SPACE SHUTTLE MAIN ENGINE
THE FIRST TEN YEARS

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Part 6 – High Pressure Fuel Turbopump Turbine Blade Failures

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Late in 1977, two failures of HPFTP turbine blades occurred just two weeks apart [25]. On November 17, Test 902-095 on Engine 0002 was cutoff prematurely, while operating at 70 percent power level, by the HPOTP vibration redline monitor. The average HPOTP vibration level had increased from 3 g rms to over 70 g rms. However, it was subsequently discovered that the vibration originated in the HPFTP which violently shook the entire engine. The test was not shut down by the HPFTP vibration monitor because it had a built-in time delay of 0.240 seconds, and the HPOTP redline time delay was only 0.100 seconds. A post-test inspection revealed that a first-stage turbine blade had broken off and inflicted significant damage to both turbine stages. Figure 17 shows the damage to the first-stage wheel. The engine was shut down safely with no other engine damage. Two weeks later, on December 1, 1977, Test 901-147 on Engine 0103 experienced a similar failure at slightly above 80 percent power level. This time the damage was more severe. The turbine blade debris caused the rotor to seize up, resulting in the cessation of fuel flow and very LOX rich operation. Major burning throughout the hot gas system followed; but, although significant damage was sustained, it was contained within the engine with no external burnthrough. From this and other fuel side failures, it was concluded that engine failures on the fuel side would be self-contained and therefore fail-safe in the flight environment where there is engine out capability. It would be four years later

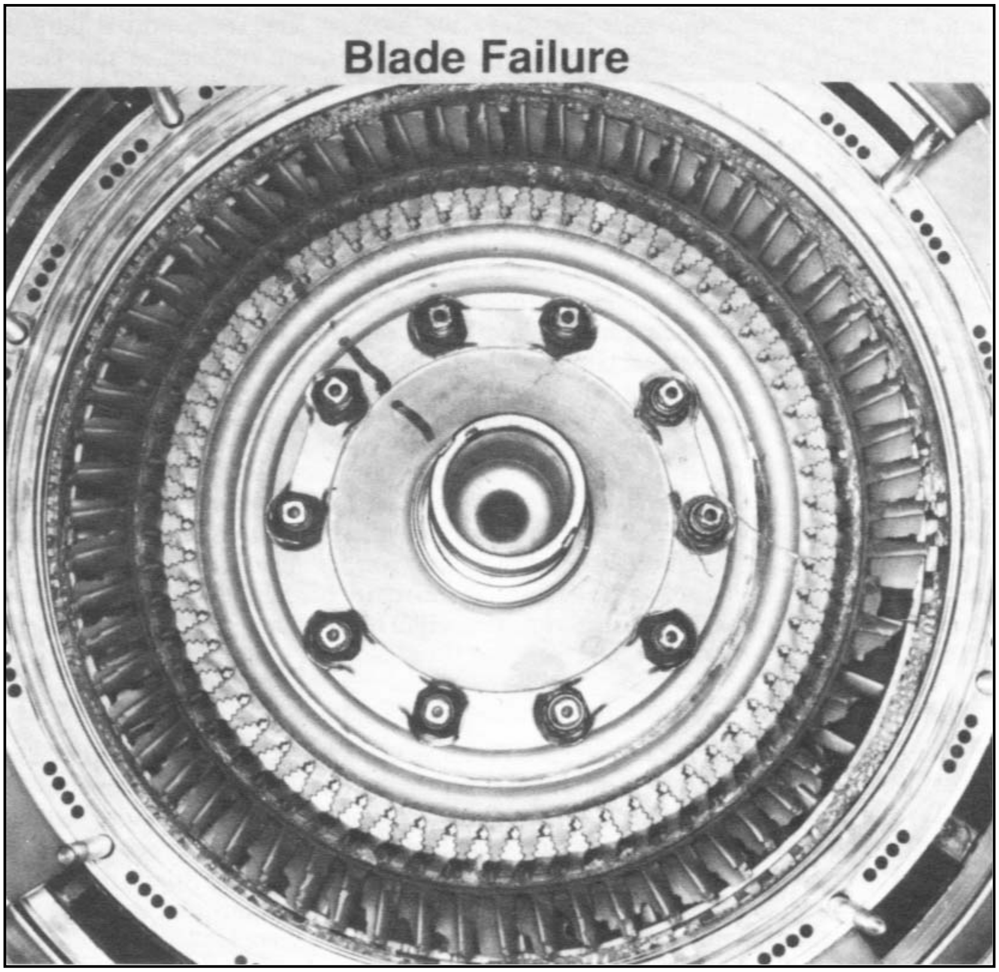

Figure 17. HPFTP First Stage Turbine - Test 902-095 (Photo No. SC89c-4-1032

(after the first flight) that a similar turbine failure at a higher power level would cause the rupture of the low pressure fuel duct and change the fail-safe conclusion.

The HPFTP turbine (Figure 18) is a two stage reaction turbine powered by hot hydrogen-rich steam produced by the FPB. The turbine drive gas is directed by 41 first-stage nozzle vanes into 63 first-stage turbine blades. The first-stage exhaust is gathered by 39 second-stage nozzle vanes and redirected through 59 second-stage turbine blades. (The number of elements were purposely made different to minimize the possibility of frequency reinforcement among the various parts.) The turbine exhaust gas is then guided by sheet metal structure through a 180 degree turn to be consumed in the MCC. The turbine blades are about one inch long by half an inch wide with a ribbed extension called a “fir tree,”, which it resembles (Figure 17). The blades are installed by inserting the fir trees into matching slots in the gold plated turbine disc, and they are held in place by pressure loading and centrifugal force. The blades are structurally independent of each other except for small spring-like devices that fit between the blade shanks in slots provided at the blade platforms. These are called dampers and are used to dampen blade vibration. Because the power generated by the HPFTP amounts to about 600 horsepower per blade, the blades are under tremendous stress. The power bending stress and the centrifugal stress are each approximately 50,000 psi for every blade. The blades are uncooled and -operate at a temperature of about 2,000 R. The turbine blade material for this, very severe environment was chosen based on tests conducted in 1971. The blades are directionally solidified castings of a nickel-based super alloy known as MAR-M-246 (developed by Martin Metals).

With the hardware evidence, data analysis and other blade samples, it was shown that the failures were initiated by a high cycle fatigue crack in the airfoil of a first-stage turbine blade, close to the root. Consultation with government, industry and academic experts led to a comprehensive laboratory test program at Rocketdyne, General Electric, TRW and AiResearch [25]. Tests were conducted to evaluate blade vibration; static loads; high-temperature, high-cycle fatigue; blade platform loading and damper performance. At the same time, material property tests were run to determine thermal shock effects, heat effect on microstructure, and characteristics of fatigue and stress rupture failures.

A centrifugal stress and dynamic response evaluation machine known as the Whirligig was activated at Rocketdyne to test the turbine wheels with blades up to 38,000 rpm while measuring the blade stress with strain gages. Damping rating tests were conducted with various damping designs while using high-pressure gas jets to pulse the blades over a range of frequencies. From these tests, it was discovered that the turbine blade fatigue was caused by locked-up blades

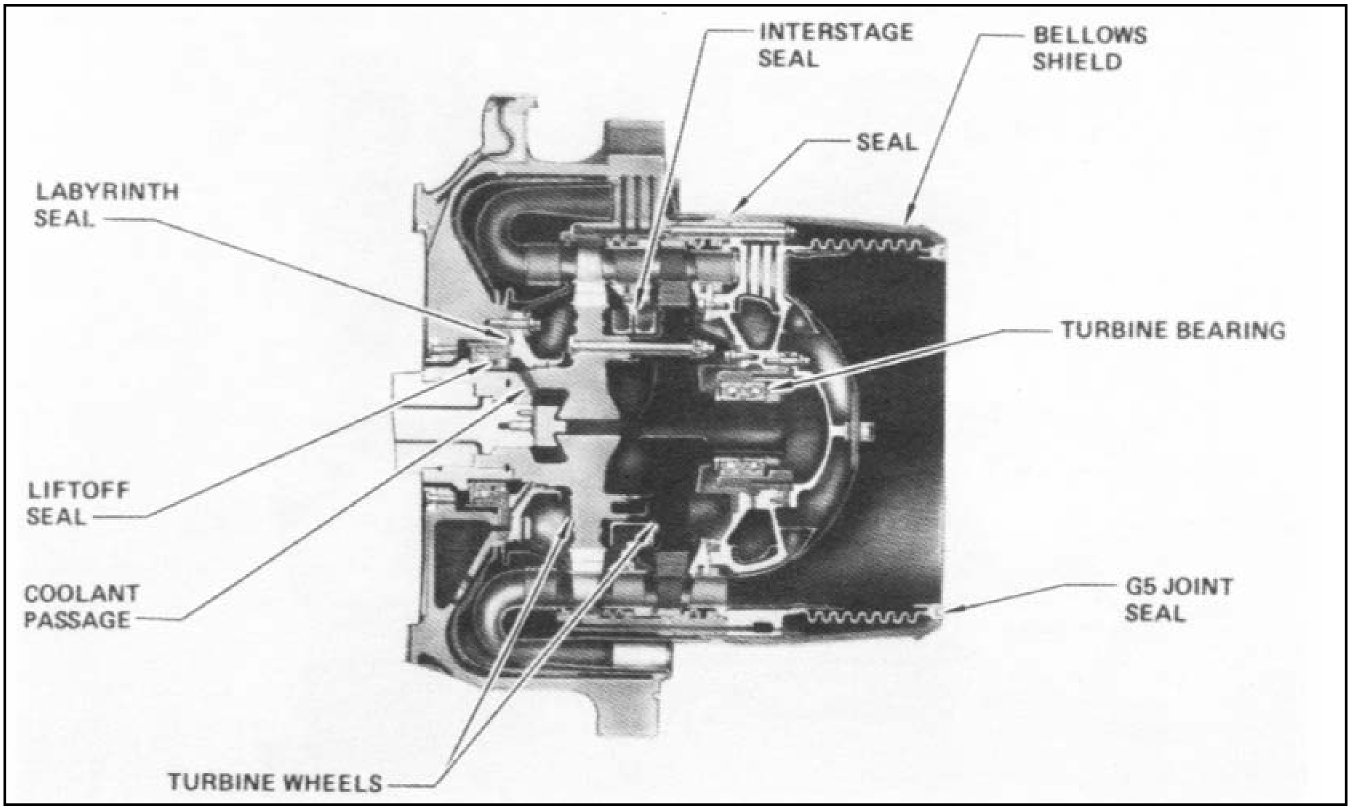

Figure 18. HPFTP Turbine Section (Photo No. SC433-20)

and that all damper configurations tested were effective in reducing the effect of engine-induced vibration modes that could contribute to blade failure. An optimized, lightweight precision-tolerance damper design was selected after a review of the Whirligig test data (Figure 19). The new damper design was incorporated along with changes to preclude blade lock-up either in the wheel or blade-to-blade. A looseness verification was added to the assembly procedures.

Although turbine blades would receive high priority attention for many more years, the specific failure modes associated with Tests 902-095 and 901-147 were eliminated by these modifications. [29]

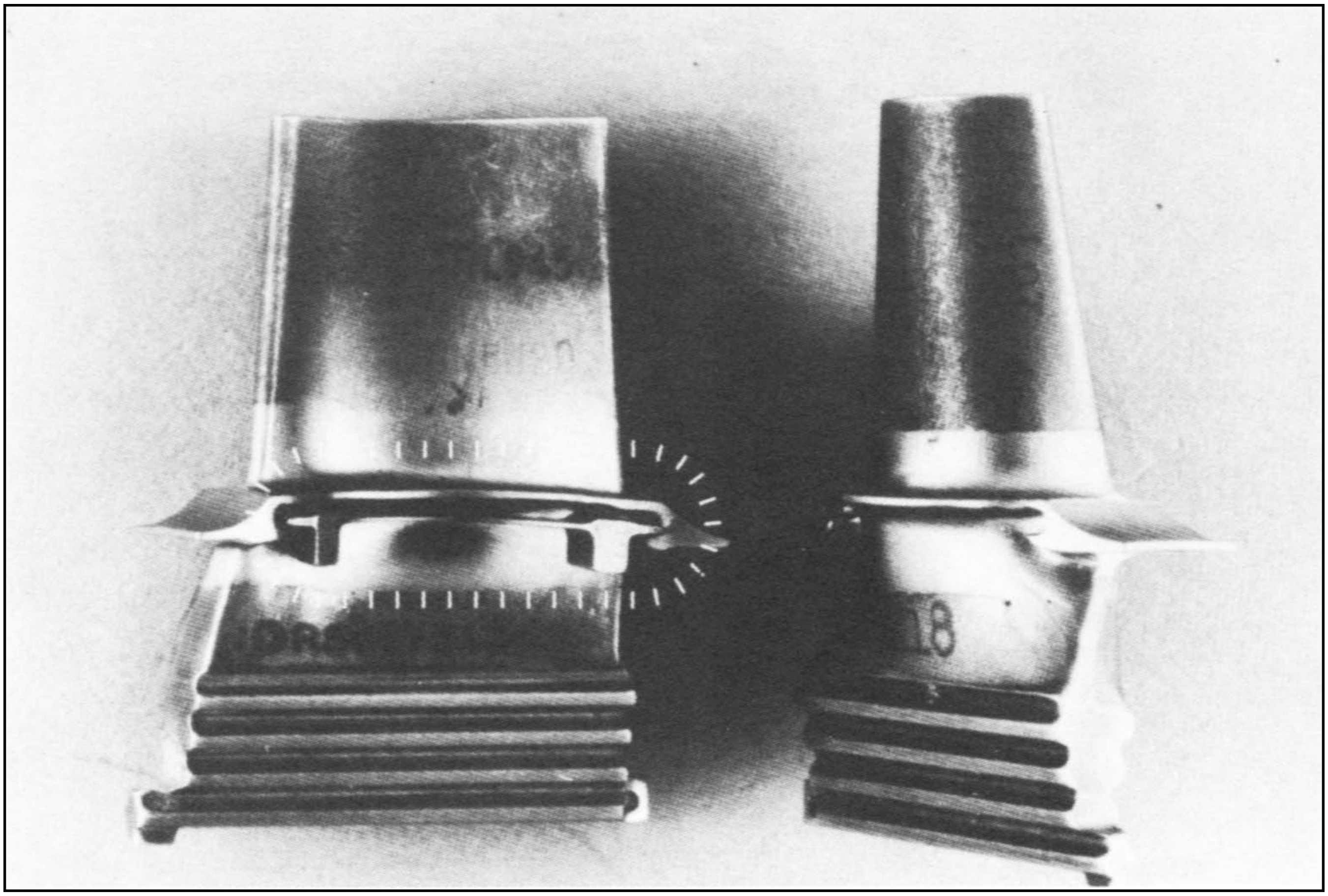

Figure 19. HPFTP First Stage Made Precision Damper (Photo No. 307-291A)