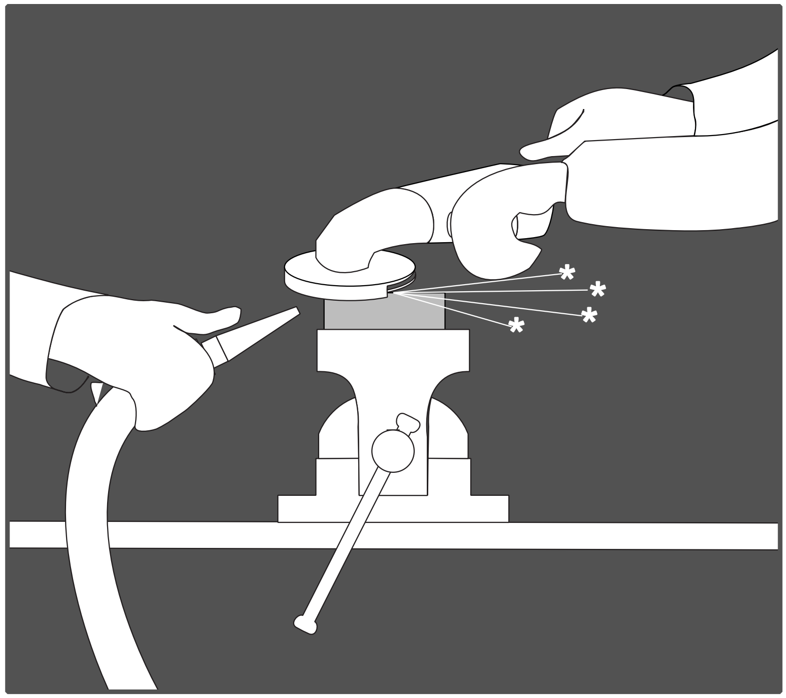
2.2.2.5 Reproduction of Failures and Damages



"**Damage reproduction**" is a controlled process under defined test conditions which attempts to recreate damage that occurred during operation. A reproduction can only be regarded as successful if the damage has been simulated so that it is **identical to the original damage in both the micro and macro areas**. This is an extremely difficult task since damage is usually influenced by several different factors that act simultaneously.

Surprisingly, successful test configurations do not necessarily exactly correspond to those during operation. Although at least the relevant weak points of the affected parts must be the same as the originals, the operating loads can be simulated by a different configuration. The criteria for success is, as mentioned earlier, sufficiently exact reproduction of the damage.

The least elaborate type of reproduction test is the simulation of single influences (Ill. 2.2.2.5-1). These tests can, for example, serve to understand single physical or chemical influences and may therefore be extremely limited when compared to the actual operating conditions.

The reproduction of damages **is a decisive step for understanding accidents**, and if successful, it is a convincing argument. Because reproductions can never simulate all operating influences exactly as they occurred, the correct selection of the relevant influences and test parameters, along with a proper test configuration, are prerequisites for a successful reproduction. Designing these tests requires **many years of experience** with engine and test technology, as well as a **good "feeling" for engineering**.

A successful reproduction of operating damage, e.g. through variation of the influences and/or test parameters provides important **information for risk assessment** and makes possible sufficiently safe corrective measures and their verification.

Tests based on successful reproductions are also extremely important for the **development and verification of repairs**.

A further field where reproduction tests are applicable is the **estimation of damage and remaining life spans**. It is common, for example, to use overspeed tests to simulate fatigue damage at rotor components caused by start cycles (Ill. 4.4-3)

There is often a temptation to minimize testing times in order to save money, decision time, and risks. Here, one must ask if damage with creep symptoms that developed over several thousand hours of operation can be sufficiently realistically reproduced in an acceptable short test of a few hundred hours. Experience has shown that an estimation of the remaining life span is only successful if the activated **damage mechanism is the same as during operation.** If, for example, a crack develops over a long period of operation due to material changes (e.g. due to diffusion, volume 3, Ill. 12.5-6), then the test parameters for estimating the life span must be selected in a way that realistically simulates the damage process as it occurred during operation. If not, an unsuitable test can result in no damage occurring. The damage process that occurred during operation may not even begin to appear, whereas a new damage mechanism might occur to which the part reacts as a new component would.

With all technical tests, verifications, and reproductions, one should always remember that **the engine will have the final say** (example 4.4-2), which means that engine operation will make clear whether the test results were accurate, whether the right conclusions were drawn, and whether the measures taken were correct. Still is true „**the engine will tell us**“.

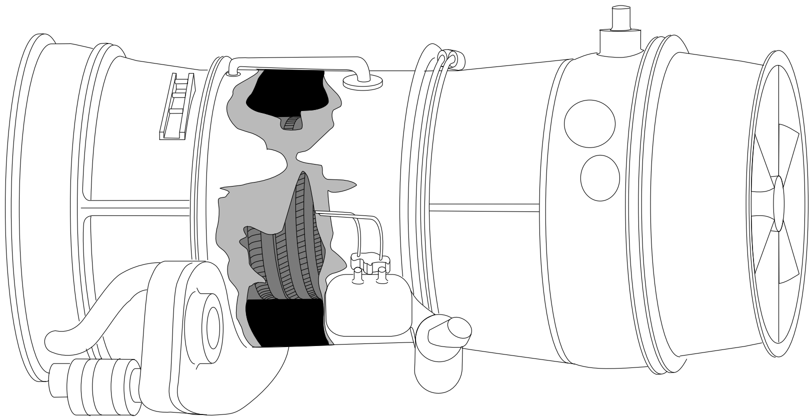
Ill. 2.2.2.5-1: *When I was a young engineer in the 1960‘s, one day I was called to a testing rig because an engine had burned down. It was hard for me to understand how an engine made from massive metal could burn down. However, I could see on the testing rig that the compressor section of the engine had all the characteristics of a fire of the metallic components. Although, as an engineer, I knew that in procedures such as thermal cutting, steels are locally burned by supplying oxygen, I was not aware that massive metal parts could burn in the air flow of a compressor.*

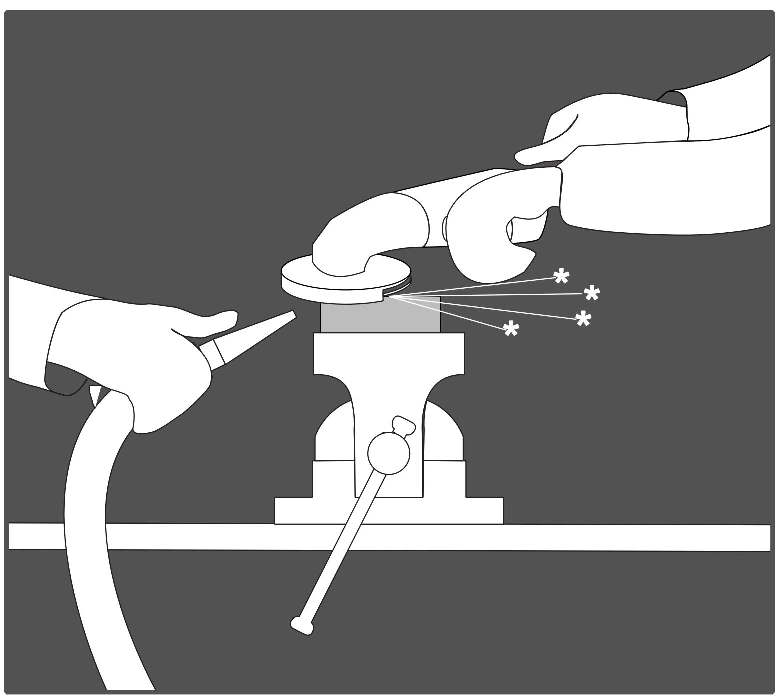
I then read in a chemistry book that ***titanium burns*** *if there is sufficient oxygen and a high enough temperature. In order to better understand the process, I conceived a simple reproduction test.*

A thin titanium sheet, roughly the size of one of the burned down compressor blade leaves, was held in a vise and attacked with a hand-held grinder. My colleague then directed a jet of air onto the highly heated ground surface. We observed the formation of white sparks. Evidently the swarf particles burned up during their flight. This effect can also be seen in thermal cutting of steels. It was possible, therefore, to heat sections of titanium to the ignition temperature through grinding or rubbing.

This realization enabled us to understand the damage process and its causes. As it later turned out, ignition had occurred due to rubbing. The

Simple demonstration tests not infrequently provide decisive insights.



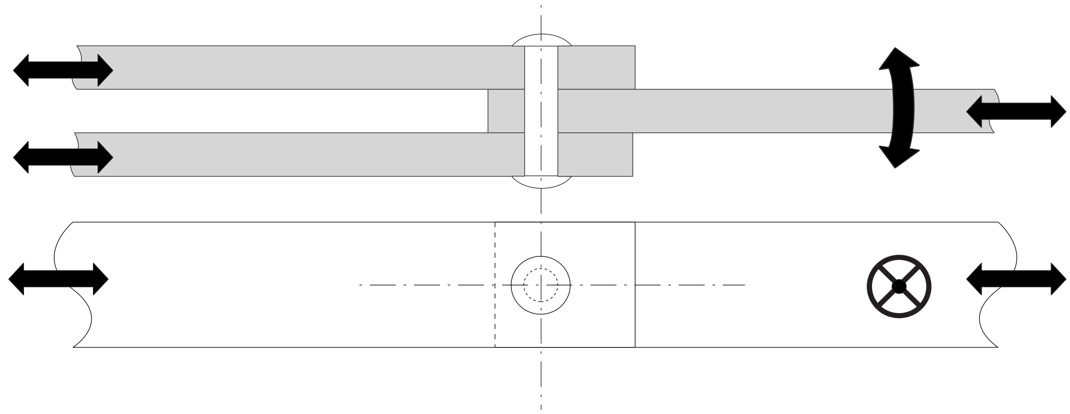


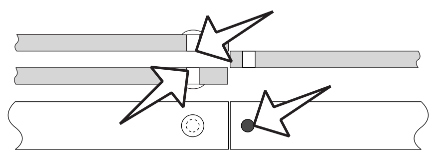
2.2.2.5-1

pressure and speed of the air flow in the undamaged compressor were evidently sufficient to sustain burning of the fire for a short time.

Reproduction of Failures and Damages.

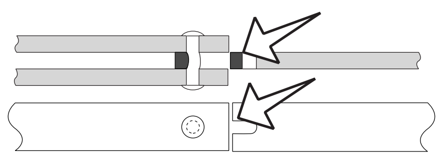
Depending on the loads, engine parts can have very different weak points.



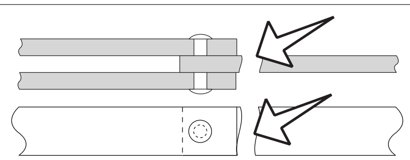


Failure due to tensile overloads

Rivet is sheared off

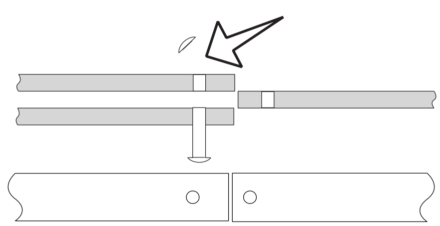


Link plate is torn out

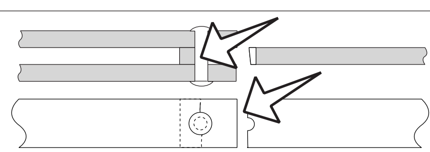


Failure due to high dynamic loads

Due to fracture at a stiffness jump



Dynamic fatigue fracture in the rivet head



Failure due to low dynamic loads and friction damage (fretting)

Ill. 2.2.2.5-2

Ill.2.2.2.5-2: *Depending on which damaging influences become active during a test,* ***the same test configuration can have completely different results.*** *It is therefore very important that* ***all relevant influences are simulated****, and that the load parameters are as close as possible to operating conditions. Tests that lead to believe that the strength is higher or the life span is longer than in practical operation are especially dangerous. On the other hand, tests that are "on the safe side" may be more expensive and take longer, but they do not endanger the functions during operation.*

If ***corrosion*** *occurs during the mechanical stressing, or there are* ***fretting*** *zones on the contact surfaces, or there is* ***creep*** *(Ill. 5.3.2-4) in the hot parts, then various results are possible, depending on the duration of the stress. If, for example, the cyclical loads in operation are low-frequency and those in the test are high-frequency to save time, then certain influences will not be able to act on the parts as they would in operation. Measures such as this can influence the measured strengths and also change the location of the failure.*

A riveted connection is intended to serve as an example. The strengths, life spans, and weak points determined by a component test are dependent on the test parameters. It is stressd by a combination of tension, compression, and cyclical bending.

- If the ***loads are continuous tensile****, one can expect the rivet to shear off or the middle lug to break out, depending on the dimensioning.*

- If it is assumed that ***high dynamic stress*** *(in the LCF range, Ill. 5.4.1.1-2) does not result in wear damage to the contact surfaces, then a fracture is likely to occur at a stiffness jump, or the rivet head is likely to break off due to a fatigue fracture.*

- At ***low dynamic (but high-frequency) loads****, below the fatigue strength of the undamaged material, one can expect* ***friction damage*** *to result in a* ***fatigue fracture*** *spreading from the rivet bore.*

Ill 4.4-3: ***Spin test rigs*** *are standard engine testing devices. In these containers, which are usually evacuated to minimize the power required, rotors or rotor components are brought up to test RPM. The tests can be conducted statically with a single acceleration (e.g. with overspeed tests) or cyclic (e.g. with LCF life span tests).*

*Experience has shown that only parameters similar to those during actual operation lead to usable results. For example, cyclical tests of titanium alloys at operating temperatures require that the RPM peaks are held (****dwell time****, Ill. 5.4-12 and Ill. 5.4-13 and volume 3) for a sufficient amount of time (several minutes) in order to simulate the relatively short life span of damage in practical operation.*

In order to obtain meaningful results, it is necessary for the test sample to be identical to the one involved in the accident, both in material and machining (and with any flaws it may have). Therefore, a test must be seen as suspect if, for example, disks are being tested that were manufactured using a different ***casting process*** *(volume 3) or a* ***different forging process*** *(volume 3) than the original parts used in operation.*

On the other hand, comparable tests with identical configurations and test parameters are useful for certifying engine parts with alterations. With engine parts such as turbine disks that have considerable ***temperature gradients*** *in the engine, the thermal strain must be considered (Ill. 5.4.2.1-2). Cyclic spin rig tests with overlayed temperature gradients similar to those during operation are the "high art" of testing. Usually, it is only possible to overlay a stationary temperature gradient onto the cyclic rotating disk. A simulation of the changing gradients during transient operation (e.g. start-up, shut-down) usually fails due to an inability to sufficiently quickly draw the heat out of the blade in the vacuum.*

Example2.2.2.5-1 (Ill. 2.2.2.5-3, Lit. 2.2.2.5-1 4.4-1): In a helicopter engine, the turbine disk of the first gas generator stage fractured during operation after about 6500 starts. Inspection showed that several run-in disks of other engines of the same type had small cracks in the radius of the front transition to the hub. An attempt was made to simulate the damage with **cyclical tests** in a spin rig (in the **LCF zone**), and then to determine the stress with the aid of computer calculations. The test was conducted at **room temperature** (!), although the part would certainly be subject to high temperature gradients during operation. The RPM peak was set at 20% above 100% operating RPM, resulting in the testing loads being 44% greater than the operating loads (without thermal stress!).

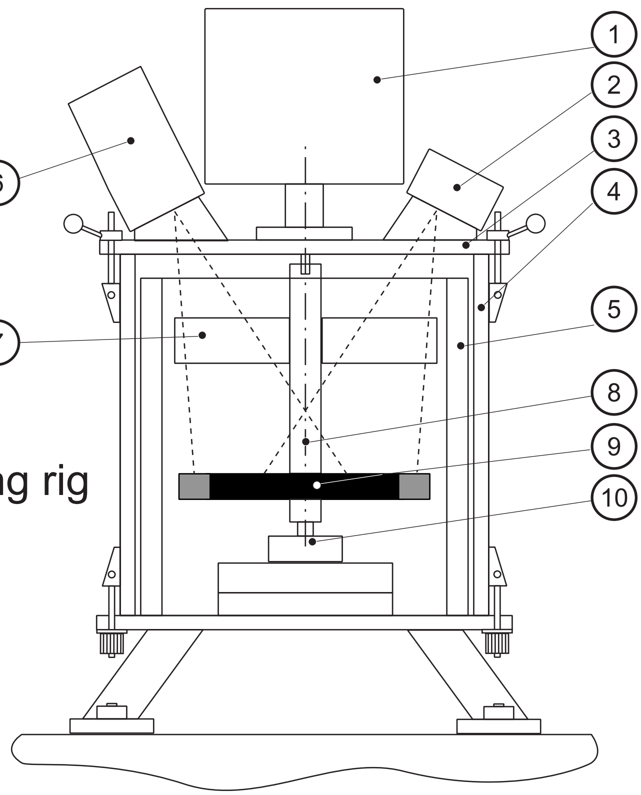
The tests were conducted on three turbines that had already experienced between 5000 and 7000 start-ups during operation. Two of the disks already showed small cracks in the transition radius. This seemed to be preliminary damage in the critical area. During the spin test, two of the three tested turbine disks showed damage behavior that was different from that during operation. In both of these cases, cracks spread from the cooling air threaded bores to the seal plate into the disk membrane. The 3-D calculation showed that these bores are highly overstressed both during the test as well as during operation. However, the operating damage occurred in the hub radius.

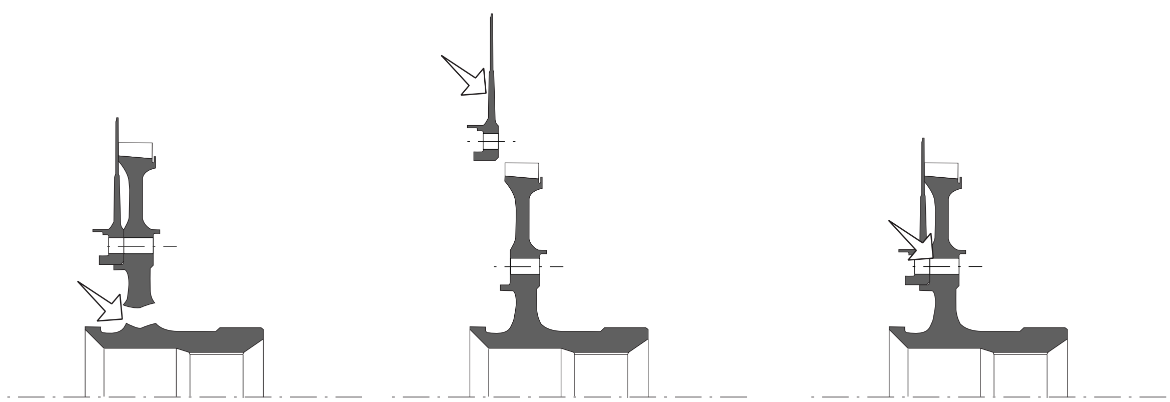
The literature includes the suspicion that the false results were due to a supporting effect from the high tension gradients around the bore. This may have been one of the deciding influences, but it can be assumed that operating data used for the calculation, as well as the test at room temperature, were too far removed from the real operating conditions and stresses.

Excerpt: "The lesson learned here is the knowledge that the evidence of a spin rig test is limited if the actual part is sensitive to the thermal gradients of the engine environment."

Reproducing an operation fracture in a spin testing rig is often extremely difficult.

Spin testing rig





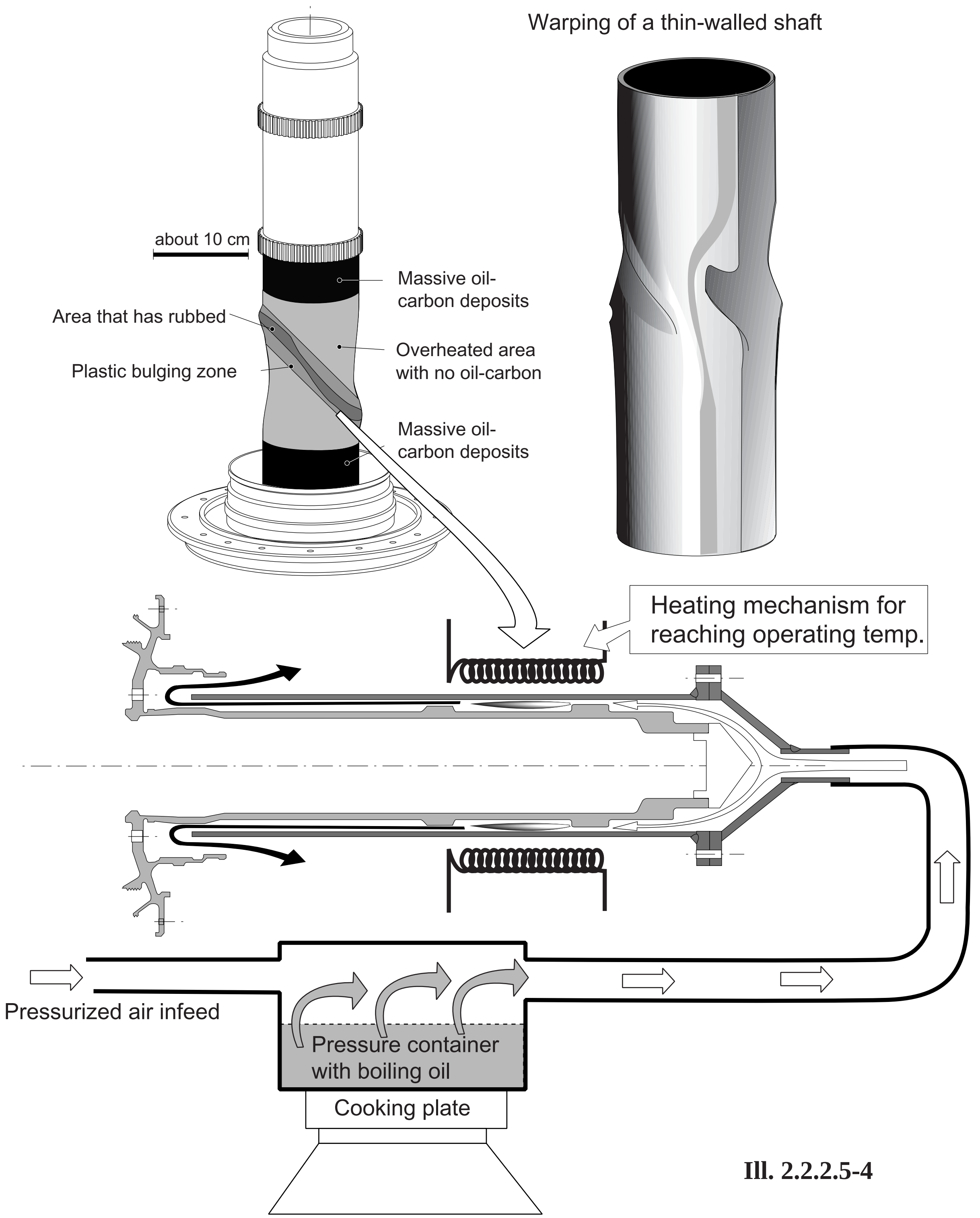
Fracture in the transition radius (operation fracture which could not be reproduced in a cyclical spin test).

Fracture of the seal plate (cyclical spin test 1).

Fracture of the bolt bore (cyclical spin test 2).

Ill. 2.2.2.5-3

Demonstration test for an oil fire between shafts



Ill. 2.2.2.5-4

Ill 2.2.2.5-4: *As a twin-jet fighter plane was conducting a test flight at high speed and low altitude, the multiple-shaft engine experienced heavy vibrations that led to the affected engine being shut-down. Disassembly of the engine showed that of the three concentric hollow shafts, one of the inner ones had reached extreme overtemperatures during operation.* ***The shaft had plastic deformations in the shape of spiralling bulges****. Heavy oil coke deposits in the shaft indicated an oil fire. The majority of the involved experts assumed that the cause of the overheating of the shaft and the deformation bulges was shaft rubbing combined with extreme flexural vibrations. As was discovered during the investigation, several liters of oil were missing, which was attributed to an oil leak resulting from the damage. The possibility of an* ***oil fire*** *(volume 2, chapter 7.1.4) was also considered, but classified as unlikely. For example, it seemed implausible for there to be a* ***fire between the shafts****, and no one could see how it would be able to stabilize itself in the area in question.*

A very experienced test engineer then constructed a testing apparatus within a few hours, and although it was simple, it convincingly demonstrated what had happened. He put the shafts in a concentric order, as in the operating engine, heated the engine oil on a hot plate (correct oil type) in a container, through which he forced hot pressurized air to recreate the conditions in the aircraft. A connecting pipe then ***fed hot air that carried the oil vapor*** *into the space between the shafts and brought them up to operating temperatures. He was able to ignite the oil/air mixture by simulating extreme operating conditions. A ring-shaped shaft* ***balancing collar*** *acted as a* ***flame holder*** *and stabilized the oil flame so that, in a fraction of a minute, the shaft was heated up to the point that it was plastically deformed by the torsion moment it was meant to transfer from the turbine to the compressor, just as had happened during operation.*

The test also revealed that under these operating conditions, a large oil fire can burn up several liters of oil in minutes.

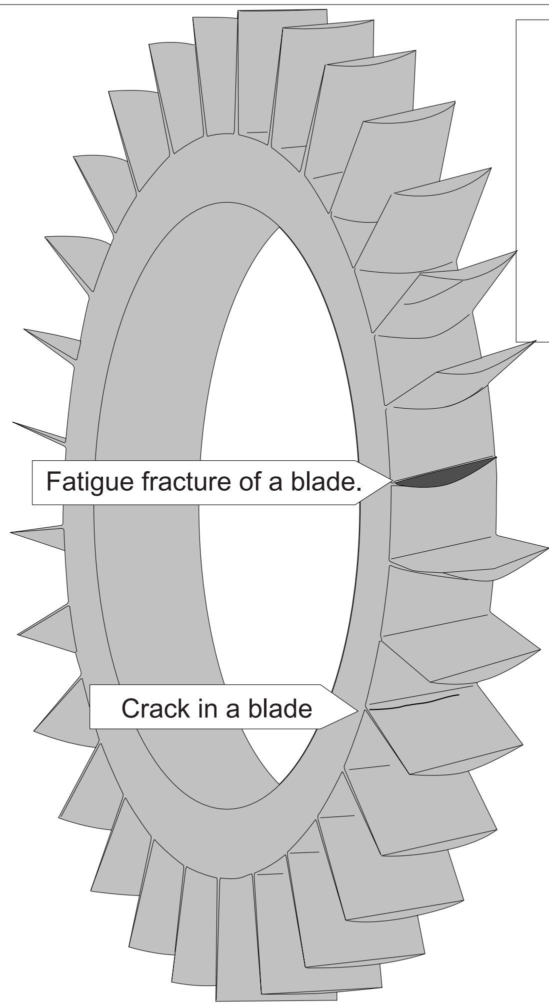
Later measurements on other test engines confirmed these observations and conclusions.

Ill 2.2.2.5-5: *The* ***afterburner pipe*** *of a fighter aircraft burned down during start-up. The thrust nozzle and the remains of the afterburner were only held on by the four control rods of the thrust nozzle adjuster. The start was successfully terminated.*

Inspection revealed that the fracture in the 1 mm thick cylindrical shell was probably a dynamic fatigue fracture that originated at flange for the control rods. Timely detection of the cracks through non-destructive inspection was almost impossible while the engine was installed, since the crack ran for a long distance along the inside of the pipe in a constructive notch. It was unclear, what role cyclical and static thermal stress played during afterburner ignition and operation. It was also not known if the fracture was due to HCF or LCF. The working hypothesis was that the forces from the connecting rods braced against the pipe and initiated a crack. The task of a part test should be to reproduce the damage and all of its macro- and micro-characteristics, in order to test the damage hypothesis and further explain the causal influences and loads.

Two test assemblies were created. One assembly was based on the working hypothesis that the stress from the connecting rod forces was the cause of the cracks. However, despite large overstress and a great deal of effort, it was not possible to reproduce a crack similar to that which occurred during operation.

The second test assembly was based on the ideas of an experienced test engineer. Relying on his "engineer's feeling", which is necessary for conceiving of successful part tests, he developed the hypothesis that the pipe cracked due to repeated flexure during curving flight and other G-forces (e.g. the impact when landing). He designed a test assembly in which the engine-



Example 2.2.2.5-2 (Lit. 4.4-4):

Excerpt: “The core (of an advanced engine gas generator), which contained a number of advanced-technology features, failed....after about 6 hr. of runs at...test facilities.

...Inspection of the ...core showed that one **blade was lost** from the second rotating stage of its five-stage, high-pressure compressor and that a second blade had become close to detaching before the tests were terminated. Investigators originally believed the failure might have been caused by ingestion of a **foreign object**, but teardown and inspection results have eliminated that suspicion.Instead, they are now focusing on “some type of **vibratory** action“ as a cause of failure.

The ...team is now **attempting to simulate the failure** ...

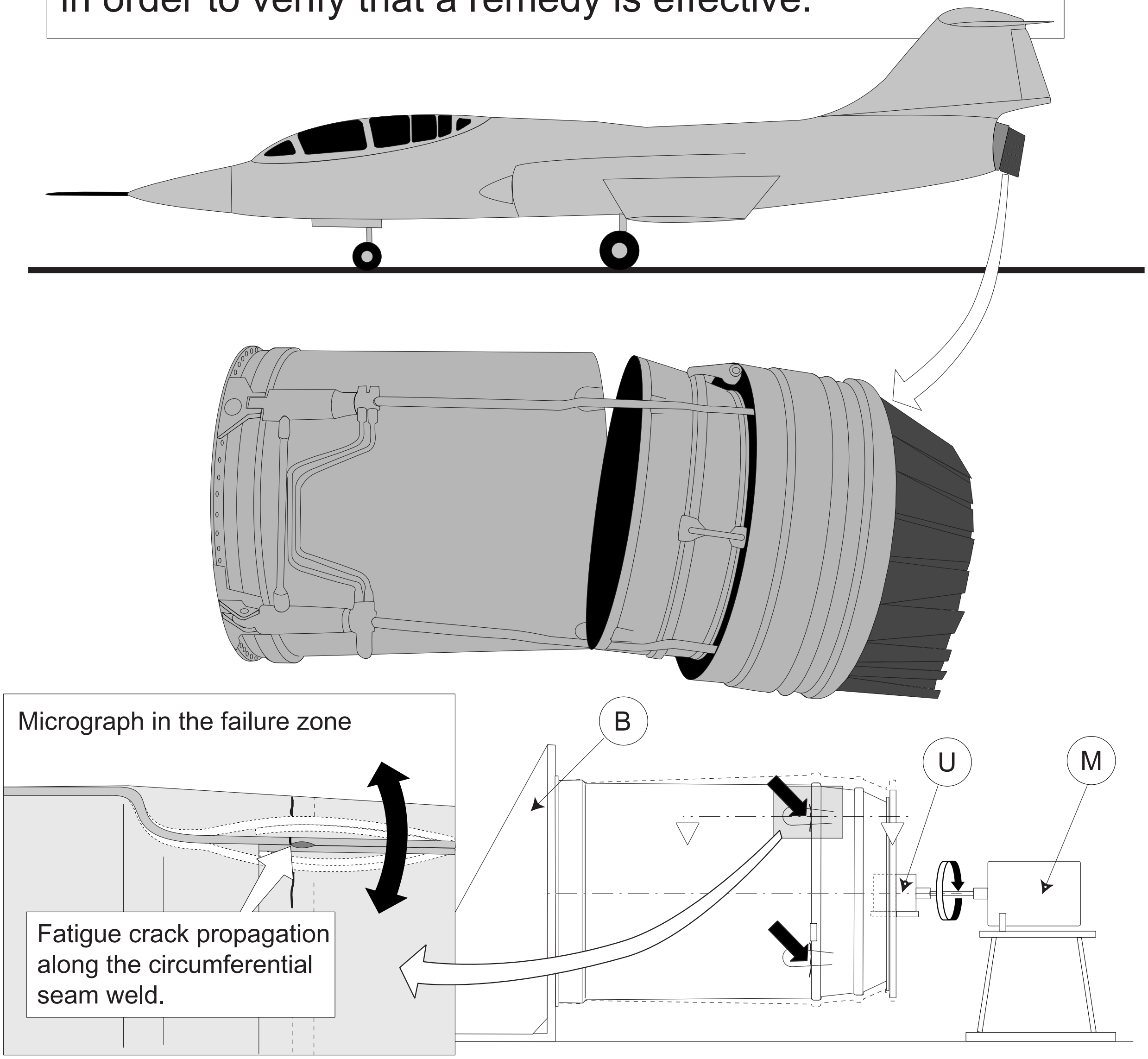
While no company likes failures, they are not uncommon with advanced turbine engine gas generator cores, and **each failure helps expand the knowledge base**, an official said...“

Comments: This example shows how important it is to **test new technologies** under **actual operating conditions**. Because obviously a so called „bling“ (bladed ring) was concerned (sketch is schematic), which lacks a damping at the blade roots, a especially susceptibility for a vibration exitation must be expected.

Testing samples under laboratory conditions may be a prerequisite for operating tests, but this does not replace tests on turbine testing rigs, and these do not replace tests conducted in engines under actual operating conditions. In case of the „bling“ an individual exitation force is crucial for the for the use in operation.

*side of the afterburner pipe was bolted to a solid frame (**B**) and the a mechanical vibration-inducing device (**U**) was affixed to the opposite side (fastening flange to the engine) concentrically in the flange plane. The frequency of the vibrations could be adjusted by adjusting the RPM of the electric motor (**M**).*
*Observation with a **stroboscope** immediately revealed **extreme bending loads due to its stiffness and unique shape** in the area where the cracks occurred. This explained the cause for the*

Confirming a damage hypothesis in an engine part test is the high art of damage investigation, and is necessary in order to verify that a remedy is effective.



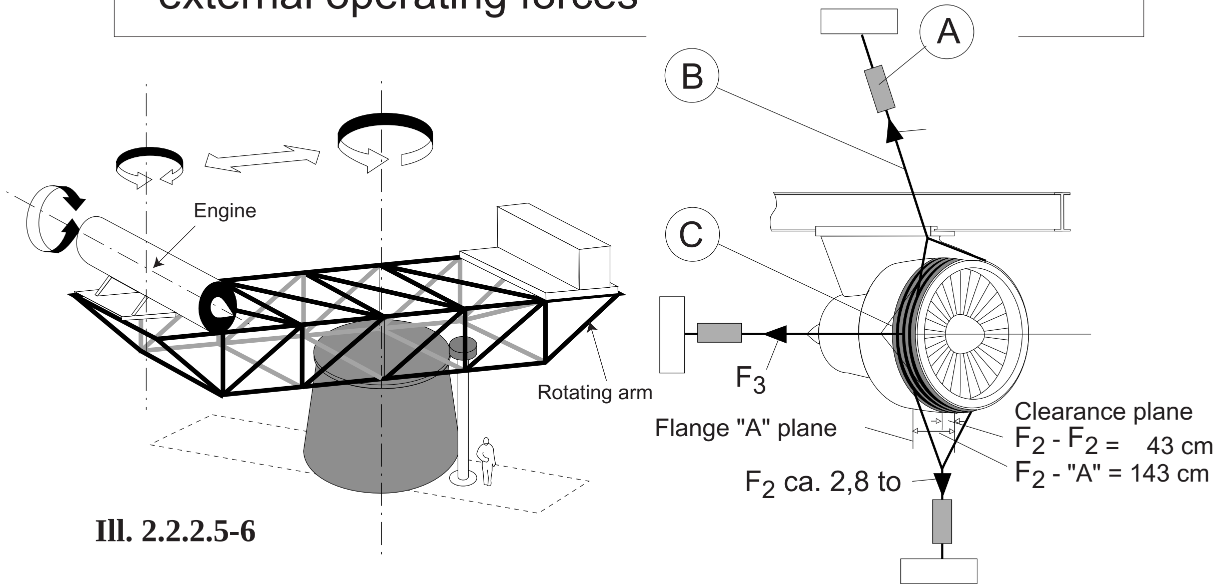
Ill. 2.2.2.5-5

crack initiation.

This test made it possible to come to conclusions regarding the spreading of the cracks and the influence of constructive and manufacture-technical characteristics.

It also presented the possibility of a suitable crack testing procedure on installed engines, as well as rapid development of corrective measures. It provided the basis for certification tests for the necessary corrective measures and repairs.

Testing rigs and loading assemblies for simulating external operating forces



Ill. 2.2.2.5-6

Ill. 2.2.2.5-6: *The top diagram (Lit. 4.4-2) depicts a* ***testing rig*** *concept that makes tests of engine behavior under high G-forces possible. It can be used to inspect elastic housing, rotor deformations and the resulting clearance changes at the blade tips and labyrinth seals.*

This example is intended to show the technical effort required for the investigation of important engine behaviors. Naturally, this type of testing rig requires a long development and testing period. This much effort and time will rarely be invested into isolated damage cases. Therefore, the testing rig must already be available if it is needed to reproduce a certain type of damage. Experts should at least be aware of where they can find an already-built testing rig suitable for their problem.

The bottom diagram (Ref. 4.4-2) shows a device that can ***simulate operating loads*** *on the nacelle of a large fan engine. This example illustrates how a relatively simple device can be used to determine the effects of complex operating loads. "****A****" is a hydraulic load cylinder, which creates the simulated operating loads (e.g. aerodynamic loads on the nacelle, or landing shock) that are transferred by the wires "****B****" onto the fan housing "****C****". This assembly is used to determine the elastic deformations of the engine and its components so that they can be compared with calculations and used to design improvements. Exact knowledge of the size and direction of the loads is necessary for this.*

4.4.1 Recommendations for Reproducing Damages

Due to the complexity of many operating factors (e.g. corrosion, wear, erosion), the reproduction of damages is a “high art“ and requires above-average “**engineer‘s feeling**“ and experience. It is an important test of truth and absolutely necessary for verifying the success of corrective measures.

• If at all possible, only assign this task to someone who has already conducted successful reproductions in other cases.

• Understand that it is extremely rare for a reproduction to be satisfactorily successful on the first try! Iterative, long-duration procedures are the rule.

• A **successful reconstruction** results in damage that is identical to the original in all relevant macroscopic and microscopic aspects. Deviations from the original indicate that the reproduction is not sufficient (yet).

• Ensure that the influences and parameters of the reproduction test assembly are as close to operating conditions as possible! Remember that, for example, abbreviated tests, higher loads, or greater test frequencies (especially with hot parts) can lead to different damage mechanisms that, despite some similarities (e.g. location of the fracture) are not a usable reproduction (Ill. 4.4-2). This is especially true when determining the extent of the damage, i.e. the remaining life span.