THE COMBUSTION OF TITANIUM IN GAS TURBINE ENGINES

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The combustion of titanium in gas turbine engines has been, in recent years, a source of concern for the aircraft industry. The unpredictable nature of the titanium combustion incidents and the massive damage which can accompany an occurrence, was sufficient to initiate considerable experimental research and redesign activity in the 70s. Nearly all current aircraft gas turbine engines have suffered some metal ignition damage. This paper will summarize, in a general form, the type of incidents which have occurred, including the damage assessment and the probable causes. It is worthy to note that titanium combustion is typically a secondary event. That is, some failure preceded the metal combustion and created an environment conducive to the ignition of a titanium component. The source of failures, in most cases, was deduced from damage assessments and engine histories but does represent a relatively accurate picture of the problem. The range of potential failures will also be discussed and categorized to provide a common ground for understanding titanium combustion incidents.

The research conducted in the 70s to attempt to understand the combustion process and examine means of neutralizing or eliminating the problem will be discussed. Some of the early considerations will be described and re-interpreted based on current technology. The application of recent research and the benefits derived from that application will be explained.

INTRODUCTION

Titanium has been an integral part of the aircraft propulsion system for over 20 years. Its use is justified by a high strength-to-weight ratio, good strength retention at moderately high compressor temperatures and excellent corrosion resistance. For these reasons, titanium usage increased into the late 60s and early 70s, finding its way into nearly all the gas turbine engines developed through this period. The application of titanium, although accompanied by numerous advantages, was not without some disadvantages, including cost, machinability and combustibility. The first two are an accepted integral part of the use of titanium whereas the latter problem is an unacceptable feature, especially in an aircraft power plant.

Titanium has a wide application base in the gas turbine engine (see Figure 1). The fan/compressor is the main benefactor of titanium technology. Fan blades, vanes, cases, rotors, splitters and various support members are routinely fabricated from titanium. Similarly, the compressor blades, vanes, cases, and rotors, at least to the mid-high pressure compressor location, also benefit from titanium usage. Additional titanium can also be found in fan ducts, low pressure turbine components, nozzle members, heat shields and other miscellaneous parts.

HAZARD POTENTIAL

With this widespread use of titanium, it is obvious why a strong concern exists relative to its combustibility. But why is titanium a potential combustion hazard? Table 1 is a listing of the physical properties of some selected metals which relate to the relative combustibility of titanium. Three of the five metals listed, titanium, iron and magnesium, ignite before they melt. Thus, they do not have the benefit of the latent heat of fusion as a potential heat sink. The heat of combustion of titanium is high, albeit less than either aluminum or magnesium, however, its specific heat and probably more importantly, its thermal diffusivity, is considerably lower than aluminum or magnesium.

To put these combustibility factors in more of a relative perspective, see Figures 2, 3, and 4 which include the resistance to ignition, the relative fire severity for equal weight and the relative fire severity for equal volume, reference 1.

The relative energy to ignite the metal was found by considering surface temperature of the metal subject to a specified heat flux

$$T = 2Q\sqrt{\frac{t}{\pi K \rho c}}$$

where

T = surface temperature °K
Q = heat flux
t = time
K = thermal conductivity J/(sec)(m)(°K)
ρ = density Kg/m^3
c = specific heat J/(Kg)(°K)

If we now rearrange and substitute T_{ign}, ignition temperature, for T we get

$$2Q\sqrt{t} = T_{ign}\sqrt{\pi K \rho c}$$

Therefore the relative resistance to ignition for a constant heat flux over a fixed time interval is proportional to $T_{ign}\sqrt{K\rho c}$.

The relative fire severity for equal weight is determined by examining the heat of oxide formation for the metal, expressed in joules per Kilogram - mole, and dividing the heat of formation by the number of metal atoms in the oxide molecule times the atomic weight. For example, the heat of oxide formation for titanium is 94.5×10^7 J/Kg-mole, the number of titanium molecules is one and the metal atomic weight is 47.9. The energy released (E) is therefore

$$E = \frac{94.5 \times 10^7}{1 \times 47.9} = 1.9 \times 10^7 \text{ J/Kg}$$

The relative fire severity for equal volume is merely the energy per unit weight times the density of the metal or $E\rho$.

From Figures 2, 3 and 4, it can be seen that titanium has a relatively high combustibility quotient. It combines a potentially high fire severity with a relatively low resistance to ignition. Aluminum on the other hand has a potentially high fire severity but exhibits a relatively high resistance to ignition. Magnesium tends to fall in between titanium and aluminum on a comparative combustibility criteria.

Titanium, therefore, obviously warrants special consideration from a safety standpoint when its use in the gas turbine engine is intended. Studies pertaining to the ignition of titanium have been available for over 20 years, some of which were used to define the limits of acceptable titanium use, especially in the mid-60s, when interest in the potential hazards of titanium combustion in gas turbine engines began to rise. Figure 5 illustrates a typical application of the Stanford Research Institute study, reference 2, with representative stage pressure and temperature conditions plotted as an overlay. Since the pressure and temperature of a specific stage is not a constant factor, varying as a function of power setting and altitude, several different operating conditions would normally be plotted to determine the application limits. The time at each operating point could also become a determining factor for exceeding the combustibility limit. More important than these considerations, however, is the experimental basis for the curve dividing sustained combustion from non-sustained combustion. Titanium was tensile fractured in a non-flowing environment. A number of experiments, both reported, references 3, 4, 5, and 6 and unreported, have demonstrated the ill advised use of the SRI curve for setting sustained combustion limits.

More recently, the effects of velocity on sustained combustion of simulated blades have been demonstrated, references 3 and 5. As a result, the sustained combustion curve was re-developed as a function of leading edge Reynolds number and temperature, reference 7. Data from reference 5 was plotted on the N_{Rc} vs T curve and agreed quite favorably with defined combustion areas, reference 7. Figure 6 illustrates the possible use of the N_{R_c} vs T sustained combustion curve to help define the limits for the use of titanium in a representative compressor environment. From the figure, for the compressor conditions plotted, stages 5 and 6 would represent a risk for the use of titanium 6Al-4V and similar commonly used titanium alloys. The latter distinction was made because Figure 6 does not represent the sustained combustion limits for all titanium alloys, reference 8.

Another caution should be exercised concerning the use of Figures 5 and 6 for establishing design goals and that is the lack of consideration for centrifugal effects on the combustion process, especially as it concerns melt removal. The retention and removal of molten titanium from the burning metal has been found to be an important factor in the self-sustained combustion of bulk titanium. In spite of this problem, the Reynolds number plot is currently one of the better 'quick and dirty' guides for establishing the combustion design limits for the use of common titanium alloys in the gas turbine engine.

Good design practice, however, rarely permits the 'quick and dirty' criteria to drive the design pholosophy. It requires, rather, a look at the parameters involved in the problem, isolating those deemed important, and cataloging the risk associated with the potential failures. Table 2 presents a simplified summary of the factors involved in a titanium incident. Generally, the combustion process consists of an energy source creating a localized temperature rise, a fuel source (titanium) and oxygen (air). The heat source creates a condition where ignition occurs and a supply of oxygen produces a self-sustained combustion. The combustion will continue so long as titanium and air are available and the heat loss from the metal does not equal or exceed the heat generated from the oxidation process. In equation form

$$\frac{dE}{dt} = \text{Qcond} + \text{Qrad} + \text{Qconv} - \text{Qreac} - \text{Qinput}$$

During the pre-ignition phase, the equation is basically reduced to

$$\frac{\Delta E}{\Delta t} = \text{Qcond} + \text{Qconv} - \text{Qinput}$$

except for the fracture initiation sequence where Qreac becomes a dominant heat source. Once ignition has occurred, the equation can be considered

$$\frac{\Delta E}{\Delta t} = \text{Qcond} + \text{Qconv} - \text{Qreac}$$

since the heat of reaction will be a dominating heat source. The equations above are, of course, a simplified form of a much more complex problem. A detailed, generalized solution of the complex combustion process is described in references 7 and 10 and represents the best model currently available to assess the self-sustained combustion of titanium airfoils.

Before self-sustained combustion can occur, however, an ignition source must have evolved. Table 2 lists a number of potential ignition sources possible in the gas turbine engine.

The high energy rub is without question the most prevalent initial ignition source for titanium components in the gas turbine engine. High energy rubs occur as a result of blade tips rubbing against the case, or case coating, as a result of excessive radial displacement of the rotor, rubbing of blades against trapped debris; i.e., broken blades and vanes, loosened bolts, nuts or pins and numerous externally ingested objects; and rotor/stator rubs as a result of rotor axial displacement. Trapped blades and radial displacement of the rotor comprise the major sources of combustion initiation in the engine.

A very small number of incidents have resulted from aerodynamic heating, stall/surge. No distress marks resulting from rubbing were observed on either rotating or stationary components. The end result of these instances was minor trailing edge damage, an ignition but not a prolonged self-sustained combustion. In a stall event, the local temperature rises very rapidly, creating a high rate of heat flux to the blade/vane. Since convective heat dissipation is low and the conductive heat transfer, especially for thin trailing edges, is also very low the high heat input can cause localized ignition. Once the engine recovers, usually in milli-seconds, the heat removed by convection overwhelms the combustion process and effectively blows it out. Figure 7 is an example of the trailing edge burn.

A fracture initiated burn results from the exposure of unoxidized titanium to the airstream. As oxidation occurs, the exothermic reaction causes the temperature of the solid in the immediate vicinity to rise to the ignition point. Although fracture initiated combustion has occurred in the laboratory, the engine is devoid of any similar verified instances, with one questionable exception.

Molten titanium droplets are the major source of propagating a fire from its initiation site to downstream components. The titanium droplet is a high thermally reactive element. Evidence of the reactiveness of the molten titanium is seen in Figure 8 which is an exhaust plume, 8 ft. long, of molten titanium droplets from a test sample 1" x 2.3" x .060". It should be easily seen from this example the potential for massive damage from multiple blade combustion in a confined environment such as a gas turbine engine.

Once ignition has occurred, factors such as temperature, pressure, velocity, component geometry, and molten metal dispersal interact resulting in either minor or major damage. Minor damage includes both reparable and replaceable components. Major damage refers to massive destruction of the compressor, multiple blade/vane rows reduced to fractions of their original heights and sometimes, but not always, including case penetration. The difference between minor and major damage is typically a function of the rate and amount of molten titanium generated and its dissipation, i.e., separation from burning parts and impingement on downstream components.

Figure 9 is an artist's conception of a propagation scene. The blade at the left of the figure has ignited at the tip leading edge. As the burn surface regresses, molten titanium flows rearward toward the trailing edge driven by aerodynamic forces and radially outward due to aerodynamic and centrifugal forces. As the burn progresses, molten titanium builds until the aerodynamic and centrifugal forces overcome the melt surface tension thus causing dispersal of the droplets on the case and downstream components, vanes and blades. If the molten titanium separates as fine droplets widely dispersed, they will probably coat the vanes, blades and cases and extinguish. If, however, the buildup is substantial in a short period of time, in cascade experiments the downstream blade ignites in less than two seconds, the burn will progress and ignite additional components. The effect is an extremely intense, rapidly expanding fire which continues as long as fuel (titanium) and combustion conditions permit. Events of this nature, including the most damaging, are probably over in a matter of seconds rather than minutes.

The preceding discussions and descriptions may generate fear in some concerning the potential dangers, however, the fear is probably a slight overreaction. A healthy respect is warranted and the use of titanium should be accompanied with an understanding of the problem, the type of incidents that have occurred and the potential design/material solutions which can effectively reduce the hazard.

INCIDENTS

A total of 340 recorded incidents are included in the data summarized in this section. The data gathered, from a variety of sources, is not complete. Some of the facts surrounding particular incidents are sketchy and are included and interpreted as completely as practical. In addition, a large number of minor incidents were probably overlooked in routine overhaul operations because the blades were reparable, e.g., light trailing edge burns, or beyond the tolerance limit for repair and not recognized as a significant event. The data has also been disguised to protect the proprietary rights of the sources. Also, additional plots or correlations could have been provided, however, the more parameters employed, the more likely the sources would suffer undesirable identification.

Figure 10 is an indication of rates of minor to major incidents for high bypass turbofan engines and low bypass plus turbojet engines. Also plotted are the relative number of case penetrations for each class of engine. For the high bypass engines, 58% of the incidents resulted in minor damage whereas 64% of the low bypass engines and minor damage, the ratio not being significantly different for the two classes of engine.

Case penetration, on the other hand, reveals a different picture. Fifty-seven percent to the HBTF engines had case penetrations whereas 36% of the LBTF cases were penetrated. The data indicates less resistance to case penetration by the HBTF, a conclusion which may be valid but warrants further analyses. For one thing, the majority of penetrations in the HBTF engines were at manifold locations, a fact not equally shared by the family of LBTF engines. To fully understand the implication of these comparisons would require an examination of a number of design/ operational factors most of which were not available for this analysis.

Figure 11 presents the comparison of minor/major damage for gas turbine engines as a function of thrust ranges. The ratio of minor to major damage is fairly consistent with the exception of the 20-30000 lb thrust class. Once again, the implication of this deviation should come from an in-depth analysis of the engine design, operational status, and the failure mode at the time of the incident. A similar statement can be made about Figure 12 where the trend of case penetration is similar for three of the thrust classes but significantly different for the 10-20000 lb thrust class.

A comparison of incident ignition sources is contained in Figure 13. Tip rubs occur when the rotor experiences a radial displacement creating a mechanical interference between the rotor blade tips and the case. Excessive rotor movement can be caused by a number of factors including bearing failures, compressor/turbine disk failure, fan blade breakage, hard maneuvers, or hard takeoff/landings.

The FOD/IOD refers to foreign objects or internal objects (primarily but not limited to broken blades) being trapped in the flowstream such that the rotor rubs against the captured object. Most trapped debris is collected at the outer diameter of the flowpath resulting in tip rubs.

Root rubs involve the ignition of a titanium blade/vane at the inner diameter of the flowpath. Most of these occurrences are the result of either axial rotor movement or a component failure in the rotor hub region. The stall only situation was described previously.

The representation of incidents as a function of operational status is shown in Figures 14 and 15. The sea level and attitude test stand data is self-explanatory except for the lack of data on power setting. An interesting analysis could be performed on the relationship of minor/major damage and penetration/non-penetration criteria for sea level and altitude test stands as a function of power setting.

Takeoff represents a full power situation and as far as titanium combustion is concerned, a critical part of the flight envelope, since the stage pressure and temperatures are at a high level and rotor motion radially and axially are expected. Examination of Figure 15 produces a possible explanation for the high percentage of case penetrations for the HBTF, Figure 10. During takeoff, the high centrifugal forces would tend to concentrate melt on the case/manifold structure and the high pressure/ high temperature environment results in a faster burn rate and an increased likelihool of self-sustained combustion, reference 5.

Once again, the data in this section was accumulated from a variety of sources with no continuity on the amount of information available. Summing the data on each of the different graphs will lead to different totals. Further, the list is not inclusive. Incidents have occurred which have not been disclosed for a variety of reasons, not the least of which is the non-recording of probable incidents at the numerous overhaul facilities.

Figure 16 is an artist's conception of typical burn patterns. The burn shown in Figure 16a, b, c, and d are progressive burn patterns. In that sequence, the initiation would probably have been at the 'b' location with 'a' being an upstream trailing edge ignition and blowout. The blades and vanes downstream from 'd' would have been replications of 'd' and could have been fabricated from metals other than titanium. Figure 17 was an example of an actual burn progression (propagation). Figure 18 is a typical example of a case penetration. Penetrations can include small holes at various locations, 360° - stage wide holes, or a massive total consumption of the entire case over the compressor section. The majority of examples are contained, fortunately, in the former category.

The preceding sections might lead to the conclusion that titanium in the gas turbine engine is a hopeless situation and its exclusion a warranted solution. In the first place, the incident rate per million flying hours is low. The number of failures compared to other material/design problems is not alarmingly excessive and there is on-going technology providing solutions to minimize the risk of ignition and self-sustained combustion. The following sections will describe some of the technology developments and design changes intended to minimize the titanium hazard.

RUB PREVENTION

Although titanium combustion is a secondary failure rather than a primary cause, it would be naive to believe all sources of primary failure could be resolved. The more likely attack is to minimize the potential for combustion once another precipitating failure occurs. The approaches are primarily concerned with the prevention of ignition.

Ignition from tip rubs can be attacked from a number of directions. One of the more obvious techniques is to open the clearances, not throughout the compressor, of course, but primarily in the critical regions. The critical regions are the latter stages using titanium, which is probably the mid high compressor region.

The early stages have two factors in their favor, first the pressures and temperatures are lower and the blades are thicker. Intuition and limited data point to an increased difficulty to ignite the thicker blade. Increasing the clearance is not a highly recommended approach because of the efficiency penalty and decrease in stall margin, a very risky approach for a stall prone compressor. Further, the clearance increases would not ne on the order of 50-50 mils which may be required to prevent ignition from tip rubs following a component failure.

A more acceptable approach is the application of a rub tolerant material in which titanium rubs are suspected. The search for an acceptable rub tolerant material, especially in the tip region, has been underway for 20 years with limited success. The materials which involve the least energy generation are also erosion prone and vice versa. The second problem with the rub tolerant material is the thickness. With weight a premium in engine design, case thicknesses are minimized, therefore leaving minimal space for the rub tolerant material. A severe rub easily penetrates compressor coatings, typically .015-.025. Once the coating has been penetrated, rubbing the case can be especially hazardous, particularly if it's titanium but also when the case or insert is steel.

Much has been said about the titanium on titanium rub as the prime factor in the ignition of titanium components. While rubbing titanium on titanium may generate more heat than other materials, titanium on steel, for example, can and has been an ignition source. Other materials such as plasma sprayed nickel graphite and felt metal have also resulted in titanium ignition during a hard rub. Suffice it to say, titanium will ignite in air if the energy generated during the rub is sufficient to bring the local titanium temperature to the ignition point.

One additional problem worth mentioning at this point is the potential for component failure and possible ignition when a material such as nickel graphite is sprayed directly over titanium. Heat generation at the rub surface can result in a titanium-nickel reaction at the coating/case interface. The TiN eutectic forms a low melting alloy and penetration can occur due to a melt thru or yield.

Internal rubs are similar to tip rub from the standpoint of material sensitivity to heat generation. Titanium stator seal rubbing against the titanium rotor hub is probably the worst situation for ignition. As mentioned before, the heat generation is high and two components rather than one are subject to ignition. Steel is slightly better and aluminum, if the temperature permits is preferred. An additional comment relating to titanium/steel rub should be mentioned, namely, molten steel is known to ignite titanium.

Figure 19 illustrates a concept which may prove extremely important to the tip rub ignition problem. The abrasive on the tip of the blade serves two purposes, first it isolates the titanium blade from the rub and secondly, the wear is primarily in the seal material on the case. Figure 20 shows the volume wear ratio of three blade tip treatments and a bare blade on plasma sprayed nickel graphite and a stainless steel feltmetal, reference 11. The high wear ratio of treatment T1 against the stainless steel was due to some flaking of the tip treatment, not wear. The life of the blade tip is one of the question marks left to be answered by engine tests and hours of use. The technology is basically too new to answer these questions.

MATERIAL SUBSTITUTION

The prime example of material substitution is the substitution of steel vanes for titanium vanes. The initial idea behind the move was based on the assumption the fire propagation centered around the flame holding characteristics of the stationary vanes. It is definitely true that replacing titanium vanes reduces the amount of titanium available for ignition and combustion. It does not follow that propagation will be eliminated by this substitution (see Figure 21). The vanes in this picture were steel, the blades titanium.

Figure 22 illustrates typical substitution of steel or nickel base alloys for titanium. The amount of substitution is based on the weight margin allowable for the particular engine and the degree of hazard interpreted by the manufacturer. The substitution of a steel case for a titanium case, for example, involves a serious weight penalty, but may be viewed as a necessary penalty if case penetration and subsequent burning/external damage is deemed intolerant. One point worth mentioning is that a steel case is not impenetrable but it is viewed as a less hazardous event.

A potentially superior answer is offered in references 12 and 13. The first concerns the use of a coating on the titanium component to inhibit ignition from melt impingement. The second is the substitution of a less combustible alloy, Table 3. Without going into detail on these concepts, the application would most probably be a static component where the stress effects are lower, particularly vanes and cases. In addition, the combination of a more resistant alloy with an inhibiting coating could be a highly acceptable solution.

Consistent with the use of coatings as a protection against fire propagation is the use of a coating to increase the fatigue life of the blade. Just such a coating, platinum, has been developed and applied to compressor blades, reference 14. Since blade fracture and entrapment is another of the major sources of titanium combustion, the use of a platinum coating, especially in the root area, cannot be overlooked. Figure 23 is a graph of the number of cycles to failure for a platinum coated airfoil. An increase of 25-30 percent in fatigue strength is possible with a coated airfoil, an important consideration not only for a potential fire problem but also from the standpoint of durability.

One final technology should be mentioned, although it is not a material substitution. Protective blankets or wrappings have been used to protect external fuel and oil lines as well as to increase the probability the fire will be contained in the flow path. The techniques used to date have proven fairly effective, particularly a carbon cloth type barrier used on fuel and oil lines. The blankets are a preventive feature for catastrophic failure, not a technique to minimize the fire hazard such as coating and alloy intended applications.

FIRE EXTINGUISHMENT

Very little will be said about titanium fire extinguishment in the gas turbine engine because for, practical purposes, it is an improbable action. In the first place, detection is extremely difficult since the fire occurs in the gas path with hundreds of viewing obstacles for a typical U-V detector. Secondly, the sensor would have to differentiate between a fire and sparking, which occurs in a rub that does not cause massive combustion. Thirdly, once detection occurs, a system must be triggered to dispense an extinguishing agent to the proper location. By the time this occurs, the fire may have done its damage or at least a major portion of its potential damage. And last, the number of extinguishing agents considered acceptable is extremely limited (see Table 4).

SUMMARY

Titanium is undoubtedly a desirable material for use in the gas turbine engine. This material application is not without problem, one of the more important of which is its combustibility. This paper has discussed some of the early thinking on the subject, examined a number of documented incidents and presented a brief summary of potential solutions to the problem. Titanium combustion is an intense reaction, but its intensity can be reduced and its ignitability can be minimized. The major sources of ignition have been identified and means to reduce the ignition potential have been investigated, some of which are currently in use, while others are in the research and development phase.

Current studies are producing results which should minimize the effects of titanium combustion. Coatings, alloys, tip treatments, protective blankets and combinations of the above, consistent with good design practice, will allow the designer the luxury of considering titanium as an engine material with a much greater margin of safety and reverse the current trend of titanium removal from the gas turbine engine.

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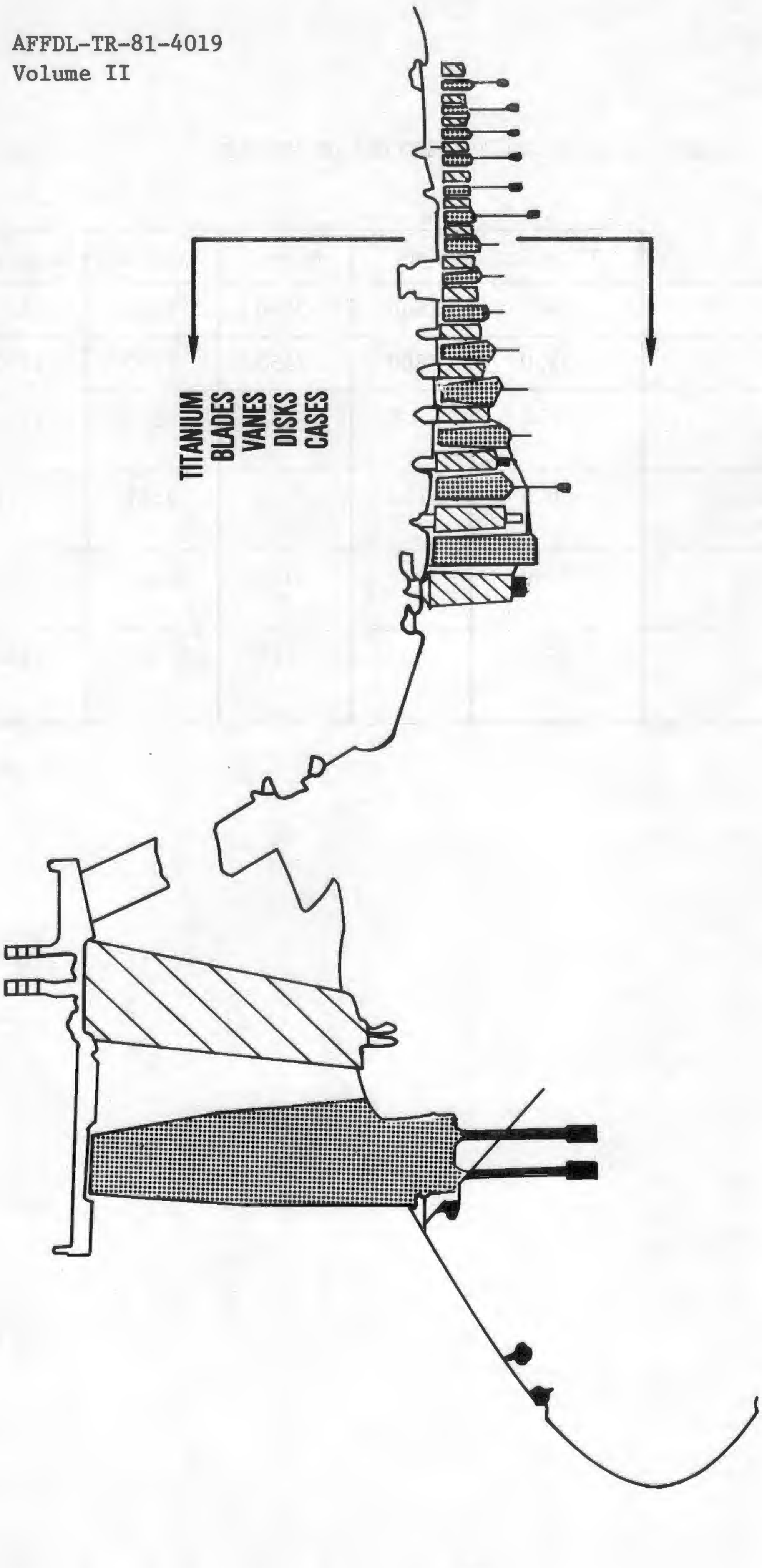

Figure 1

TABLE 1 PHYSICAL PROPERTIES OF METALS

	Titanium	Iron	Nickel	Aluminum	Magnesium
Ignition Temp	2900	1800	2550	1800	1150
Melting Temp	3250	2800	2450	1200	1200
Thermal Conductivity W/Cm^oK	.18	.8	.11	1.9	1.26
Thermal Diffusivity Cm^2/sec	.076	.23	.04	1.07	.9
Heat of Combustion J/g	19000	7000	4100	31100	25000
Specific Heat J/Kg^oK	578	503	469	938	1026

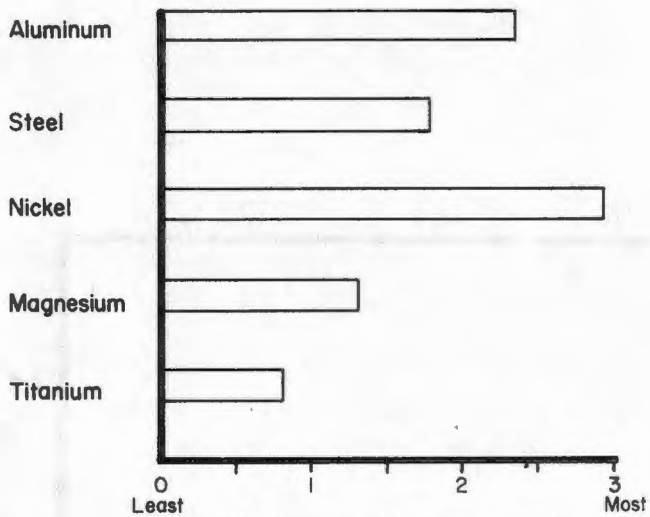

FIGURE 2 Relative Resistance

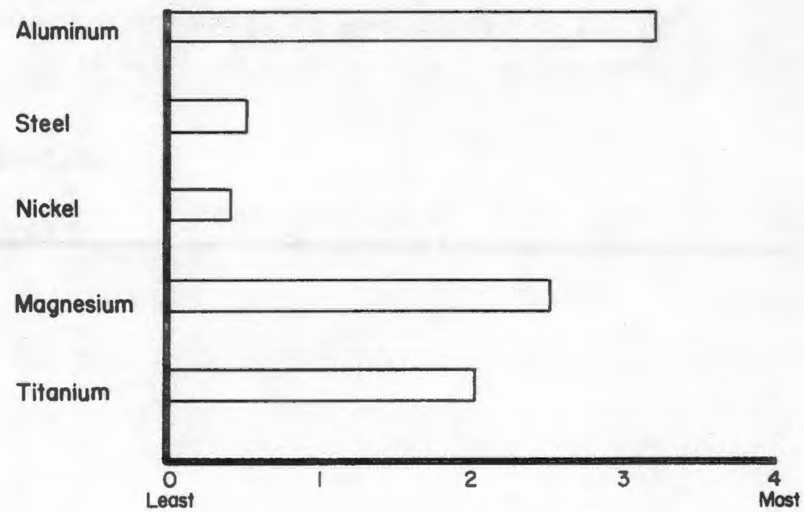

FIGURE 3 Potential Fire Severity for Equal Weight

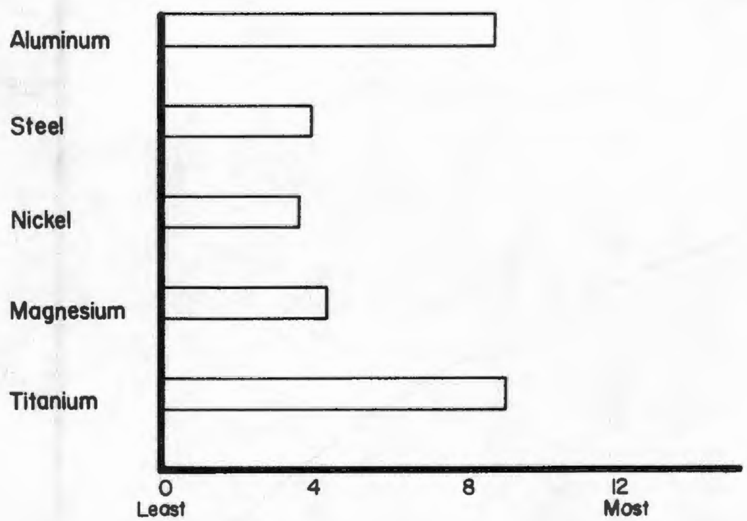

FIGURE 4 Potential Fire Severity for Equal Volume

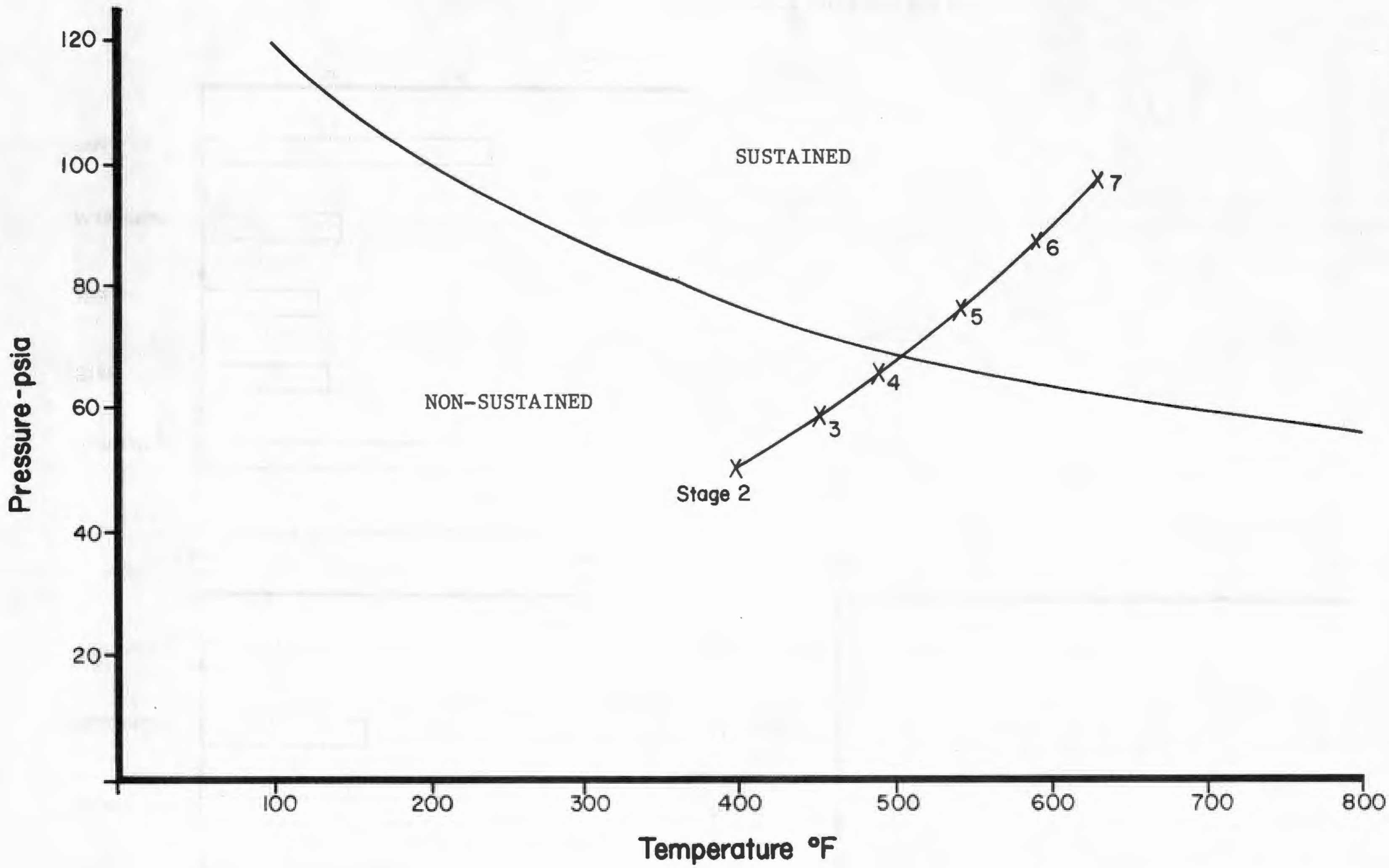

FIGURE 5 P vs T Plot of Sustained/Non-Sustained Combustion

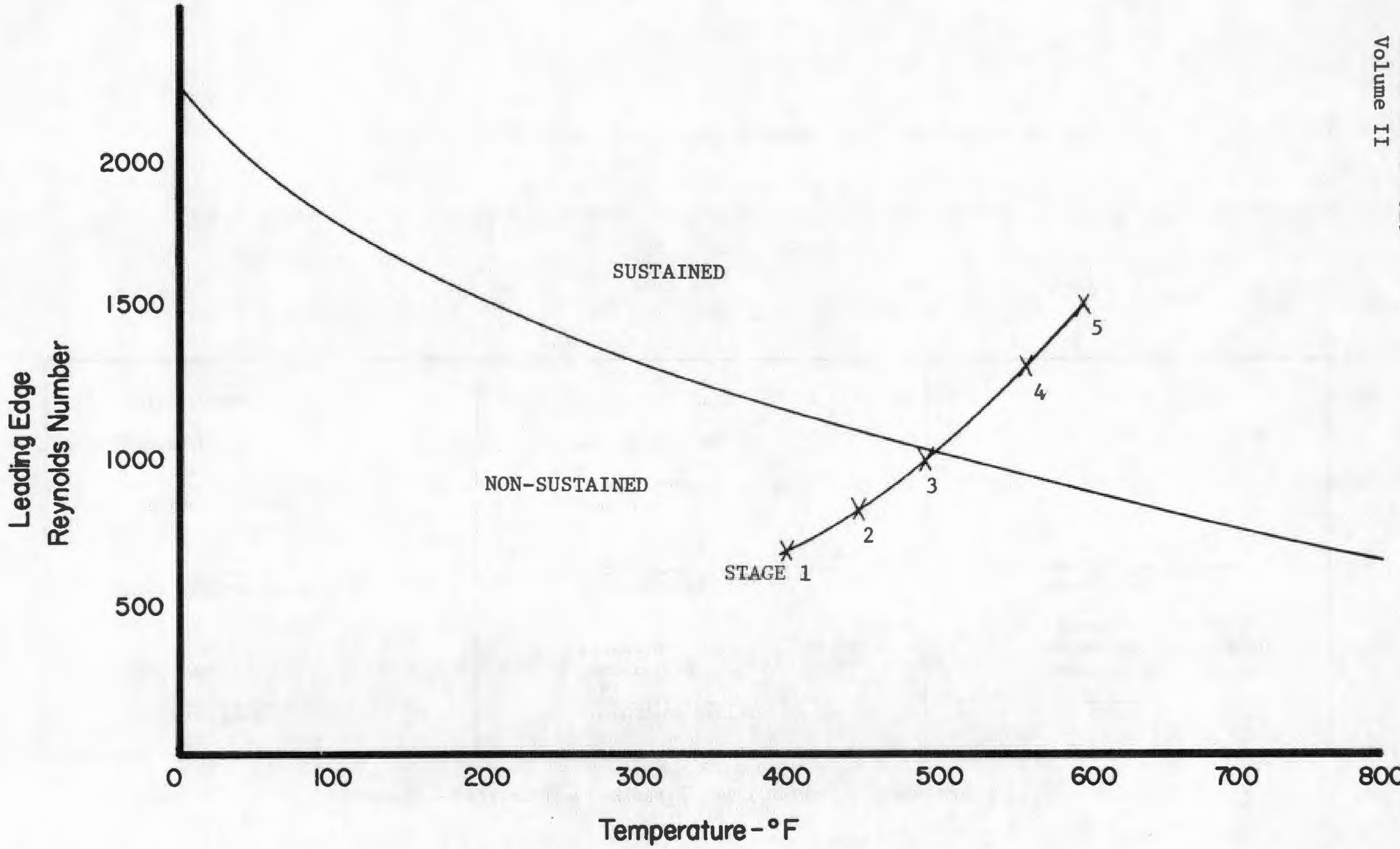

FIGURE 6 Reynolds No. Plot of Sustained/Non-Sustained Combustion

TABLE 2 FACTORS INVOLVED IN TITANIUM COMBUSTION

[ENERGY] + [TITANIUM] + [OXYGEN] $\rightarrow$ [HEAT GAINED] - [HEAT LOSS] =

IGNITION SOURCES	COMBUSTION FACTORS	RESULTS
High Energy Rub	Temperature Pressure	Minor Damage Component Replacement Component Repair
High Heating Rates-Stall	Aerodynamics Velocity Turbulence	Major Damage Engine Replacement Loss of Aircraft
Tip Recirculation	Geometry Thickness	
Fracture	Melt Dispersal	
Melt Droplets		

FIGURE 6 Reynolds No. Plot of Sustained/Non-Sustained Combustion

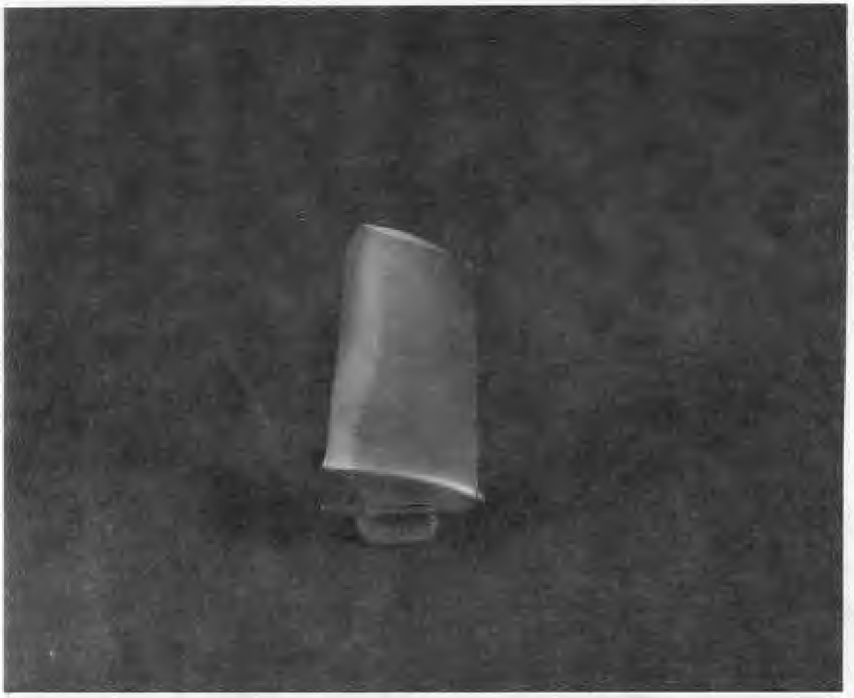

FIGURE 7 Minor Trailing Edge Burn

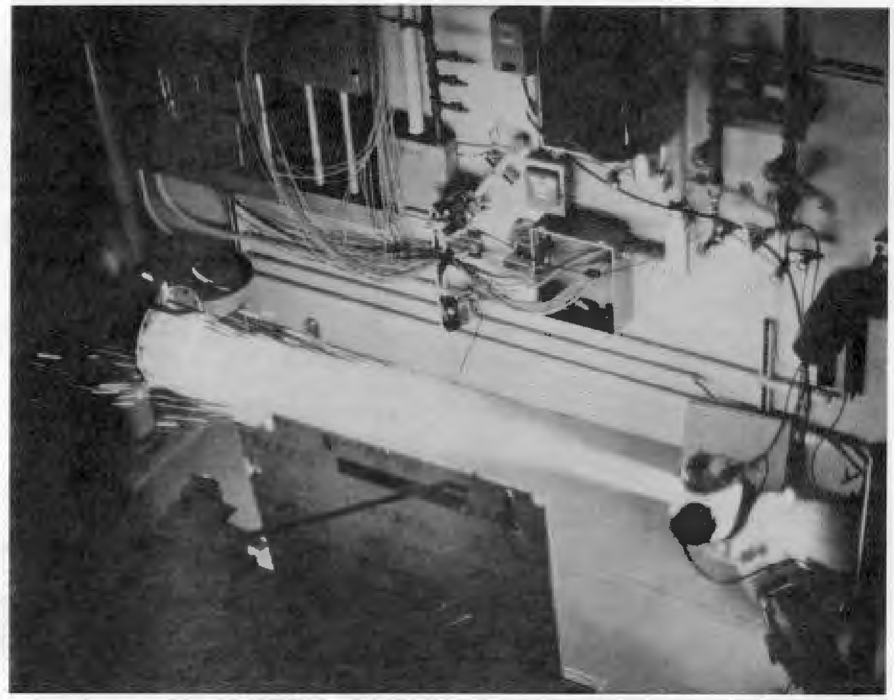

FIGURE 8 Exhaust Plume from Titanium Combustion Rig

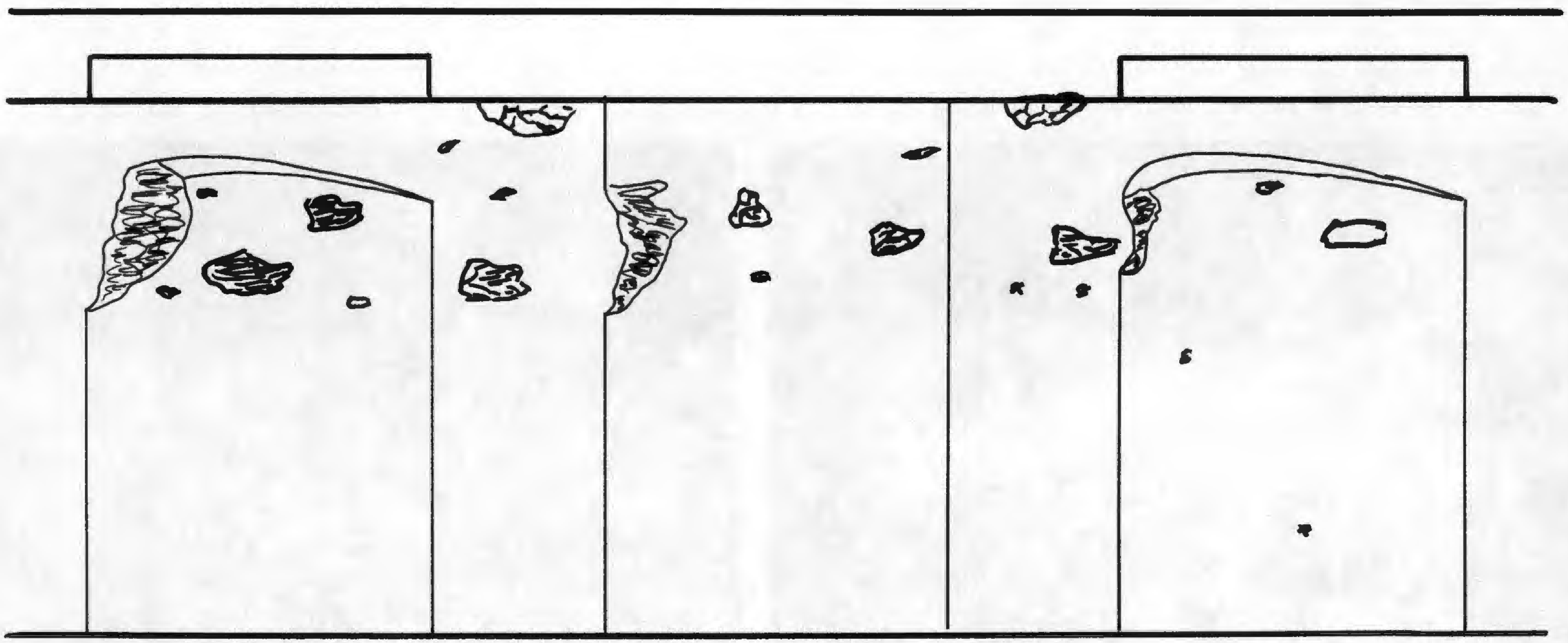

FIGURE 9 Propagation of a Titanium Fire

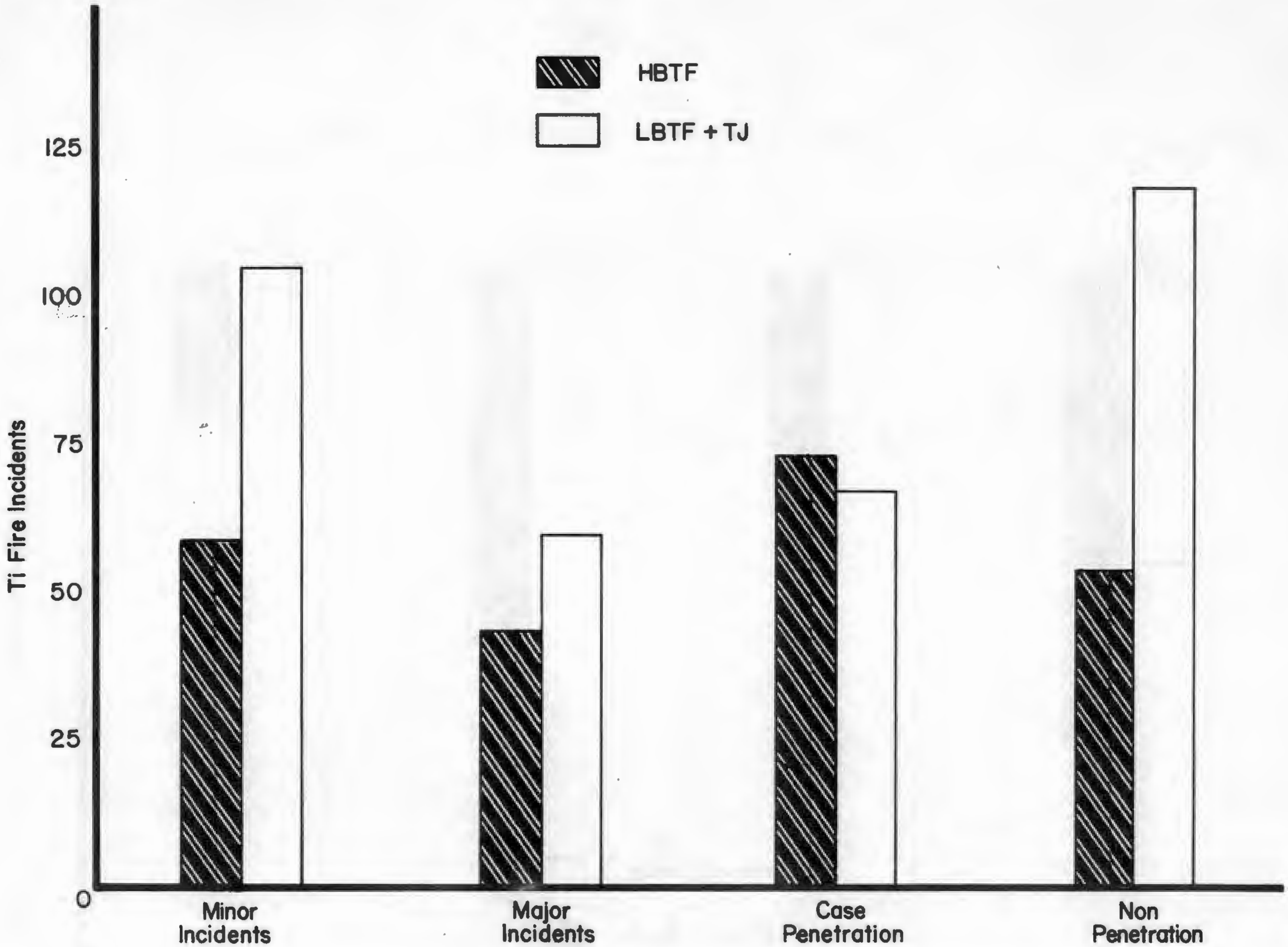

FIGURE 10 Minor/Major Incidents - Penetration/Non-Penetration for HBTF & LBTF Engines

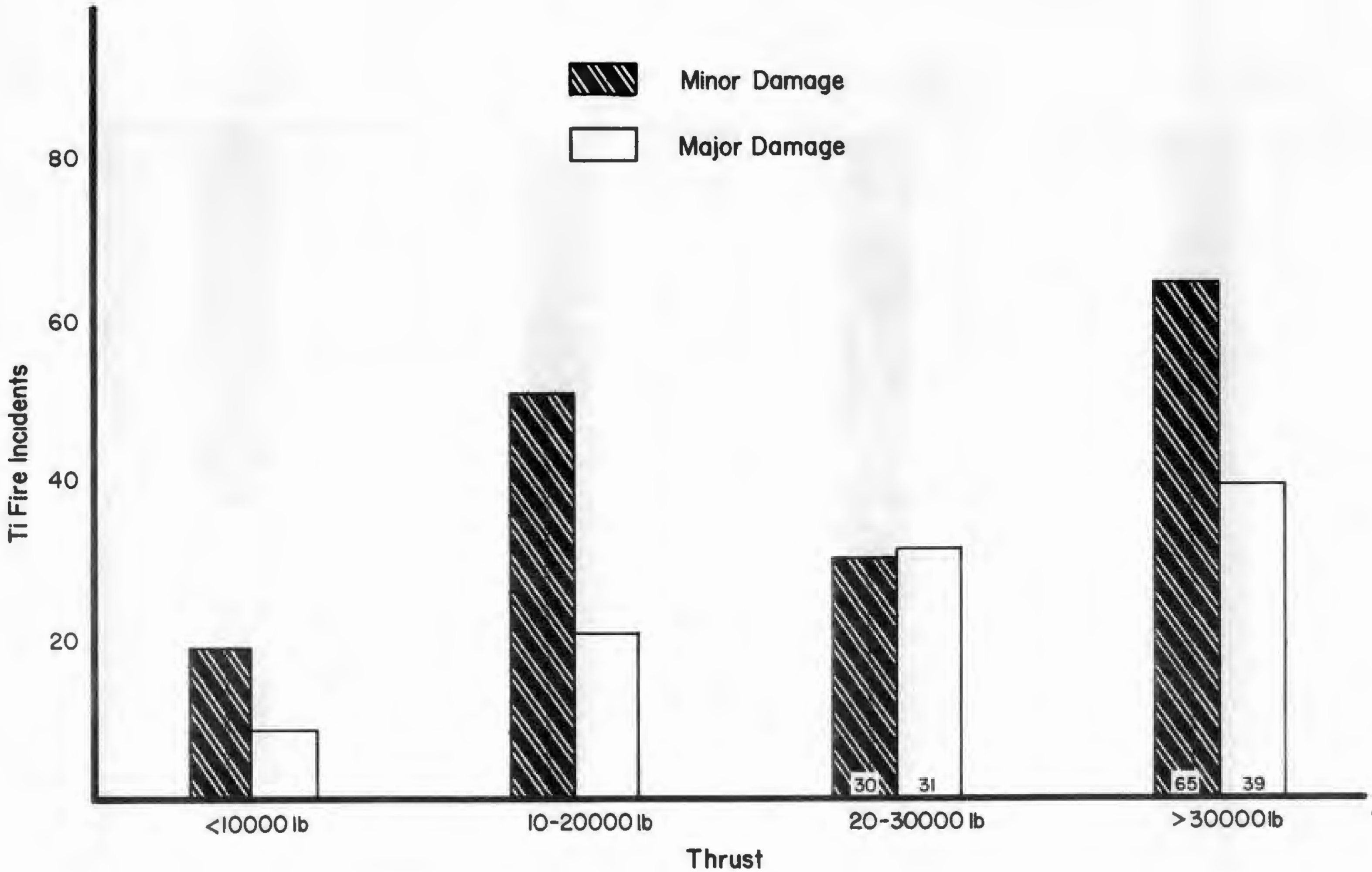

FIGURE 11 Minor/Major Incidents versus Thrust Class

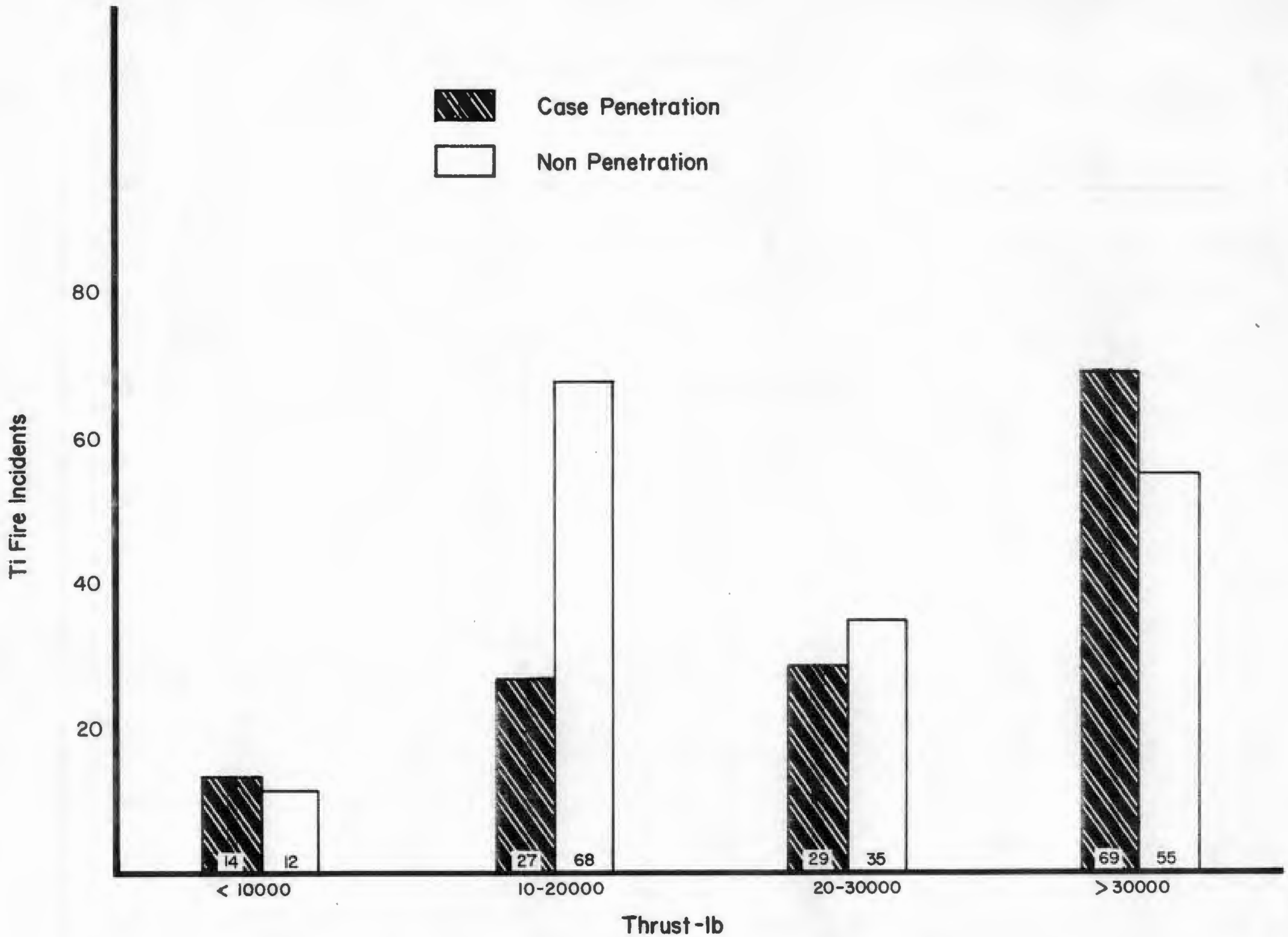

FIGURE 12 Penetration/Non-Penetration versus Thrust Class

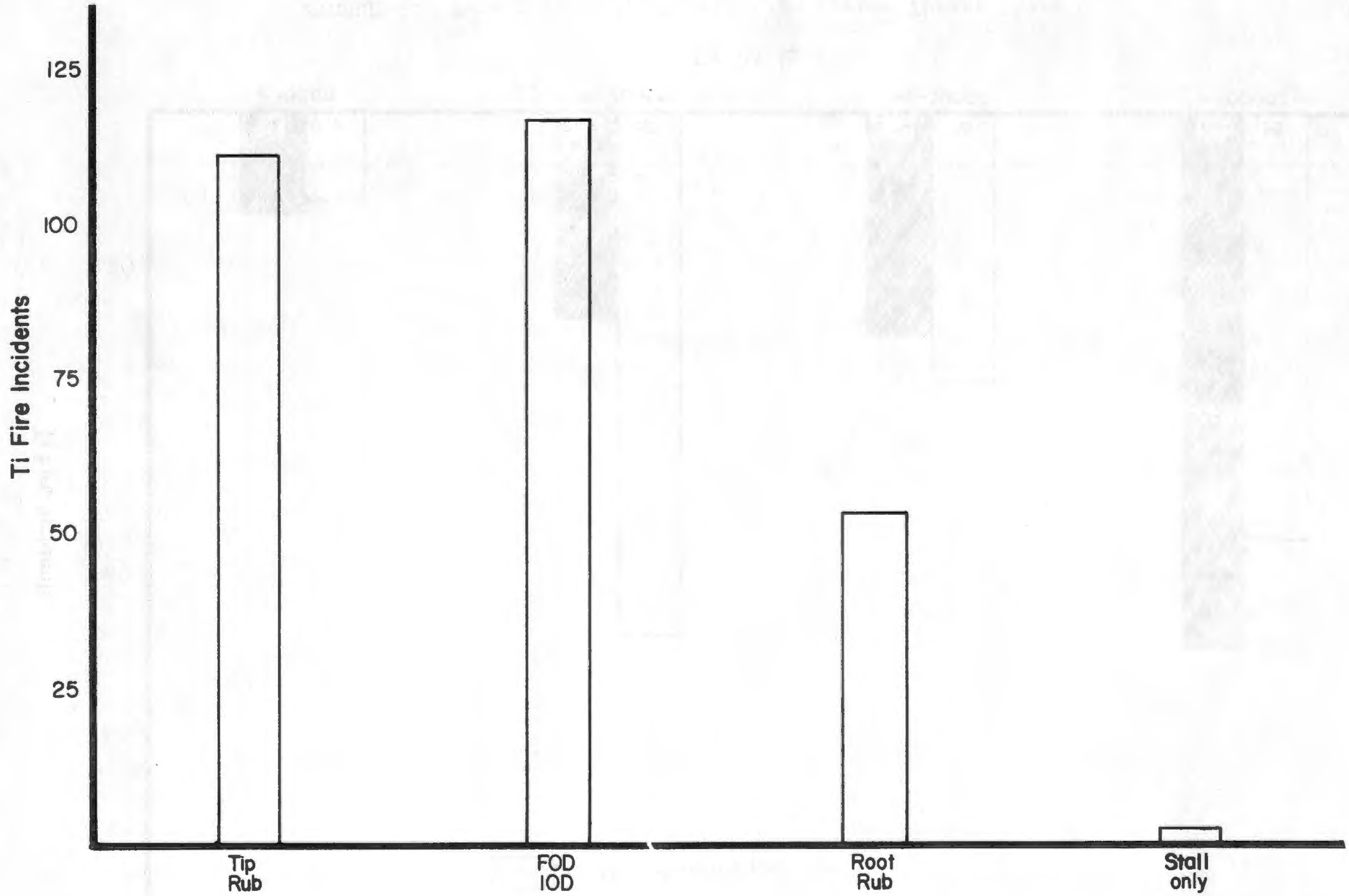

FIGURE 13 Fire Incidents as a Function of Ignition Source

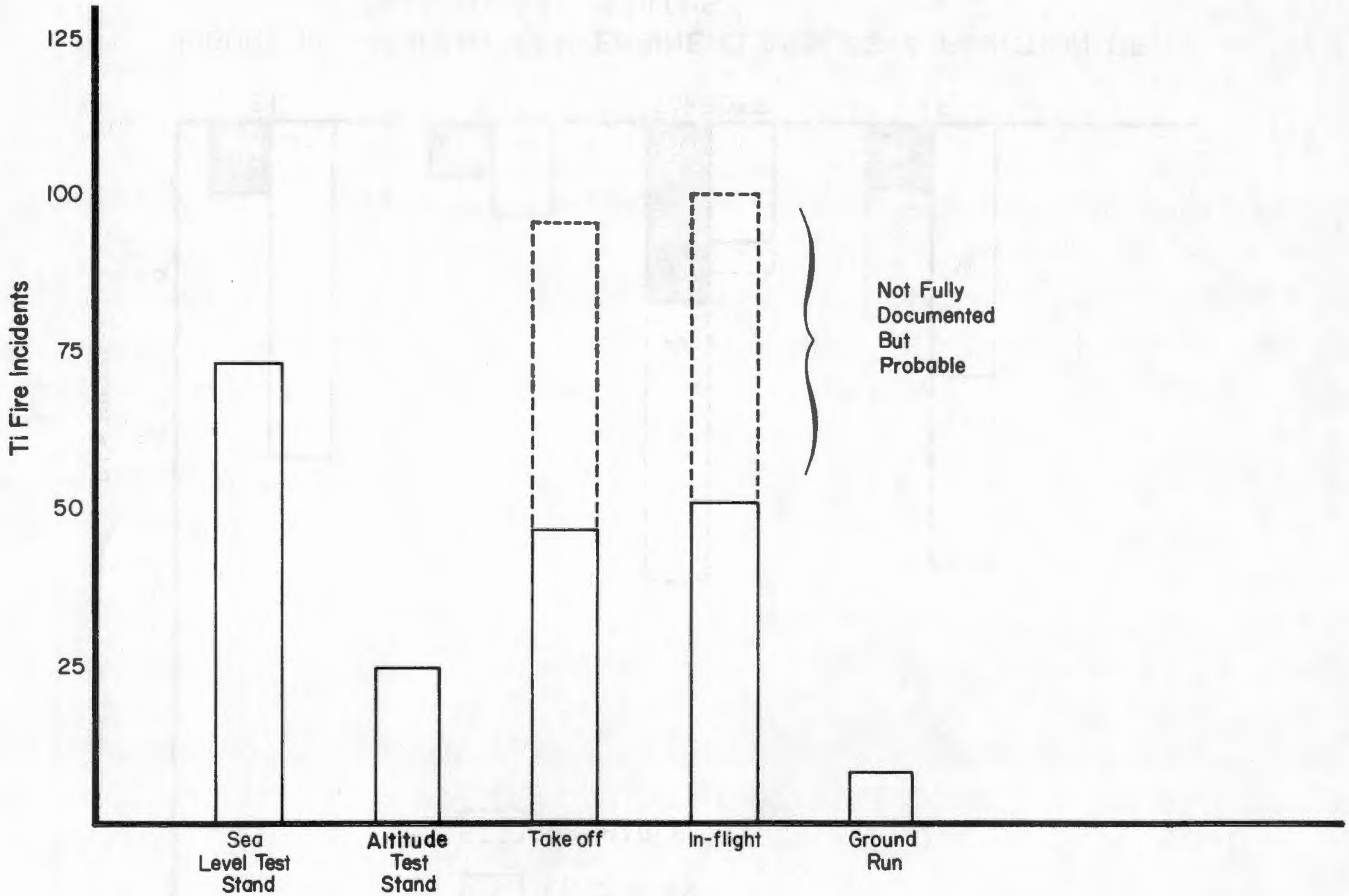

FIGURE 14 Fire Incidents as a Function of Operational Status

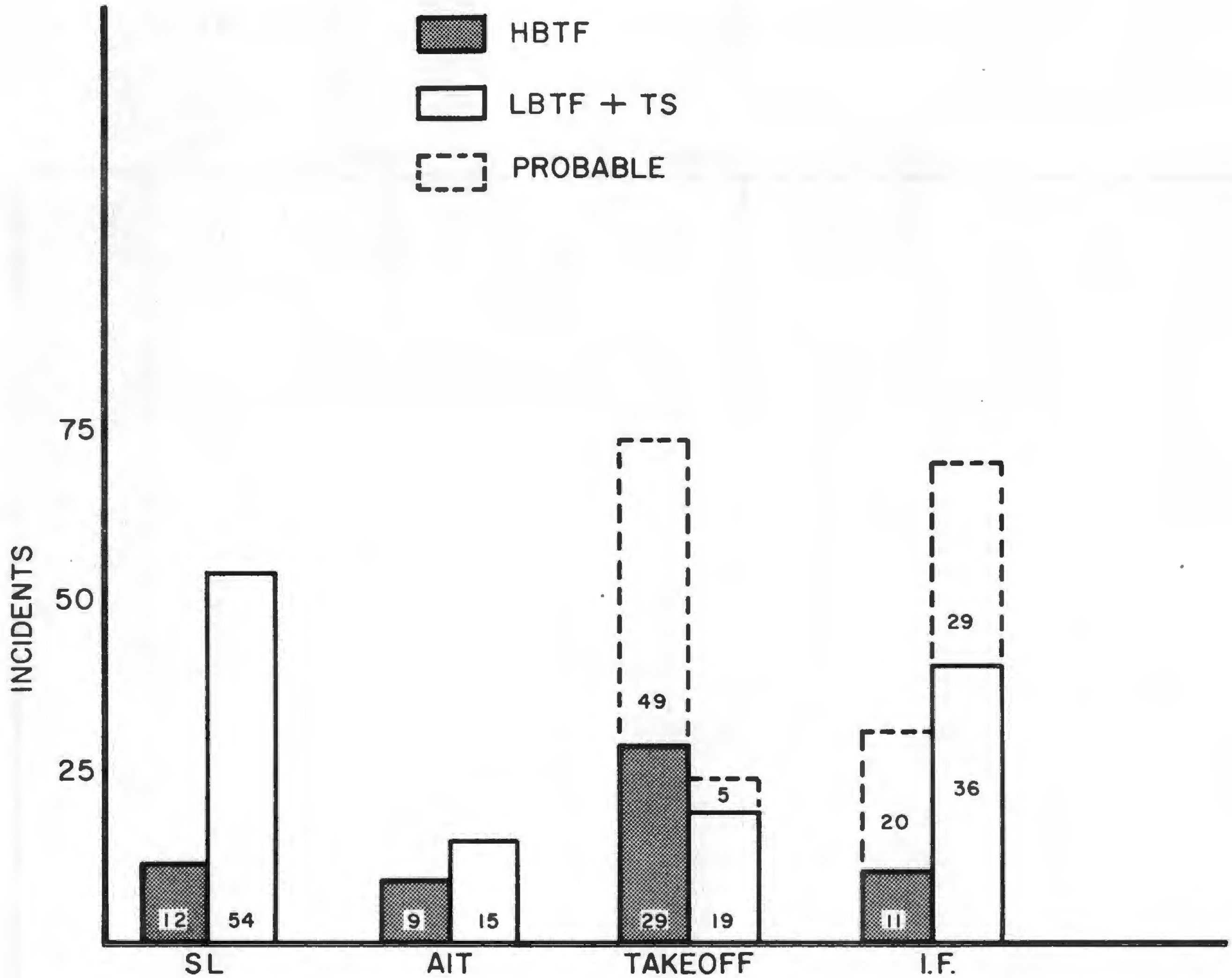

FIGURE 15: INCIDENT PER ENGINE CLASS AS A FUNCTION OF OPERATIONAL STATUS

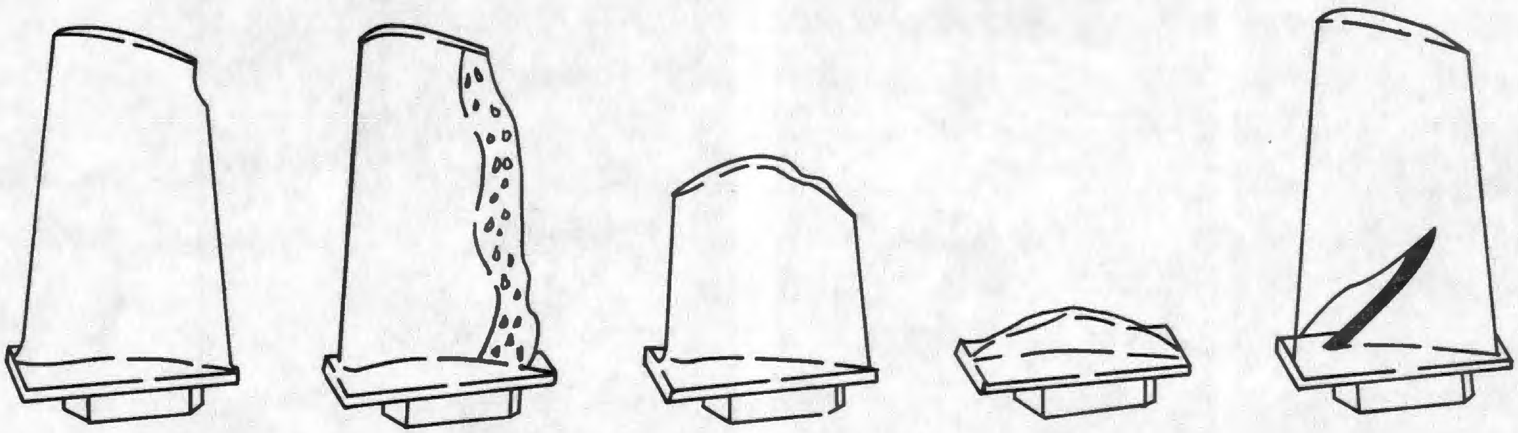

FIGURE 16 Typical Burn Patterns

FIGURE 17 Actual Burn Progression Involving Three Mid-Engine Stages

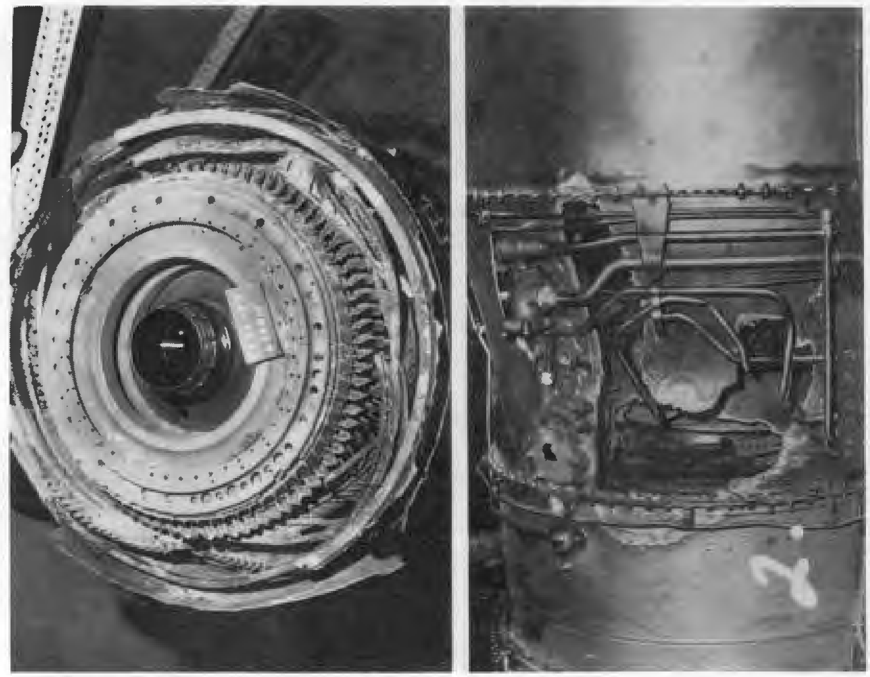

FIGURE 18 Typical Example of Case Penetration

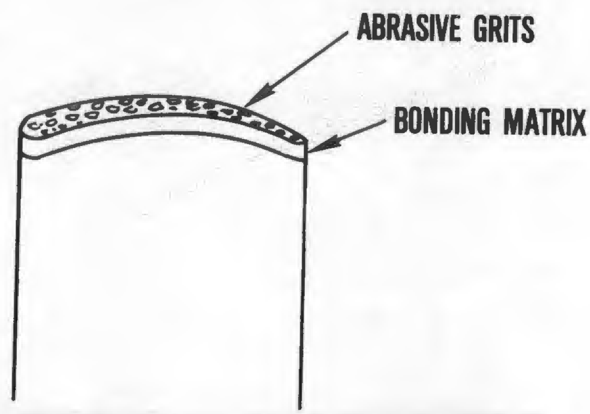

FIGURE 19 Abrasive Blade Tip

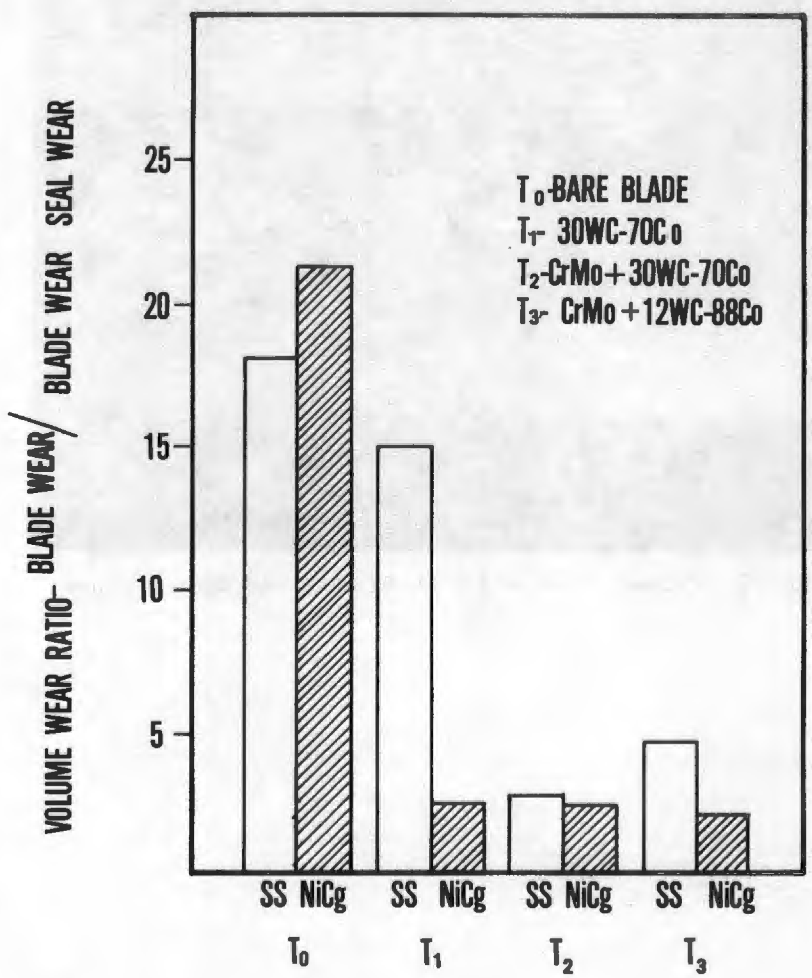

FIGURE 20 Comparative Wear of Blade Tip Treatments

FIGURE 21 Propagation with Ti Blades and Steel Vanes

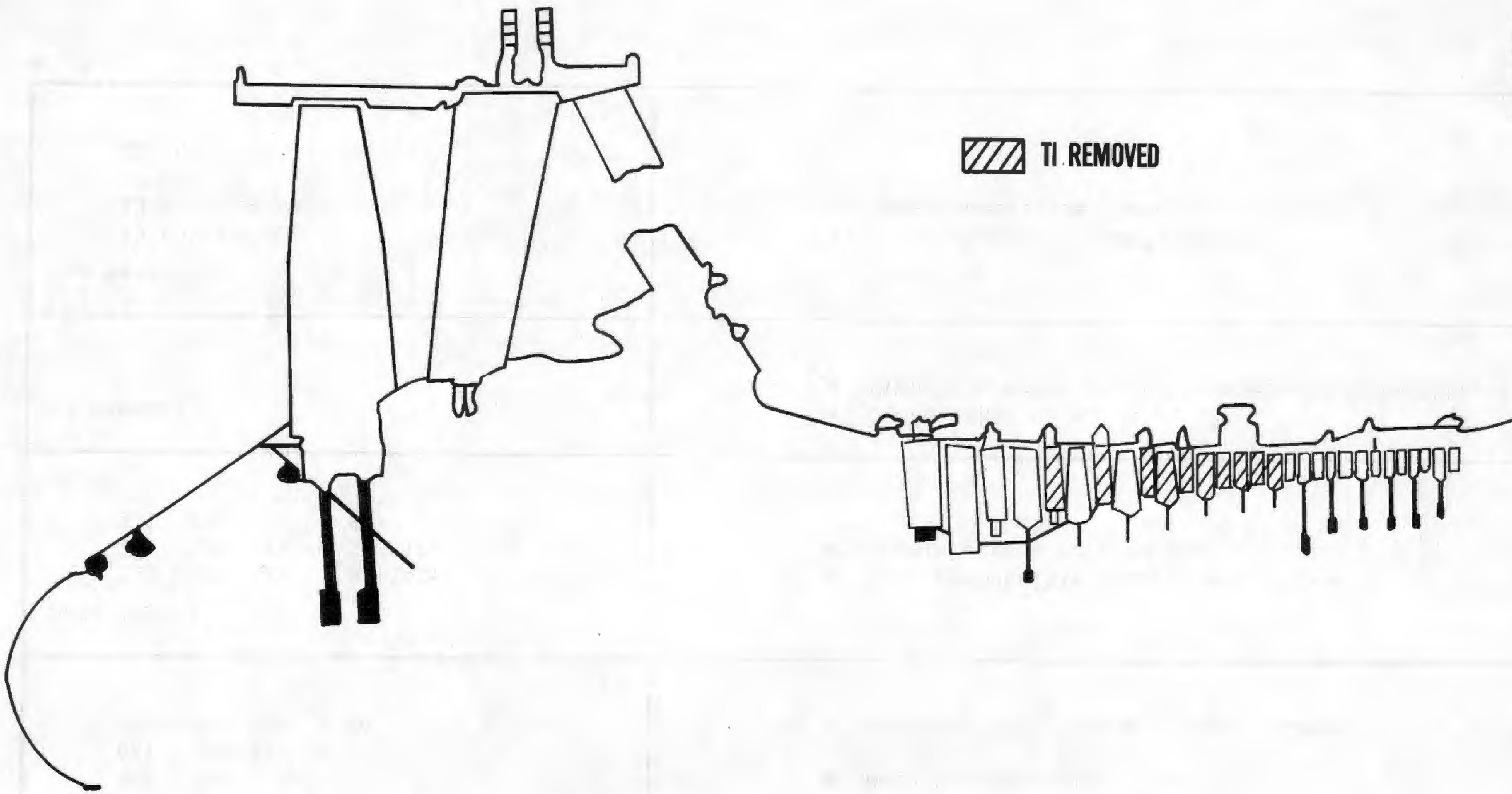

Figure 22. Typical Components Involving Titanium Removal

TABLE 3 TITANIUM ALLOYS

Common Alloys 6Al - 4V 8Al 1V 1 Mo 6Al 2Sn 4Zr 2 Mo 6Al 2Sn 4Zr 6 Mo	Remarks • Burn relatively easily • Burn Equally well • Commonly used turbine engine alloys
Beta Alloys 3Al 8V 6Cr 4 Mo 4Zr 3Al 8V 7Cr 4 Sn 1Zr 3Al 15V 3Cr 3 Sn	• Less combustible than common alloys • Possible vane or case application
Aluminides	• Combustible up to 24 wt. % • High Al content non-combustible/poor ductility
Low Melting 13 Cu 1.5 Al 13 Cu 5 Mo 9 Fe 11 Co	• Developmental castable alloys • Less combustible than common alloys

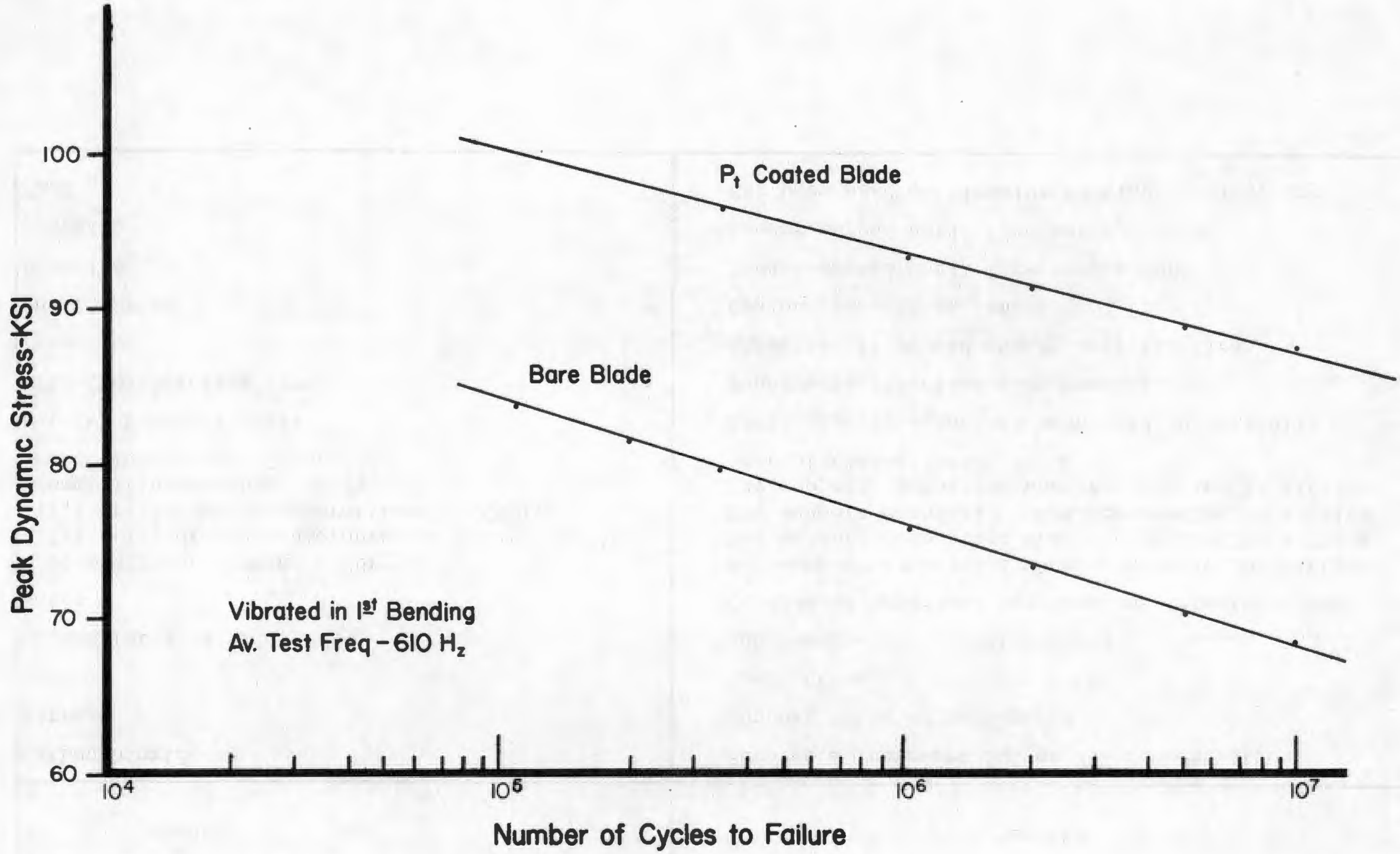

FIGURE 23 Fatigue Strength Improvement of Pt Coated Blades

TABLE 4 FIRE EXTINGUISHING AGENTS

Agent	Remarks
Carbon Dioxide	Burn rate increased 50% at 23% concentration
Nitrogen	Support titanium combustion
Foam	Ineffective for titanium fires
Carbon Tetrachloride	Ineffective for titanium fires
Water	Considered hazardous when used on titanium fires
Dibromadifluoromethane - $CBr_2 F_2$	May support combustion when accompanied by airflow
1,2,2 trifluoropentachloropropane $C Cl_3CF_2CFCl_2$	May support combustion when accompanied by airflow
1,1,1 trifluorobromachloroethane $CF_3CHBrCl$	May support combustion when accompanied by airflow
Bromotrifluoromethane $CBrF_3$	May support combustion when accompanied by airflow
Bromochloromethane CH_2BrCl	Best of the halogens
Met-L-X Powder - NaCl+	NAPA suggests agent has been used successfully
Trimethoxyboroxine (TMB)	Found more effective than Met-L-X
Pyrene G-1	Effective if spread evenly over the fire
Dow 230 Flux	Copious quantities can control fire
Dolomite	Powder spread until fire extinguishes
Graphite	Powder spread until fire extinguishes
Sand	Has been used on titanium turnings - fine, dry