TITANIUM FIRE IN JET ENGINES

T Uihlein, H Schlegel
Daimler-Benz Aerospace
MTU Motoren- und Turbinen-Union München GmbH
Dachauer Str. 665
80995 Munich
Germany

ABSTRACT

In aero-engines, titanium fire occurs in the fan and compressor where titanium is indispensable because of its high strength-to-weight ratio. Titanium alloys are mainly used for blading, casings and disks. Consequently, if bearing- or blade-failure occurs, the possibility of an uncontained titanium fire cannot be excluded.

A titanium fire is a very short event of about 4 to 20 seconds duration depending on the engine design and the operating conditions. It is a violent conflagration accompanied by temperatures as high as 3,300°C. This energy destroys surrounding materials, including steel and nickel alloys, by burning and melting. When this happens, the airframe structure can be severely damaged, even resulting in the loss of the aircraft. Extinguishing the fire is impossible because of its rapid propagation and the very short time between its detection after uncontainment and its termination. Common fire-extinguishing agents are not suitable for quenching a titanium fire because their composition is inadequate and sufficient quantity is not available. But these agents can prevent propagation of the fire in the engine bay.

The risk involved can be avoided by such measures as intelligent design, fire-preventive coatings, and use of titanium alloys that are not easily combustible. The development of preventive measures calls for rig tests in order to simulate burning conditions, and to verify the efficacy of the measures. Titanium can then be used safely in advanced-technology engines for modern aircraft.

1. INTRODUCTION: What is a titanium fire?

In a burning match one can see that a fire (here represented by the flame) generally is a process in which combustion takes place accompanied by the emission of light, heat, and usually also flames and smoke, as a result of reaction with oxygen; or as the chemist would put it, as a result of exothermic oxidation of a combustible medium (fuel).

That metals can also burn can be illustrated by two examples, namely a flash-bulb and a cutting torch:

- In the former, a fine magnesium or aluminium wire inside a gas-filled bulb is ignited via a filament and (as with the match) an oxidant. Combustion is supported by the oxygen atmosphere.
- In the latter example, when cutting steel plate, the surface of the workpiece is first heated by the oxy-acetylene flame, then the metal burns or melts away when the supply of acetylene is stopped and the flame is sustained by pure oxygen.

The combustion of a metal is not a diffusion reaction with oxygen at the surface of the metal, but is a heterogeneous reaction. In other words, solid, liquid, and gaseous phases are present, which hinders the process, meaning that metal and an oxidant must be transported to the site of combustion, for example by solid and liquid phases of both the metal and its oxides. Combustion occurs as a rapid, partially explosive process, and is influenced by the properties (eg thermal conductivity, ignition point, etc) of the metal, the size and shape of the object concerned (thin wire, sheet, or compact component), and the ambient conditions. Generally, the presence of oxygen, a bare metal surface, and the supply of heat, for example as a result of friction, are required for the ignition of a metal. The metals and their alloys which are among the most susceptible to ignition are titanium, zirconium, uranium, lead, tin, and magnesium.

We speak of a titanium fire in an aero-engine, which is the subject of this paper, when the "fuel" is a titanium alloy. The relative ignition temperature (eg 1,600°C in a standard atmosphere) is usually exceeded as a result of friction between the rotor and stator of the compressor. The high oxygen engine, where there must be a certain correlation between the pressure, temperature, and flow velocity of the air. The fire will be sustained only for as long as the requisite amount of oxygen or "fuel" is present.

The consequences of a titanium fire which burns out of control, when temperatures in excess of 3,300°C [1] occur, can be severe blading damage, and burnthrough of inner casings in titanium and even nickel alloys. In extreme cases, burn-through of the outer engine casing can result, and this is defined as an "uncontained titanium fire". If vital airframe structures and installations are affected, this can lead to the loss of the aircraft. Examples and the consequences of an uncontained titanium fire are shown in **figures 1 and 2**.

2. TITANIUM FIRE IN AERO-ENGINES

In 1954 when a titanium alloy was used for the first time in a jet engine (J77) [2], presumably nobody considered the possibility of titanium fire. But now that we are aware of the danger, why is the use of this material in aero-engines becoming more and more widespread? The answer lies in titanium's high strength-to-weight ratio.

2.1 CHARACTERISTICS OF TITANIUM

2.1.1 Mechanical properties

Titanium is a material that exhibits specific strength properties that are superior to those of steel or nickel alloys up to a temperature of 450°C. When protected with a thin oxide skin, it has better oxidation and corrosion properties than steel. However, the temperature resistance of most titanium alloys is poorer than that of steel and of the nickel alloys used in the hot section of engines, despite the fact that they have a melting point that is some 100 and 200 K higher respectively.

The outstanding advantage of titanium is its density of 4.5 g/cm^3, making it some 40 per cent lighter than steel (with a density of 7.8 g/cm^3) and about 50 per cent lighter than nickel (with a density of 8.9 g/cm^3). One result of this is that the use of titanium makes better thrust-to-weight ratios possible than could be achieved with other materials.

With regard to wear and notch sensitivity titanium is characterized by some disadvantages, but as far as the subject of this paper is concerned, they are of significance only in so far as primary blade damage could occur as a result.

engines

Titanium alloys, such as Ti-6Al-4V, Ti-2Cu, Ti-6Al-2Sn-4Zr-2Mo, and Ti-6Al-4Sn-3Zr-1Nb-0.5Mo (IMI834), are used in modern aero-engines for fan and compressor (blading, rotor disks, casings), gearboxes, and the low-pressure turbine. Because of the restrictions concerning their creep strength and notch sensitivity, they are suitable for use only for peak temperatures of up to a maximum of between approximately 350 and 600°C.

The suitability of titanium for higher service temperatures also depends on its fire resistance, and severe restraints are placed on this aspect in view of the increasing economic demands for better thrust-to-weight ratios. These demands can be met only through
- lighter components with thin, reinforced walls,
- higher pressure ratios,
- higher component temperatures, and
- higher flow velocities.

2.1.3 Properties of titanium that can promote titanium fire

Properties of titanium and its alloys that can promote fire are
- the metal's ignitability, and
- its exothermic, partially explosive reaction with oxygen.

In addition, there is the
- risk of the fire spreading to downstream components in titanium as a result of the spin-off of molten, energy-rich droplets from rotating components.

These disadvantages are associated with the thermodynamic properties of titanium and its alloys (compared with Ni and Fe) [1, 3]:

- Low thermal conductivity (TC [W/mK]):
  $TC_{Ti} \sim 0.2\ TC_{Ni} \sim 0.3\ TC_{Fe}$

- High combustion energy (Q [J/mol]):
  $Q_{Ti} \sim 4.9\ Q_{Ni} \sim 2.3\ Q_{Fe}$

- High combustion temperature:
  $T_{Ti} \sim 3{,}300°C$

- Rapid reduction in ignition temperature with increase in oxygen pressure

- Ignition temperature (* in pure oxigen) [~°C]
  Ti: 1,330*/1,600 Ni: 1,330 Fe: 1,130/1,400
  < Melting temperature [~ °C]:
  Ti: 1,670 Ni: 1,450 Fe: 1,540

Ti: yes Ni: no Fe: no

- Protective (dense) oxide layer
  Ti: up to 450°C Ni: yes Fe: no

- Titanium burns at the surface (evaporation temperature: oxide < metal).

2.1.4 Causes of ignition

Ignition of titanium can be caused by heat generated by axial or radial contact between rotating and stationary components. Typical conditions are:

- When an object such as
  - a blade fragment (primary damage), or
  - a flat foreign body in steel or nickel alloy

  becomes entrapped at the blade tip, resulting in rotational friction against the casing, which then provides a bare, oxide-free surface necessary for ignition (metal-to-metal contact).

- At casings or seals in case of:
  - bearing failure,
  - rotor unbalance, or
  - (rarely) high g-loading under certain flight manoeuvres.

- When rubbing between seals occurs (rarely) as a result of
  - chipped linings,
  - thermal expansion of labyrinths,
  - fatigue cracking of stationary member, or
  - when radial expansion of the stationary member is hindered.

Other rare causes can be
- high-velocity impingement of a sharp-edged object against a titanium surface (own/foreign object damage),
- aerodynamic heating as a consequence of stall,
- thermal radiation by a hot body or gas.

2.1.5 Conditions which are conducive to titanium fire

Such conditions in the engine are:

- Partial pressure of the oxygen
  - provides a sufficient amount of oxidant,
  - determines its absorption rate, and, therefore,
  - governs the reaction at the metal surface.

- Velocity of the airflow through the engine determines
  - the rate at which molten metal is dispersed, and thus
    - the transfer of heat, and
    - the combustion (rate and duration)

    thus
    - the surface area available for the reaction with oxygen,
    - the amount of heat generated, and
    - the extent of the molten region.

- Pressure and velocity of the airflow are responsible for
  - blowing away the slag at the fire-front, ie giving access to oxygen to support combustion of the oxide-free surface of the titanium material (ie "fuel").

- Ratio of the component surface to its volume determines
  - the ignition time (and temperature),
  - the burning time, and
  - the extent of burning.

- Centrifugal forces, viscosity of the molten metal, and surface tension determine
  - the rate (and duration) of burning, depending on the adhesion of the molten metal.

- Ambient temperature determines
  - the difference between the temperature of the molten region and that of the adjacent metal, and thus
    - the temperature gradient, and
    - the rate of dispersion of the molten metal.

- Additional supply of energy (primary damage) causes
  - rapid ignition.

2.1.6 Conditions which hinder ignition or extinguish titanium fire

Conditions in the engine that hinder ignition or result in fire being extinguished are:

- Source of ignition is removed in time
  - when the radial or axial gap is widened in good time when rubbing occurs, ie before the ignition point of an adjacent or downstream titanium component is reached.

- The oxygen pressure, temperature, and flow velocity are not/are no longer critical
  - titanium fire does not occur if the relative ignition temperature is not reached as a result of
    - the operating conditions under part load, and
    - thicker wall cross-sections (heat is dissipated).

- The fire will die out locally or completely when
  - there is no longer sufficient oxygen available

- under deceleration or
- because the slag is not fully blown away,
- the fire front reaches a colder surface, or
- a thicker titanium cross-section,
- the heat is dissipated by a (massive and) conductive component, or
- the fire front reaches a non-combustible (or not easily combustible) obstacle (eg vane platform in a nickel alloy).

- There is no longer any titanium left:
  - The fire will then go out. But this happens only with smaller or thinner titanium blade fragments and provided that the fire has not spread to other areas.

2.1.7 Limits concerning ignition and sustainment of a titanium fire

The following limits are cited in the literature [1]:

- CAA criterion — Engine maker's approx. values

CAA criterion	Engine maker's approx. values	
p > 2 bar	p = 1 bar	p = 3 bar
v > 50 m/s	v ~ 120 m/s	v ~ 45 m/s

- Heating rate <--> ignition temperature:

40 K/s	<-->	<1600°C
100 K/s	<-->	300 to 400°C

- Volume-related surface (A/V [cm^2/cm^3]) with massive components:
  Bulk behaviour < 25.6 cm^{-1} --> ignition temperature ~1,330°C at 1 bar in oxygen atmosphere

- v > 183 m/s --> immediate ignition
  v > 275 m/s --> fire is extinguished as result of dissipation of the molten metal accompanied by cooling

- Ignition (without airflow) at
  $T_{ambient}$ and 25 bar, or
  500 °C and 7 bar.

2.2 STAGES AND EFFECTS OF TITANIUM FIRE IN (MILITARY) ENGINES

2.2.1 Preliminary stage

The preliminary stage of a titanium fire can be seen at the tips of titanium rotor blades if they rub against the inside of the casing. The material abraded from the blade tips and casing wall builds up on the blade tip, forming a wedge-shaped deposit with only very slight, local melting (**figure 3**). The first sign of a fire occurs with greater loss of material from the blade tips accompanied by the formation of a black crust at the pressure side of the blade adjacent guide vanes. These crusts can be removed only by grinding.

Loss of material and the formation of a crust also occur at the point of impact (**figure 5**) as the result of high-energy collision against a titanium component by a fragment of a blade or a foreign body, for example in a nickel or iron material.

2.2.2 Titanium fire in compressors

A local fire occurs when a fragment of a titanium blade impinges against a thin-walled section of a titanium casing. Certainly, the energy of impact is such that the fragment will normally be burnt up (**figure 6**), but burn-through of the casing wall is also possible (**figure 7**). A crust forms around the site of the fire, and temper-colouring occurs at the outside of the casing.

Rotor blades in titanium usually burn only at the tips and thin edges (**figure 8**), since the fire dies out quickly as a result of centrifugal force with burning material being spun off and the thermal energy thus being dissipated.

Localized or widespread burn-through of a titanium casing and thus a larger fire in the compressor and other components (**figure 9a**) are possible if high frictional heat occurs at the casing wall. As pointed out earlier, a flat nickel or iron object, for example, can become lodged at a blade tip in any material, and thus rotate with the blade and so cause the casing to ignite.

In addition to the burn marks, thin engine components in titanium damaged by fire exhibit typical changes, such as

- temper colouring (similar to Newton rings, **figure 10**), occurring after "low" heat-absorption on walls with lateral transition to thicker cross section,
- flat micro material displacement (**figure 11**),
- oxidation of the surface (light-grey deposit, **figure 11, 12**), occurring shortly before burn-through,
- localized intercrystalline cracking in casing rings (**figure 12**).

Naturally, the molten products (**figure 9b**) can also penetrate walls in materials other than titanium, giving rise to either local overheating or in extreme cases even burn-through, depending on the thickness of the wall and properties of the material. Although the recast layer often flakes off when the engine has cooled, the overheating damage remains.

A titanium fire of such proportions that the outer casing of the engine is penetrated is defined as uncontained. At high rotational speed, this will take a mere 10 to 15 seconds, depending on the casing material, the wall thickness, and the number of "shells". The axial and radial extent of such an uncontained titanium fire as a consequence of bearing failure is illustrated schematically in **figure 13**.

2.2.4 Secondary Effects of fire on other components

Extensive compressor-blade damage can have serious aerodynamic consequences. Lock-in surge occurs, and the control unit tries to compensate for loss of spool speed by the addition of fuel. Up to the maximum flow of fuel is injected, and the igniter plugs are reactivated. The engine tries to increase speed until it succeeds or until the fuel supply is shut off manually by the pilot again. The burning of this additional fuel increases the turbine entry temperature, contributing to premature damage to the turbine blading (**figure 14**). Furthermore, the compressor air for cooling the turbine is heated by the fire and contains combustion products, meaning that cooling is lost as the spool speed (and air velocity) decreases.

The consequences are more and more extensive burning and breakage of the turbine rotor blades, made worse as a result of centrifugal force. Extensive burning of the stator can occur, finally leading to serious weakening of the engine structure (mounts, bearing systems, etc).

If the titanium fire results in fuel lines being burnt through (**figure 9a**), a fuel-fire can occur in the bypass, but normally without serious consequences unless the ignition or melting point of the surrounding walls is reached.

The main danger of an uncontained fire is the loss of major pipelines, electrical cables, actuating levers and motors, engine-bay installations, and even airframe damage. As remote worst-case consequence, this can lead to loss of the aircraft (**figure 2**).

2.2.5 Recognition of a fire, corrective action

Because of lack of suitable instrumentation and the speed of events, the possibilities for the pilot to recognize a titanium fire and take appropriate action in flight are severely restricted. Usually, the resulting mechanical damage will trigger a vibration warning. Blade destruction (as a result of primary damage) and the fire cause lock-in surge, and an increase in exhaust temperature will be indicated, even at sub-idle, at low flying speeds at high altitudes, and with control-unit malfunctions. The pilot will only receive an engine-bay fire warning after the damage has become extreme, ie after the outer casing has been burnt through.

If he suspects a titanium fire, that is to say in cases of doubt about the cause whenever lock-in surge occurs, the pilot should shut the engine down immediately by closing all fuel valves, and so prevent the automatic adjustment of the fuel supply in an attempt to stabilize the engine speed.

The engine is not provided with fire-fighting systems. Moreover in view of the short duration of a fire (15 to 20 seconds max), extinguishing the fire would be pointless as far as the engine is concerned, since a limited once-only action by the airframe extinguisher system can be taken to prevent the fire from spreading any further only after it has reached the engine bay. The fuel supply to the engine concerned must be shut off beforehand.

It is possible that there is no compatible extinguishant for combating titanium fire. The agent Halon 1211, currently provided in the engine bay, is a CF_2ClBr solution which is effective but toxic and corrosive, since at a temperature of 450°C and above it becomes instable, decomposing into HBr-HF-HCl, and at higher temperatures even these molecules will dissociate. CO_2 is similarly unsuitable and would even support the burning of titanium, since oxygen has a greater affinity for titanium than for carbon. A conceivable alternative agent would be air containing 60 per cent argon or helium. But a high volume of noble gas would be required.

2.2.6 Disposal of damaged components (inspection, assessment)

Engine components with visible damage are generally unserviceable and are to be scrapped. With a titanium fire that has been confined to a limited area, components that have been affected by molten droplets or hot air must be inspected for surface damage. Rotor disks will normally be serviceable, but if the air used for cooling has been heated by the fire, the disks will have to be thoroughly examined.

3. PREVENTION OF (UNCONTAINED) TITANIUM FIRE

3.1 DESIGN MEASURES

In order to minimize the risk of titanium fire it is necessary to preclude the possibility of primary

- avoiding direct frictional contact between rotor and stator components in titanium (by providing an anti-wear spray or ceramic coating, and the use of steel or nickel alloy for the stationary components);

- avoiding thin casing walls (ie of weakened cross sections) in areas in which rubbing by rotor-blade tips occurs;

- avoiding very thin leading edges on rotor blades and guide vanes (notch sensitivity of titanium alloys is a cause of primary failure);

- making sure of adequate bearing safety or carrying out chip-detector inspection to avoid bearing failure with subsequent rubbing between titanium components;

- making sure of adequate casing rigidity in order to restrict thrust- or pressure-related axial movement;

- maintaining clearances to avoid thermally- or operating condition-related (hot reslam, surge, etc) relative movements between the rotor and stator, which can be a cause of rubbing;

- making sure that the axial clearance between rotor and stator is narrowest at the point where the maximum component temperature is lowest;

- providing axial contact surfaces in a material with good insulation properties and high temperature resistance to allow safe rotor braking in the event of bearing failure;

- considering the use of vanes fitted with inner shrouds rather than cantilevered design;

- considering the use of brush seals instead of labyrinth seals.

3.2 AVOIDENCE OF CAUSATIVE DAMAGE

The best protection against titanium fire is to try to avoid damage that could result in titanium fire, and to achieve this a statistical study of the damage and its causes, based on different types of engine if appropriate, is recommended. If the damage recurs, corrective action, including the above design measures, must be taken as soon as possible. At the very latest, action must be taken immediately following a case of titanium fire. The pilot can play his part by making sure he observes the engine manufacturer's recommendations, and if possible by recording essential data when a fire occurs.

In a jet engine, primary damage accompanied by secondary damage in the form of serious rubbing or the impingement of a metallic body cannot be totally excluded. Consequently, to avoid uncontained titanium fire as far as possible, endangered titanium components must be provided with protective coatings that will at least prevent burn-through in the most active, initial phase of the fire (at full-load operation).

Alternatively, new engines can be fitted with suitable new titanium alloys, or old ones can be correspondingly modified. For hotter areas, the use of materials with high aluminium content, which will reduce the risk of fire, is recommended. Alloys with a higher chromium or vanadium content (such as alloy type "C" [4]) are suitable for lower-temperature areas. However, these materials are still under development.

3.3.1 Coating properties

Coatings for protection against uncontained titanium fire need to have the following main characteristics:

- capability to prevent direct frictional contact between titanium rotors and stators to ensure ignition cannot easily occur;

- capability to give protection at least during the most active, initial phase (maximum aero-dynamic conditions) of the fire;

- good mechanical properties, such as durability, and stability under normal maximum conditions (where the latter also calls for adequate stability of the parent casing).

In addition, a number of secondary properties are required, that is to say
- high resistance to oxidation,
- high resistance to temperature changes,
- high resistance to corrosion (incl under mechanical loads),
- high resistance to erosion (when applied in the main air-flow passage), and
- good adhesion.

3.3.2 Theoretical considerations in selecting a coating

Mechanisms involved in the function of coatings

Advantage can be taken of a number of physical and chemical material properties for protecting against titanium fire. For example, there are ablatresult of their low transformation points. The resulting thermal energy can be dissipated via the airflow through the engine, meaning that the heat is largely kept away from titanium walls. Then there are coatings with very high melting points and low thermal conductivity, where despite residence time on their surface, molten titanium will not do any major harm (**figure 15**).

Other parameters are viscosity of the molten metal, surface tension, and wettability of the surface. By careful coating design, the wetting by the molten metal and the residence time on the surface can be minimized.

The inclusion of other alloy elements which reduce the solubility of oxides in molten titanium and promote the formation of an oxide skin on the surface also helps reduce the risk of fire.

As an additional measure, elements with maximum activation energy for oxidation can be included in the coating (eg Ni, Cu).

Analytical and empirical models

These models [1] are used for comparing the energy released by chemical reaction with that lost by
- thermal conductivity,
- convection,
- radiation, and
- molten metal carried away in the airflow.

The most common variables used are
- aerodynamic temperature, pressure, and velocity at the site of the fire,
- Reynolds number at cross sections of titanium components downstream of the airflow,
- physical values,
- diffusion of oxygen, and
- geometrical values.

However, because of uncertainties about energy from external sources, these models are not very reliable, and can thus be used only to a limited extent for making predictions.

4. RIG TESTS

Rig tests are one method for verifying the effectiveness of protective coatings or new titanium alloys before these coatings or alloys are used in the engine, where it must be possible to

- simulate the effects of a titanium fire in the engine, and

- check the suitability and effectiveness of coatings in the engine, and to determine the minimum coating thickness required.

4.1 LAYOUT OF TEST RIG

The main components of the rig (**figure 16**) are

- test chamber (thick-walled steel tube with good thermal-transport characteristics),

- compressed-air connection (supply from cylinders or plant system),

- air preheater (electrically-heated high-capacity system as heat exchanger),

- adjustable specimen carrier to allow simulation of various impingement angles of the hot flash (including thermocouple for monitoring the temperature of the specimen),

- titanium strip of defined mass, which is ignited in order to simulate the effects and duration of the fire,

- igniter (electrical or other, eg laser),

- exhaust diffuser with adjustable outlet,

- instrumentation for measurement of temperature, pressure, and airflow velocity,

- TV camera to allow the processes inside the test chamber to be observed and recorded (size of the molten droplets in the airflow, reactions taking place at the specimen surface, interaction with the airflow, and duration of the fire).

Note:
- The distance between the specimen and the burning titanium strip, the combustible mass of the strip, and the impingement area depend on the conditions in the engine, as do the
- air pressure, velocity of the airflow at the end of the acceleration path, and the temperature of the preheated coating carrier before ignition of the titanium strip.

4.2 RIG-TEST CAPABILITIES

Difficulties in the testing of protective coatings:

- Reproducibility of the tests is an absolute must, ie all test parameters must be precisely adhered to, and unwanted reactions (eg with rig components) must be avoided.

- A statistical record is required in order to verify coating under nominally identical conditions is recommended.

- The data concerning the combustibility of metals are relative and not absolute, because they depend on the test conditions and the nature of the test. Hence comparability of the results with those according to the literature is usually not possible.

It should be noted that no matter how carefully the rig test is planned and carried out, it can only be a substitute for running in the engine itself. The correctness of the concept and the mechanical stability of a coating can be verified only under normal operating conditions over the course of time in the engine. Only service experience will reveal any difficulties arising from the implementation of the measure tested or highlight any previously disregarded or unforeseeable variables (eg, durability of the coating under multiple loads, natural stresses in the casing, changes of aerodynamic or thermodynamic, different damage characteristics of the coating) that might change the engine behaviour.

5. CONCLUSION

In spite of the problems and the possible extreme consequences of a titanium fire, mentioned above, no-one should be deterred from ever boarding an aircraft again. Because of the relative simplicity of the flight, the rate of damage in commercial aviation is appreciably less than that with military aircraft, where the flight is characterized by constant load changes affecting numerous components. The crash rate because of titanium fire is very low, since only a fraction of the total potential primary damage results in titanium fire, and not every fire will be uncontained. Moreover, not every uncontained fire will end in the loss of the aircraft. This is attributable to the fact that all engine makers have long been aware of the danger, and are constantly introducing both design and computational improvements in order to combat the problem.

6. ACKNOWLEDGEMENT

The authors wish to thank MTU München for permission to publish this paper, and to express their gratitude to their colleagues for their assistance and cooperation.

7. REFERENCES

[1] T R Strobridge, J C Moulder, A F Clark:
Report Nos FAA-RD-79-51, NBSIR 79-1616,

[2] E S Huron, J A Miller:
2nd Int. SAMPE Metals Conference, Dayton, Ohio, 1988, 271 - 285

[3] A F Clark, J G Hust:
AIAA Journal, 12 (1974), 441 - 454

[4] G Kneisel:
Advanced Materials & Processes 144 (1993), 7.

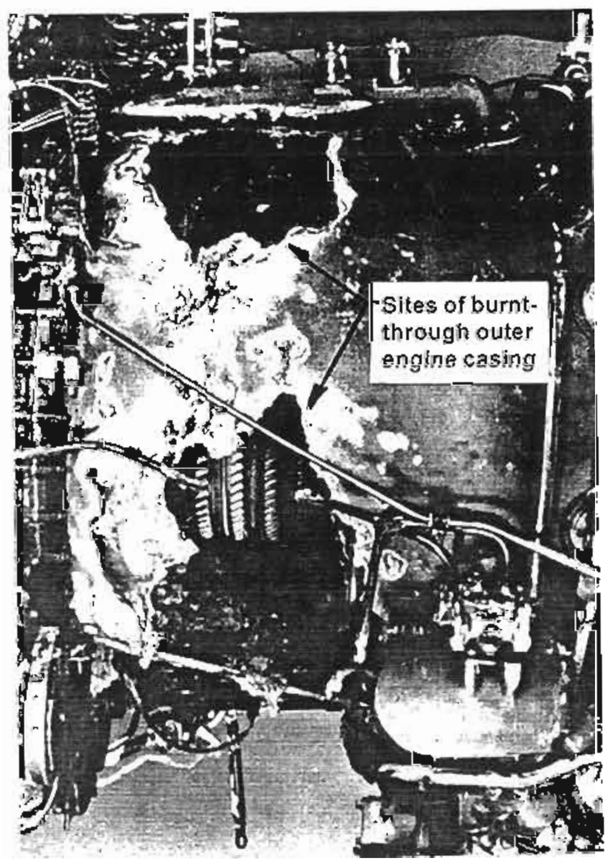


Fig. 1:

Uncontained titanium fire; the outer casing of the engine has been penetrated

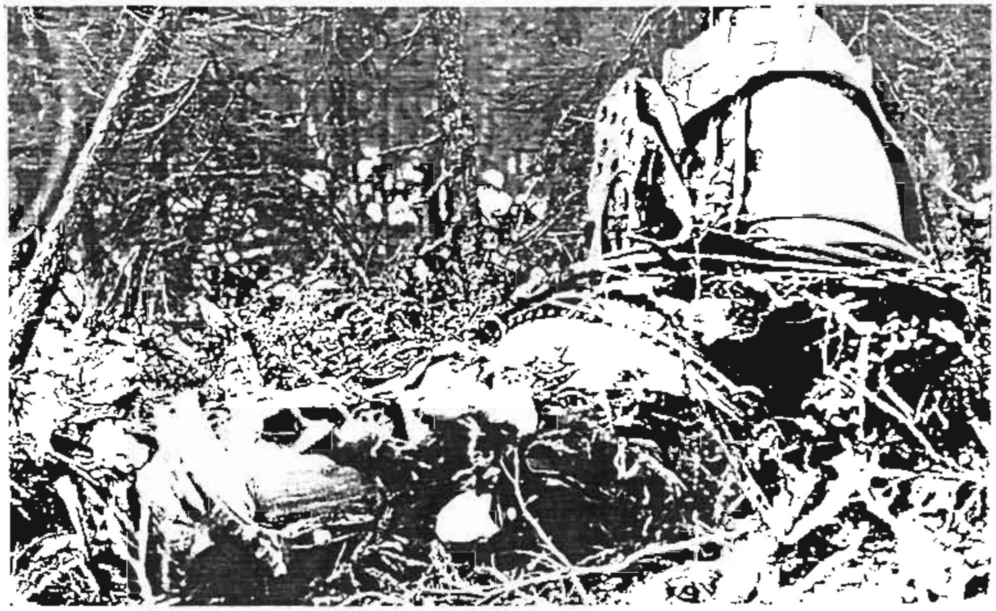


Fig. 2:

Engine after aircraft crash (with uncontained titanium fire having contributed to the crash)

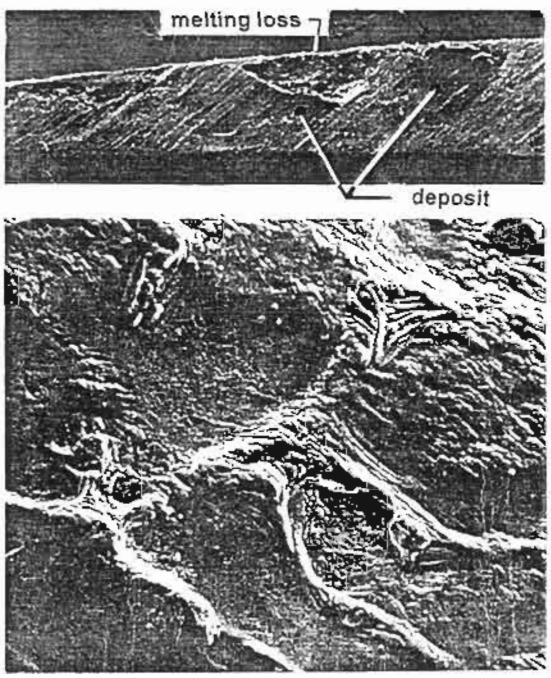


Fig. 3: Prestate of titanium fire on a blade tip;
a) Deposit (Ti-Ni material)/local melting losses
b) Typical view of the molten area (enlarged)

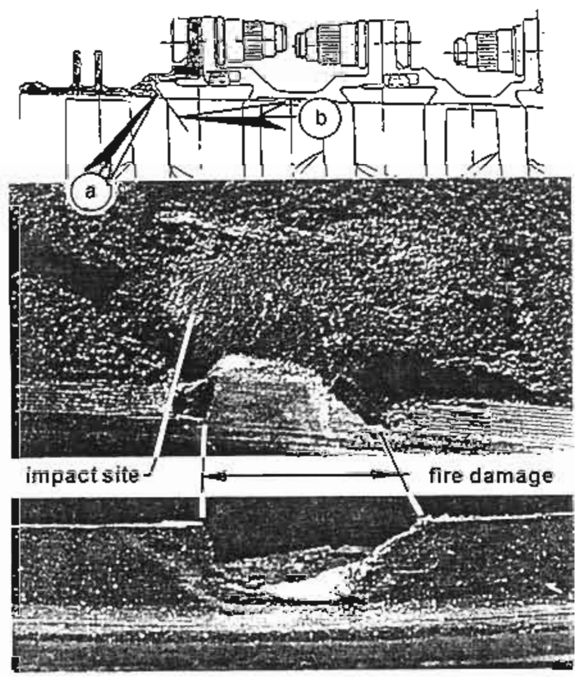


Fig. 5: Local titanium fire following hard-body impact;
a) Impact site on casing wall, and fire damage
b) Fire damage on thin casing wall

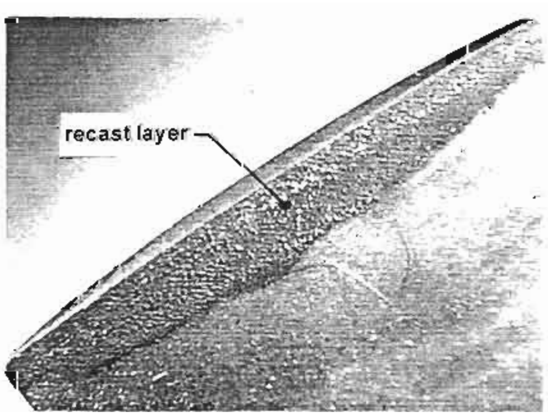


Fig. 4: Rotor blade, concave side, showing black Ti-Ni recast layer resulting from (mini) titanium fire

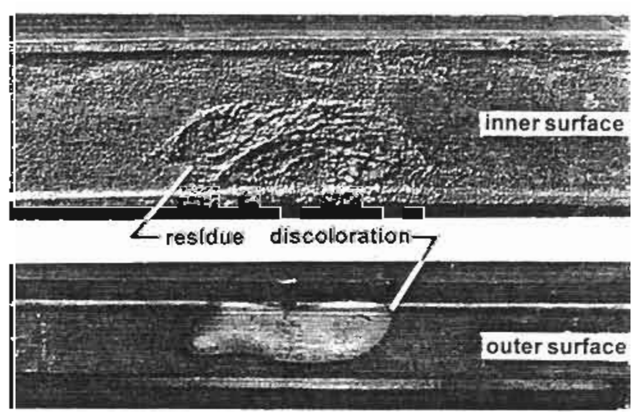
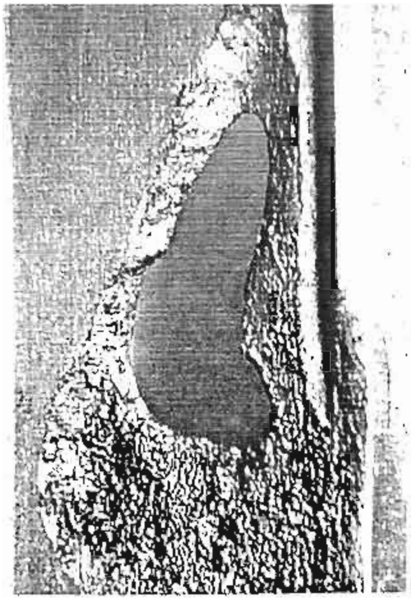


Fig. 6: Residue of a flat fragment from a titanium blade adhering to the compressor casing after ignition/fire;



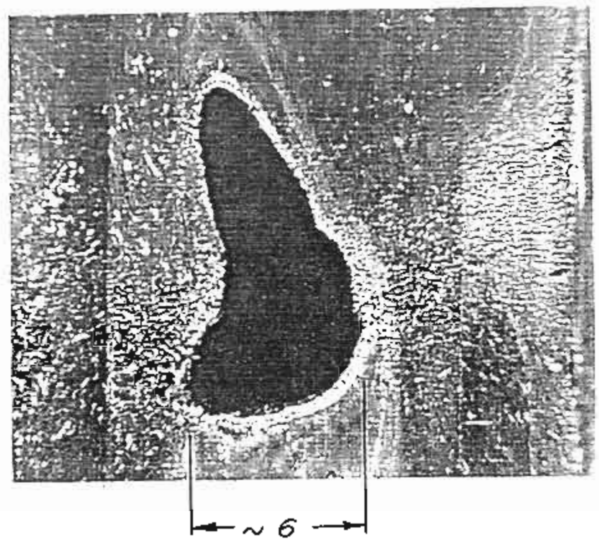


Fig. 7: Compressor casing penetrated by a local titanium fire as result of entrapment of a blade fragment followed by rubbing against the casing;
a) Inner surface of the casing (cleaned condition)
b) Outer surface of the casing (with titanium spatter)

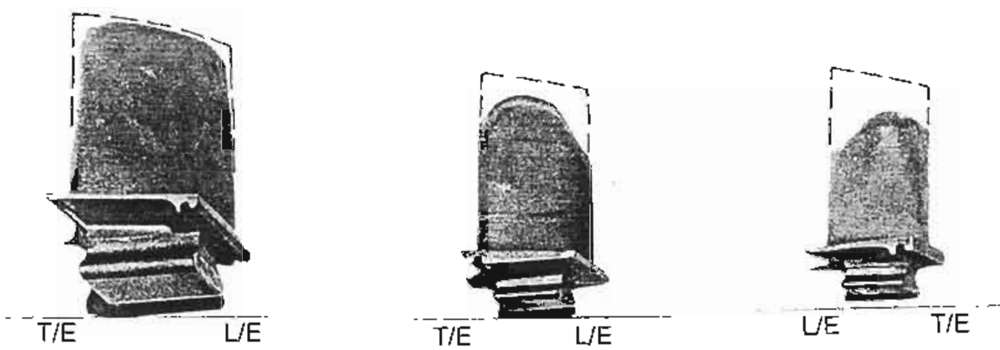
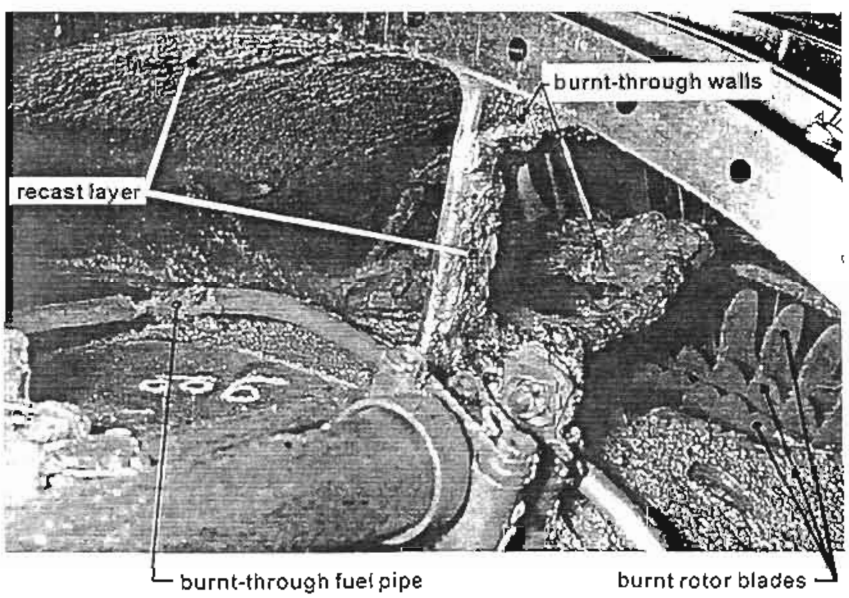


Fig. 8: Fire damage at blade tips



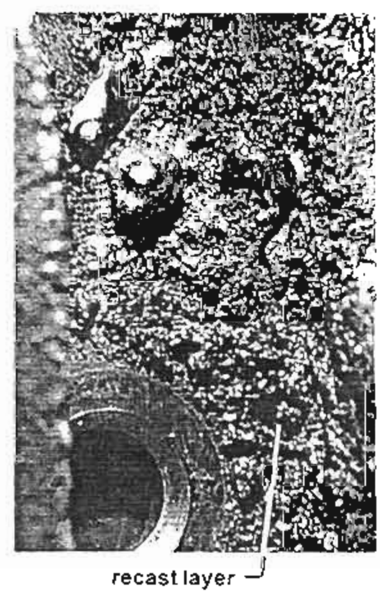


Fig. 9: Typical titanium fire with formation of a recast layer on the casing surface;
a) General view of burnt rotor blades and burnt-through casing wall with recast layer
b) Enlarged view of the recast layer

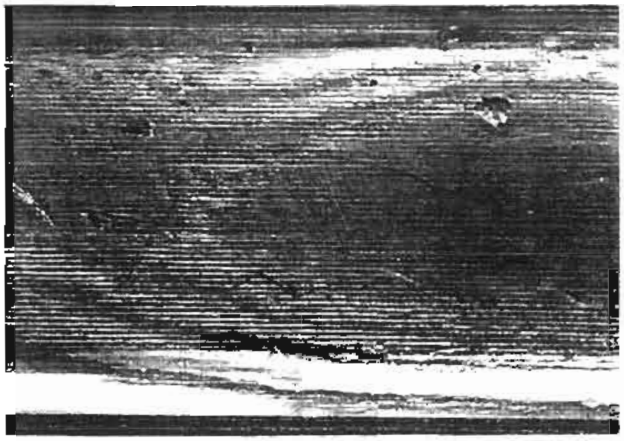


Fig. 10:

Typical sequence of 'Newton rings' on thin titanium walls, indicating incipient overheating as a result of titanium fire or contact with molten products

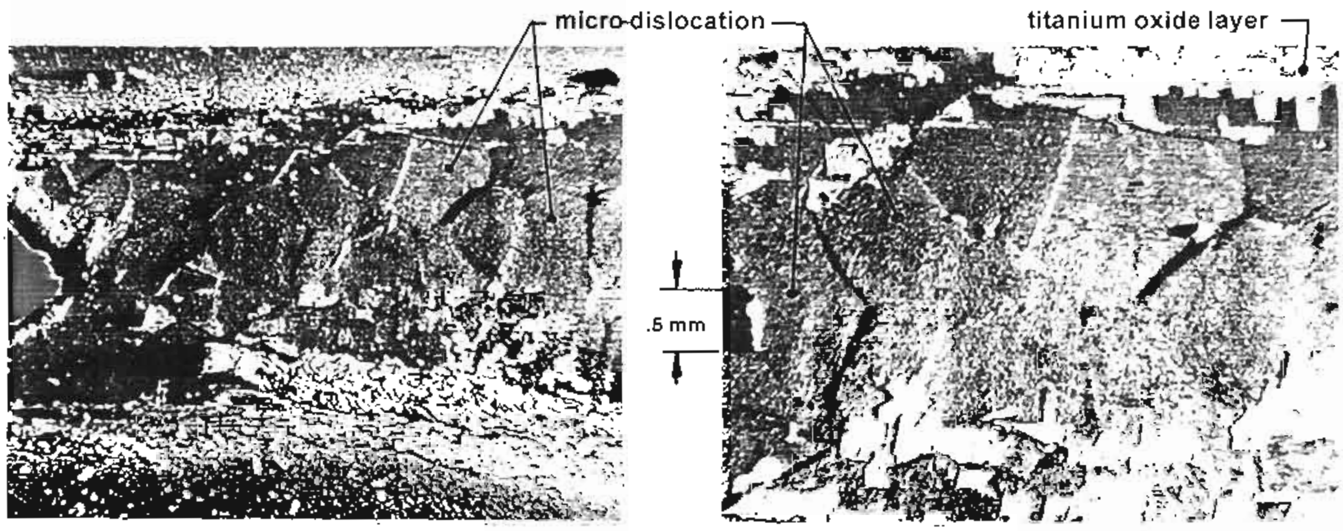


Fig. 11: Typical surface of a thin titanium wall prior to melting/burn-through: Formation of surface oxides and micro-dislocation of grains
a) Area close to burnt-through section (left-hand side) with micro-dislocation (surface oxides partly removed)
b) Enlarged view

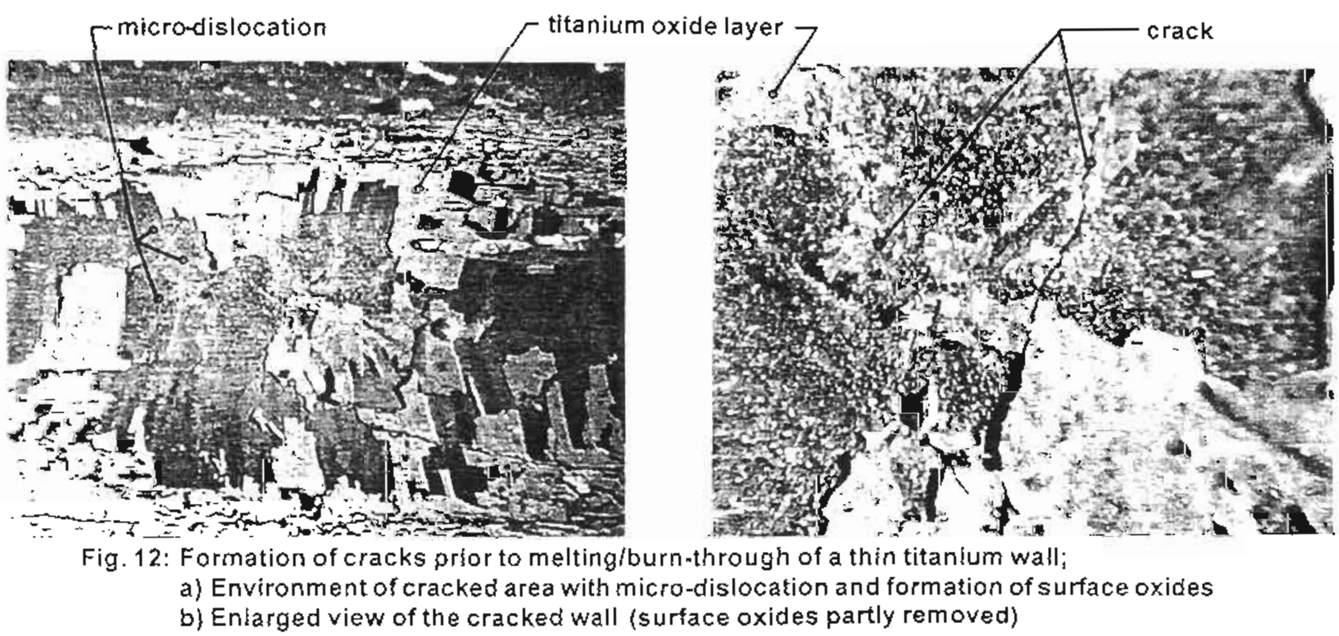


Fig. 12: Formation of cracks prior to melting/burn-through of a thin titanium wall;
a) Environment of cracked area with micro-dislocation and formation of surface oxides
b) Enlarged view of the cracked wall (surface oxides partly removed)

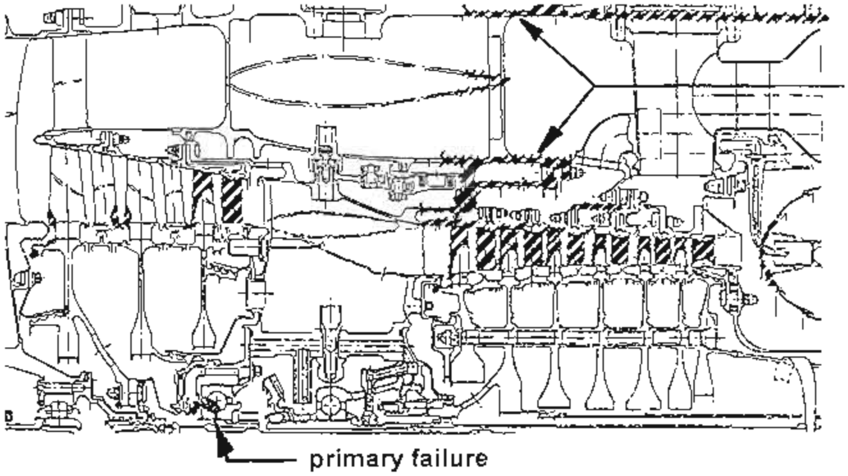


Fig. 13:

Radial and axial extent of titanium fire in a military engine (schematic)

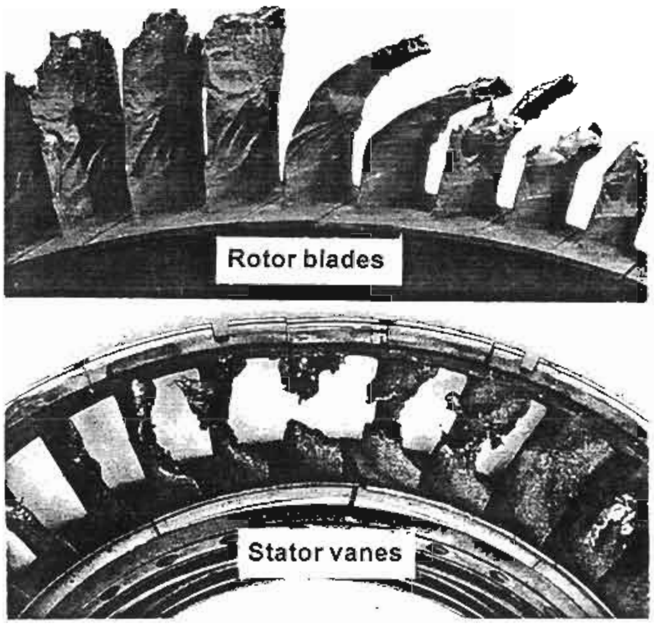


Fig. 14: Damage to turbine blading following over-fuelling subsequent to titanium fire

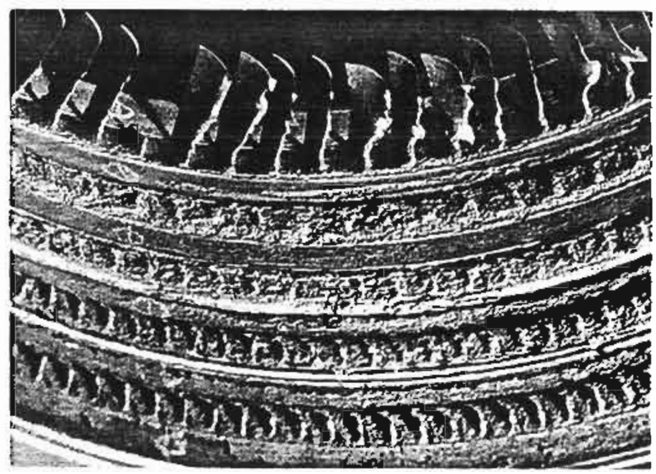


Fig. 15: Titanium fire in a compressor where casing walls are protected with a ceramic coating

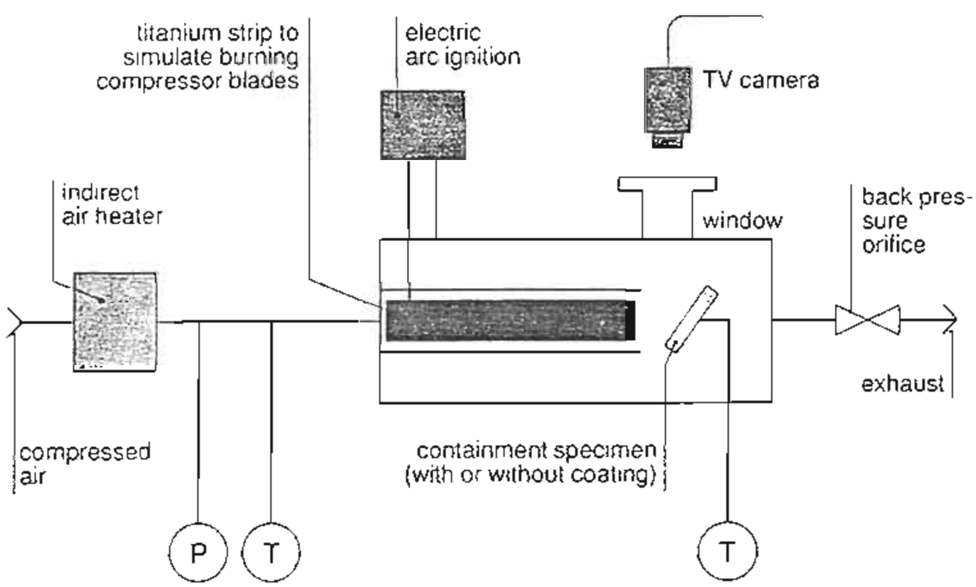


Fig. 16:

Schematic showing an experimental set-up for simulation of titanium fire, and testing of protective coatings