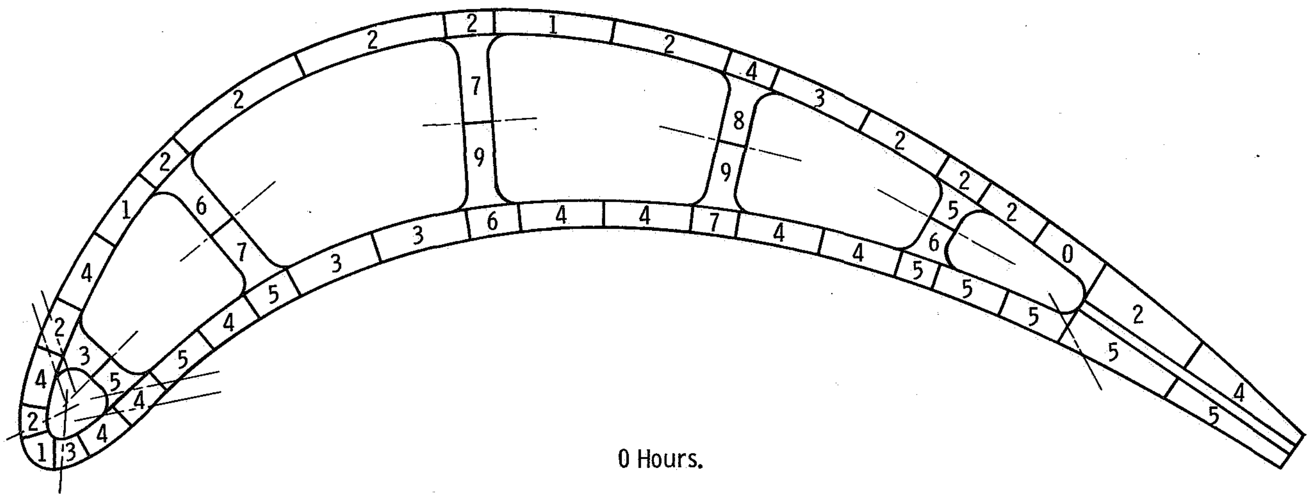


Figure 7. - Film-convection cooled blade life and strain effects with span distance.

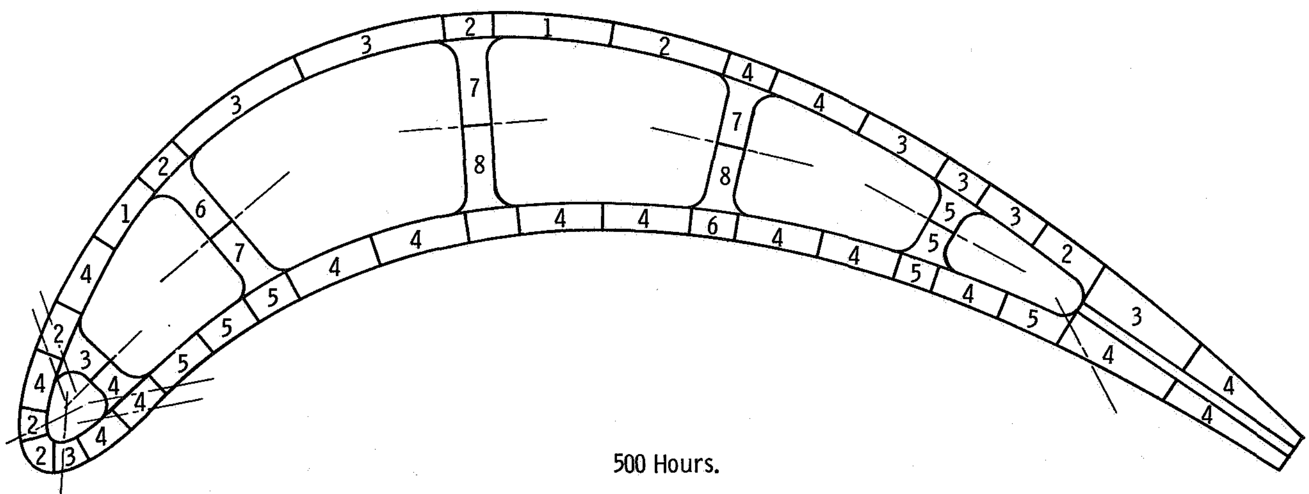
These results are determined for the critical node at each span location. Curves of section life as a function of span distance are presented with and without consideration of restoring moments due to centrifugal force counteracting the tendency of the blade to undergo creep, plastic, and thermal distortions. Strain effects are shown only for cases in which restoring moments were considered.

The total strain change, which is a measure of susceptibility to fatigue failure, is greatest at the 70 percent span location, while the greatest creep damage is at the 30 percent span location. The maximum total strain change between the 10 and 50 percent span

Key	Stress, psi	Stress, N/cm^2
0	Under -10 000	Under -6895
1	-10 000 to -5 000	-6895 to -3447
2	-5000 to 0	-3447 to 0
3	0 to 5000	0 to 3447
4	5 000 to 10 000	3447 to 6895
5	10 000 to 15 000	6895 to 10 342
6	15 000 to 20 000	10 342 to 13 790
7	20 000 to 25 000	13 790 to 17 237
8	25 000 to 30 000	17 237 to 20 684
9	Over 30 000	Over 20 684



0 Hours.



500 Hours.

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Figure 8. - Stress distribution at cruise for 70 percent span location of film-convection cooled blade.

locations is 2.1×10^{-3} to 2.2×10^{-3} inch per inch, whereas the strain-cycling results of figure 6 indicate that at least 3.1×10^{-3} inch per inch is required in order to have low cycle fatigue failure. Therefore, there is little possibility of fatigue failure below 70 percent span based on the calculated temperatures used and the experimental results of reference 6. The minimum section life with and without restoring moments being considered occurs at 30 percent span where the creep damage is worst. The effect of not taking the restoring moments into account is to show a shorter life by 15 percent at the 10 percent span, 4 percent at the 50 percent span, and almost zero at the 70 percent span. It, therefore, appears that the restoring moments can be neglected with only small error above midspan where fatigue damage will probably be most serious.

Results at 70 percent span location. - Stress distributions in the 70 percent span section at cruise after 0 and 500 hours of operation are compared in figure 8. The highest stresses and greatest stress relaxation occur in the webs which are the coolest parts of the blade throughout the mission (fig. 5(a)). The stress redistribution with time also results in a raising of the initially low stress levels on the suction side of the shell. In figure 9, total strain changes per cycle are shown for each node of the 70 percent span

Key	Total strain change, in./in. (or m/m)	Fatigue life, cycles At holes	Fatigue life, cycles Not at holes
0	Under 0.7×10^{-3}	∞	∞
1	0.7 to 1.4×10^{-3}		
2	1.4 to 2.1×10^{-3}		
3	2.1 to 2.8×10^{-3}		
4	2.8 to 3.5×10^{-3}	4500 to ∞	
5	3.5 to 4.2×10^{-3}	1500 to 4500	
6	4.2 to 4.9×10^{-3}	650 to 1500	
7	4.9 to 5.6×10^{-3}	370 to 650	3000 to ∞
8	5.6 to 6.3×10^{-3}	240 to 370	800 to 3000
9	6.3 to 7.0×10^{-3}	170 to 240	400 to 800
*	Critical node		

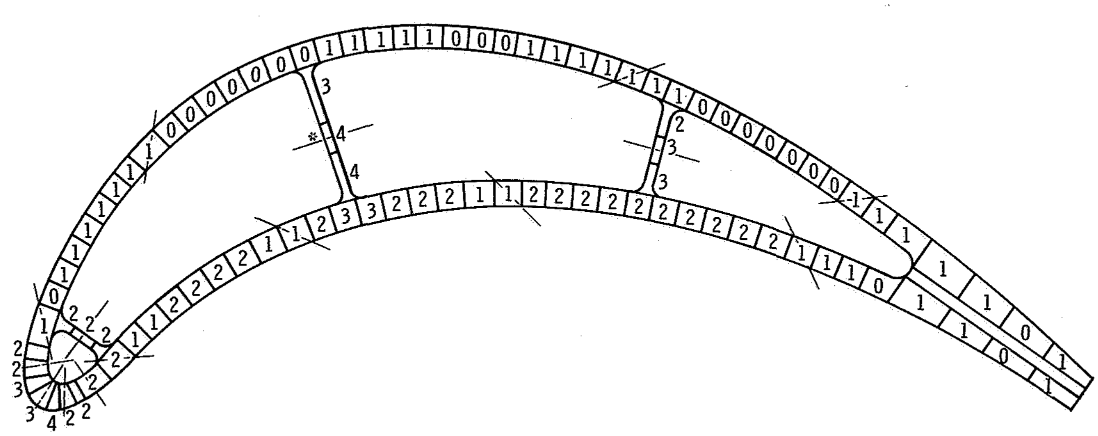

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Figure 12. - Total strain change per cycle for 70 percent span location of multiple small hole blade.

section. The maximum total strain change occurs at about the midchord of the suction side of the shell for this span location, whereas it occurs adjacent to a hole at the central web for the other span locations examined. It is evident that the maximum total strain change level shown in figure 9 is not sufficient to cause low cycle fatigue failure based on the smooth specimen strain cyclic results from figure 6 which are tabulated for reference in figure 9. However, this strain range level would be sufficient to create a fatigue problem only if it were adjacent to a hole as at the other span sections. It is apparent that none of the total strain changes at nodes near holes in figure 9 is serious enough to result in significant fatigue damage. The critical node, which is at the trailing edge at all span sections, is, therefore, determined solely from considerations of creep damage.

No plastic strain takes place at the critical node and, therefore, the total inelastic strain is equal to the creep strain as shown in figure 10 for the first 500 hours of opera-

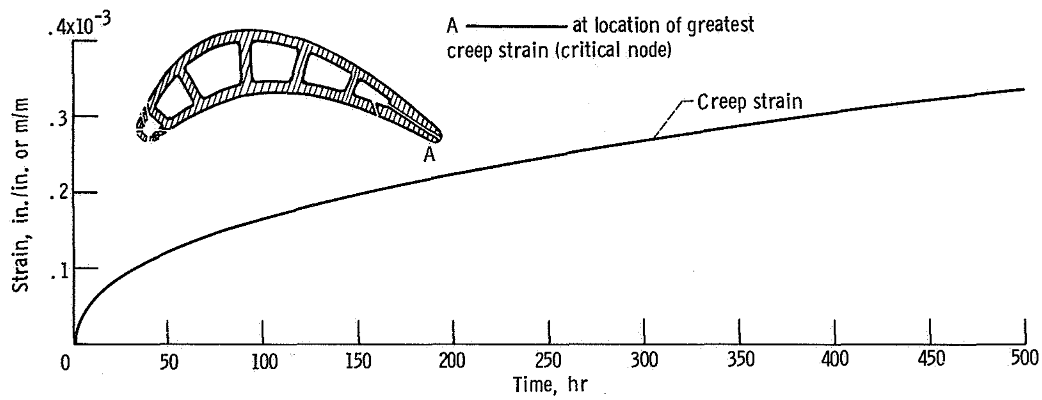

Figure 10. - Inelastic strain change with time at cruise for film-convection cooled blade for critical node at 70 percent span location.

tion at 70 percent span. There are some plastic strains at a few nodes at this span location, but the creep damage at these nodes is small compared with the critical trailing edge node.

Multiple Small Hole Blade

The highest stresses are generally at or near the webs in the multiple small hole blade and these stresses undergo the greatest relaxation after 500 hours as shown in figure 11. In this configuration the webs are the coolest parts of the blade during acceleration and cruise but are the hottest parts during most of the deceleration (fig. 5(b)).

The greatest creep strain occurs near the leading edge, while the greatest total

Key	Stress, psi	Stress, N/cm^2
0	Under -10 000	Under -6895
1	-10 000 to -5 000	-6895 to -3447
2	-5000 to 0	-3447 to 0
3	0 to 5000	0 to 3447
4	5 000 to 10 000	3447 to 6895
5	10 000 to 15 000	6895 to 10 342
6	15 000 to 20 000	10 342 to 13 790
7	20 000 to 25 000	13 790 to 17 237
8	25 000 to 30 000	17 237 to 20 684
9	Over 30 000	Over 20 684

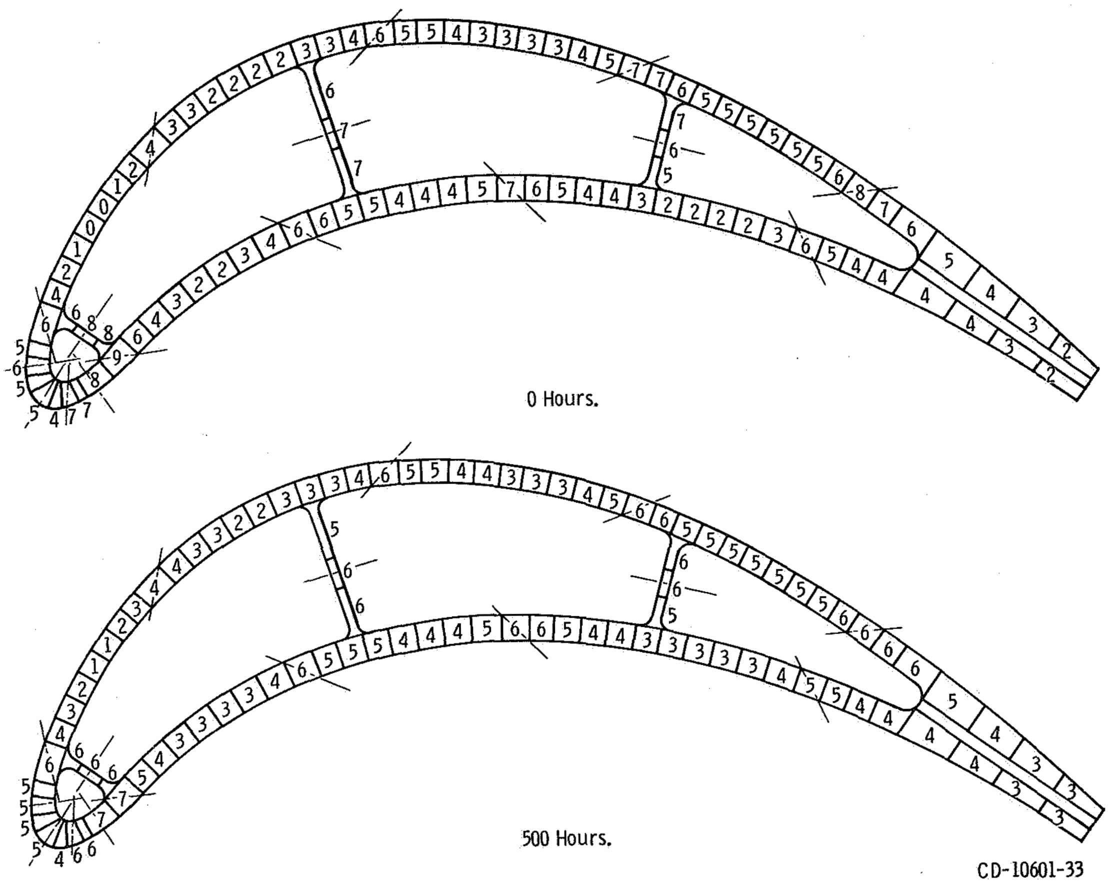

Figure 11. - Stress distribution at cruise for 70 percent span location of multiple small hole blade.

strain change and the worst combination of creep and fatigue damage is adjacent to a hole on a web, as shown in figure 12 for the 70 percent span section. It may be argued that it is overly pessimistic to calculate the blade life on the basis of a web failure since the web is not normally an important structure bearing member and any crack will probably stop short of the shell. However, a web failure may cause some unknown redistribution of the stresses which can have catastrophic results. It, therefore, seems reasonable to be conservative and base the life on the critical node even when it is at a web.

Key	Total strain change, in./in. (or n/m)	Fatigue life, cycles	
		At holes	Not at holes
0	Under 0.7×10^{-3}	∞	∞
1	0.7 to 1.4×10^{-3}		
2	1.4 to 2.1×10^{-3}		
3	2.1 to 2.8×10^{-3}		
4	2.8 to 3.5×10^{-3}	4500 to ∞	
5	3.5 to 4.2×10^{-3}	1500 to 3500	
6	4.2 to 4.9×10^{-3}	650 to 1500	
7	4.9 to 5.6×10^{-3}	370 to 650	3000 to ∞
8	5.6 to 6.3×10^{-3}	240 to 370	800 to 3000
9	6.3 to 7.0×10^{-3}	170 to 240	400 to 800
*	Critical node		

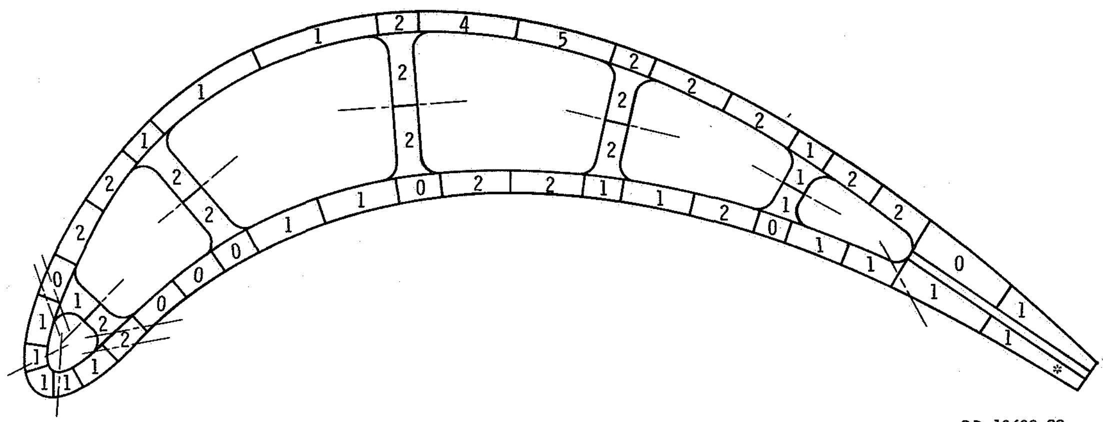

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Figure 9. - Total strain change per cycle for 70 percent span location of film-convection cooled blade.

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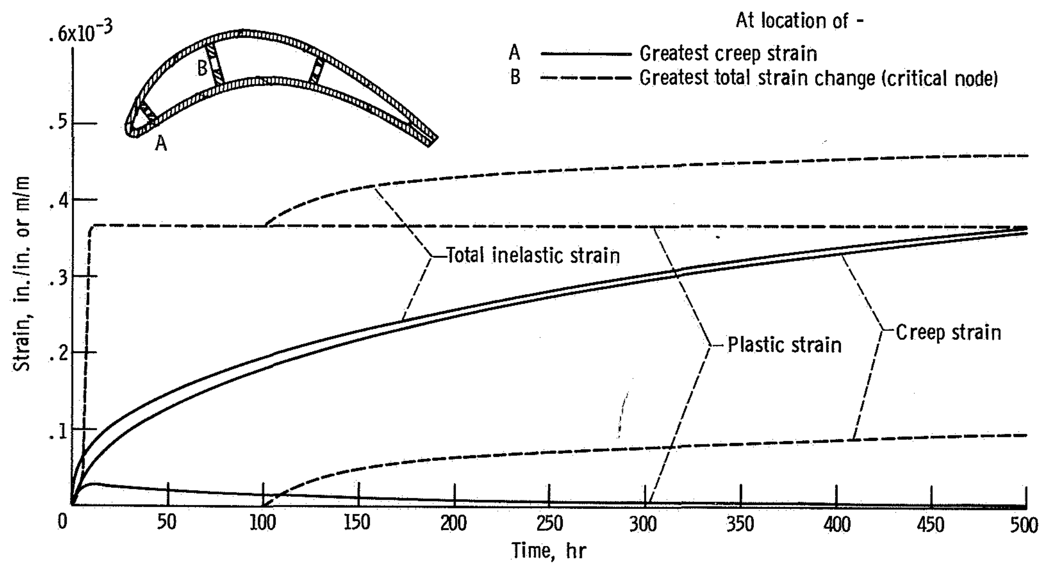

Figure 13. - Inelastic strain change with time at cruise for multiple small hole blade at 70 percent span location.

The location of the greatest creep strain (leading edge) shows only minor plastic strain at cruise; this plastic strain decreases with time as the creep strain rises in figure 13. On the other hand, at the critical node (center web), the plastic strain increases sharply during the first 10 hours and then remains fairly constant. There is no creep strain at the critical node until 100 hours of blade operation have elapsed. The total inelastic strain is greater at the critical node (center web) where the maximum total strain change occurs than at the node where the highest creep strain occurs (leading edge).

Liquid Metal Cooled Blade

The initial and relaxed stress distributions of figure 14 for the liquid metal cooled blade show relatively low peak stresses and, therefore, little stress relaxation. These small peak stresses are caused by high transient and steady-state temperature levels which result in lower stress and large plastic strains in the elastic-plastic range of the material.

As shown in figure 15, the maximum total strain change occurs at the leading edge which is also the hottest part of the blade. These strains are much higher than the maximum total strain changes reported previously for the other blade designs and are severe enough to create a fatigue damage problem even though no stress concentrations from transverse holes exist. The greatest creep strain is at the pressure face adjacent to the second radial passage from the trailing edge where the total strain change is minor.

The plastic strain is negligible at the node with the greatest creep strain and is negative at the critical node (leading edge) in figure 16. Therefore, the total inelastic strain is less than the creep strain at the leading edge.

Comparison of Cooled Blades

The stress-plastic strain histories of the critical nodes at the 70 percent span are presented in figure 17 for the fifth cycle or mission. No plastic flow takes place at the critical node of the film-convection cooled blade, and the stress-strain sequence is a simple elastic case. There is considerable initial plastic flow in the multiple small hole blade, but it has settled down to an elastic case by the fifth cycle. The liquid metal cooled blade, however, does not settle down to an elastic case but rather goes into compressive yield on the down part of every cycle. As creep progresses, part of the increase in creep strain is canceled out by compressive plastic strains on every cycle.

Key	Stress, psi	Stress, N/cm^2
0	Under -10 000	Under -6895
1	-10 000 to -5 000	-6895 to -3447
2	-5000 to 0	-3447 to 0
3	0 to 5000	0 to 3447
4	5 000 to 10 000	3447 to 6895
5	10 000 to 15 000	6 895 to 10 342
6	15 000 to 20 000	10 342 to 13 790
7	20 000 to 25 000	13 790 to 17 237
8	25 000 to 30 000	17 237 to 20 684
9	Over 30 000	Over 20 684

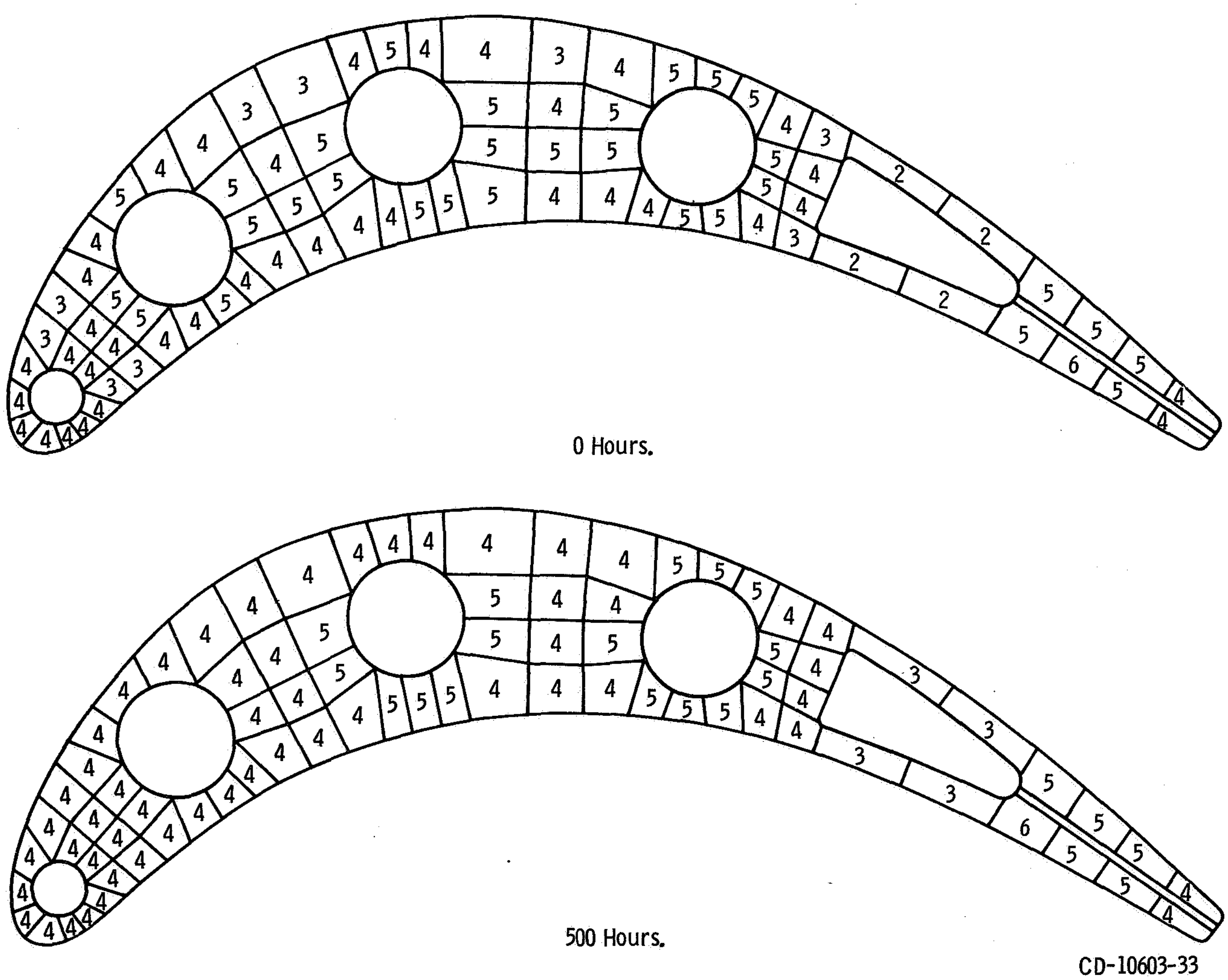

Figure 14. - Stress distribution at cruise for 70 percent span location of liquid metal cooled blade.

Key	Total strain change, in./in. (or m/m)	Fatigue life, cycles At holes	Fatigue life, cycles Not at holes
0	Under 0.7×10^{-3}	∞	∞
1	0.7 to 1.4×10^{-3}		
2	1.4 to 2.1×10^{-3}		
3	2.1 to 2.8×10^{-3}		
4	2.8 to 3.5×10^{-3}	4500 to ∞	
5	3.5 to 4.2×10^{-3}	1500 to 4500	
6	4.2 to 4.9×10^{-3}	650 to 1500	
7	4.9 to 5.6×10^{-3}	370 to 650	3000 to ∞
8	5.6 to 6.3×10^{-3}	240 to 370	800 to 3000
9	6.3 to 7.0×10^{-3}	170 to 240	400 to 800
*	Critical node		

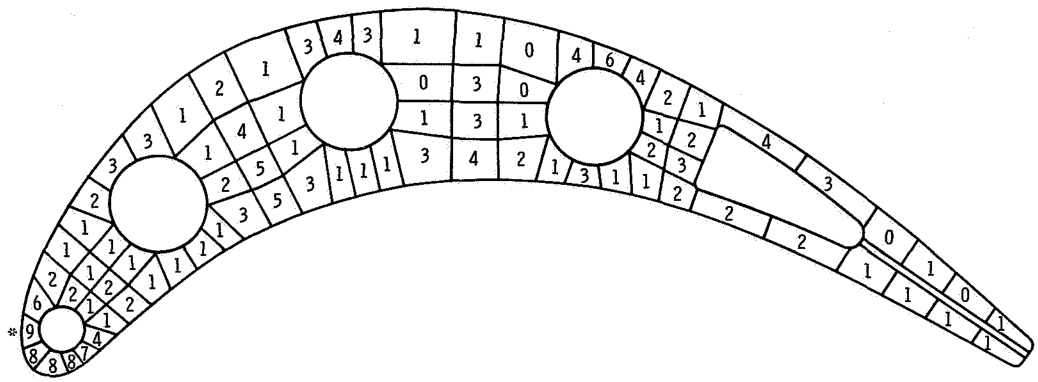

Figure 15. - Total strain change per cycle for 70 percent span location of liquid metal cooled blade.

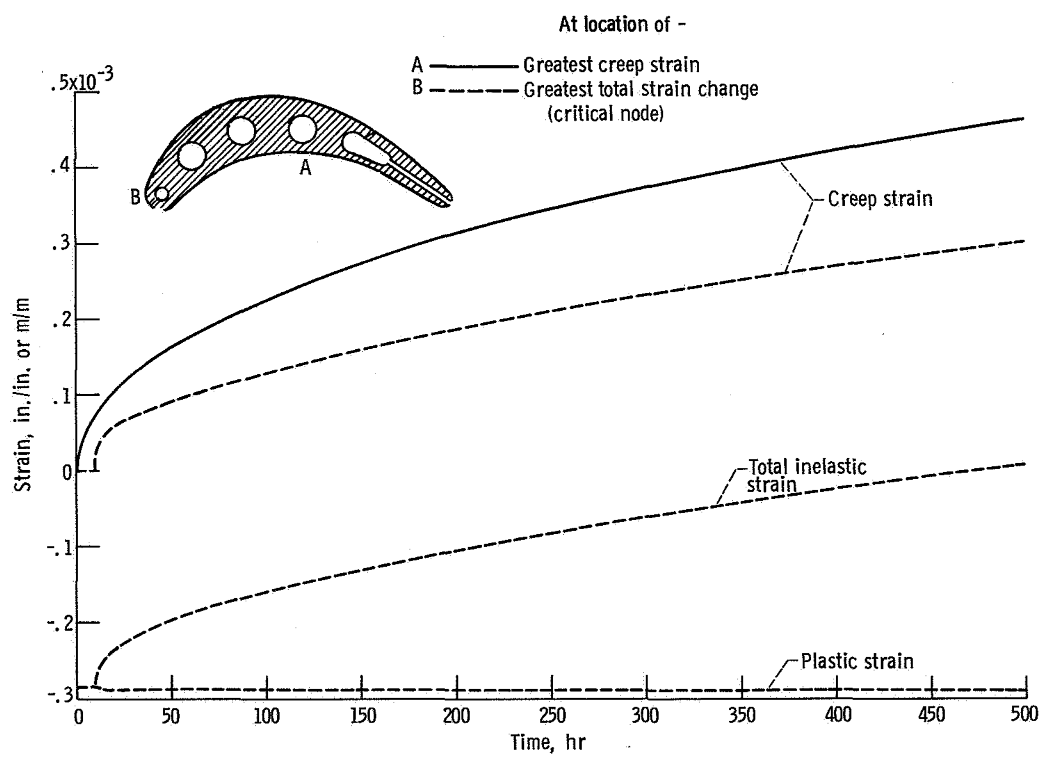

Figure 16. - Inelastic strain change with time at cruise for liquid metal cooled blade at 70 percent span location.

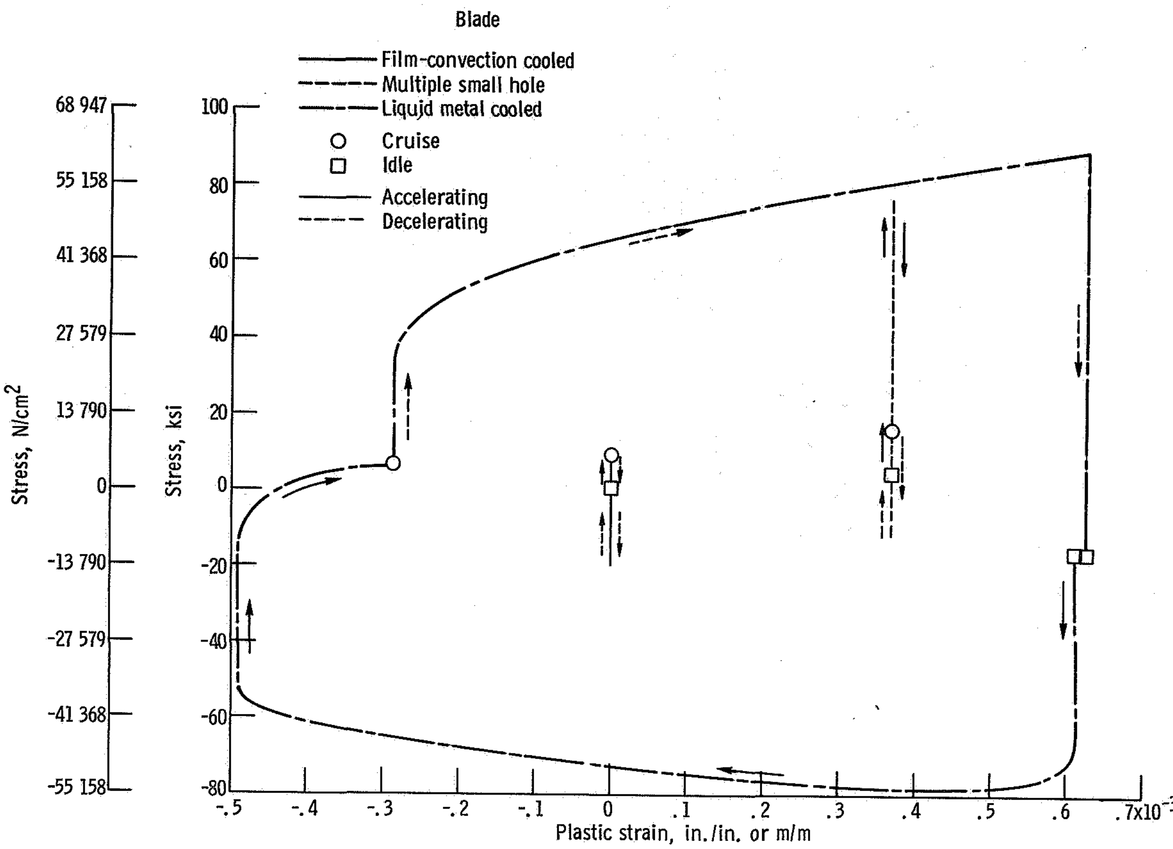

Figure 17. - Stress-plastic-strain history of blades on fifth cycle at critical node.

In table I, the section lives of the three blade cooling configurations are compared for the 70 percent span section. The blades in descending order of lives are the film-convection cooled blade with predominantly creep damage, the multiple small hole blade with combined creep and fatigue damage, and the liquid metal cooled blade with preponderantly fatigue damage. The results in table I for the 70 percent span show that the multiple small hole and liquid metal cooled blades have about 50 and 8 percent, respectively,

TABLE I. - RESULTS OF MISSION SECTION LIFE ANALYSES FOR CRITICAL NODES AT 70 PERCENT SPAN LOCATION (EACH CYCLE IS 2 HR)

Blade cooling design	Time to failure, hr		
	Based on creep rupture alone	Based on fatigue fracture alone	Based on combined creep and fatigue
Film convection	15 000	Infinite	15 000
Multiple small hole	21 000	12 000	7 640
Liquid metal	13 000	1 280	1 170

of the section life of the film-convection cooled blade. Even when the critical section of the latter at 30 percent span is considered, the liquid metal cooled blade has, at best, only 37 percent of the film-convection cooled blade's life. Since no transient temperature distributions were available at span locations below midspan for the multiple small hole blade, it is not certain that this blade has a shorter life than the film-convection cooled blade for the mission being considered, although this seems probable. It was mentioned previously that if there had been a hole adjacent to the node with the greatest total strain change at the 70 percent span location of the film-convection cooled blade, there would be a fatigue damage problem. At this node the creep damage is insignificant so that the life would be determined solely by fatigue. The section life of this configuration at 70 percent span would then become 8400 hours (if there were a hole at the node) compared with 7640 hours for the multiple small hole blade (table I) and, therefore, would not change the ranking of these configurations.

It is apparent that life predictions using only steady-state conditions can be misleading as well as unconservative in evaluating blade designs when severe transient conditions exist as demonstrated by the case of the multiple small hole blade which has the longest life of the three configurations under steady-state conditions as shown in reference 1.

In table II, the total strain levels and changes in the different configurations at

TABLE II. - TOTAL STRAINS AT CRITICAL NODE OF 70 PERCENT SPAN LOCATION (EACH CYCLE IS 2 HR)

Blade cooling design	Total strain, in./in. (or m/m)					
	Maximum during cycle		At cruise		Change during cycle	
	2	250	2	250	2	250
Film convection	0.466×10^{-3}	0.698×10^{-3}	0.466×10^{-3}	0.698×10^{-3}	1.158×10^{-3}	1.159×10^{-3}
Multiple small hole	3.149	3.232	1.055	1.137	3.362	3.363
Liquid metal	3.432	3.723	.012	.300	6.468	6.464

70 percent span are compared for cycles 2 and 250. The first cycle was not chosen because the blade has only gone through half a cycle at cruise and, therefore, the full effect of the cycling on the cruise condition is not developed until the following cycle. An interesting feature of table II is that all the blades show increasing maximum and cruise total strains but the total strain change per cycle remains virtually constant. Only the film-convection cooled blade has the maximum total strain during the cycle occurring at cruise.

The section lives presented in table I are only of qualitative value since the strain cycling test results from reference 6 are not entirely satisfactory for evaluating thermal fatigue damage. It is not certain how well isothermal strain cyclic test simulate thermal fatigue problems. There is also a question as to the applicability of isothermal, constant load creep data to cyclic conditions. Another possible source of error is that analytical life predictions are only as good as the calculated temperatures they are based on and relatively small errors or a minor maldistribution of coolant in the actual hardware due to fabrication problems can invalidate some of the results.

CONCLUSIONS

This report demonstrates how blade life can be predicted from combined steady-state and transient conditions. The following conclusions are drawn from the results of this analytical evaluation of three turbine blade cooling configurations for an advanced air-breathing engine:

1. The film-convection cooled blade shows the longest 70 percent span life and the least susceptibility to fatigue effects due to transient temperature gradients. Creep damage is the predominant failure mechanism with the calculated temperatures used. However, if the maximum total strain change computed at the 70 percent span location had occurred in a chordwise direction adjacent to a hole, as was the situation at all other span locations examined, there would be a thermal fatigue problem.

2. The multiple small hole blade has a combination of creep and fatigue damage as well as a stress concentration effect due to a hole adjacent to the critical node. At the 70 percent span location its life is about half that of the film-convection blade.

3. The liquid metal cooled blade has the poorest life because of severe fatigue damage near the leading edge. The blade life at the 70 percent span location is only 8 percent that of the film-convection blade for the same span location.

4. The critical span location varies according to the relative degree of creep or fatigue damage. It tends to be above midspan if fatigue damage predominates and below midspan if creep damage predominates. In the film-convection cooled blade, the maximum creep damage occurs at the 30 percent span location, and the greatest susceptibility to fatigue damage occurs at the 70 percent span location for the locations surveyed.

5. Life predictions using only steady-state conditions can be misleading when comparing blades if significant fatigue damage takes place. At steady-state conditions, the multiple small hole blade is superior to the film-convection cooled blade, whereas the reverse is true when severe transient conditions occur.

6. The effect of restoring moments arising from the line of action of the centrifugal force being offset from the section centroid because of creep or plasticity can be neglected with only small error for sections above midspan where the most serious fatigue damage

is likely to occur. The percent error in life from not taking the restoring moments into account varies from a maximum of 15 percent at the 10 percent span location to zero at the 70 percent span location for the film-convection cooled blade.

7. Although the maximum and minimum total strain levels tend to increase gradually with time, the difference between these levels or total strain change remains virtually constant from cycle to cycle.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 1, 1969,
720-03.

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