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SHUTTLE-SAFETY: SOME REPRESENTATIVE PROBLEMS

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SHUTTLE-SAFETY: SOME REPRESENTATIVE PROBLEMS

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Abstract

Novel safety problems are introduced by the hybrid rocket vehicle/airplane presently called the space shuttle that relate to the durability required of its systems to serve 100 missions, the short service time between flights, it special engines, fuels and cargo. This paper samples some representative problems of which those who maintain the shuttle and certify it for flight readiness should be intimately aware. While most of these problems are known to designers exploring shuttle configurations, the point is stressed that those who must maintain and operate the shuttle must develop techniques and be trained in their use for judging its condition before flight. Methods and means for inspection, maintenance, and check-out must be recognized early in the shuttle design if accommodations must be made for them in the vehicle. This paper samples some of the problems and displays their technical content to alert those who will be concerned for shuttle safety that they will see some new problems which are peculiar to the shuttle and some old problems in aggravated form for which present solutions no longer hold.

Introduction

The safety of the space shuttle is being explored by highly competent technical teams who recognize that this hybrid rocket vehicle/airplane will require our best design performance to do the mission and meet the 100 flight life expectancy. In each of the many areas of safety concern experts are engaged who can anticipate the problems facing shuttle operation. Once the shuttle is placed in operation, however, those who maintain and operate it assume safety responsibility from the designers and fabricators who created the vehicle. Early familiarity of the maintenance and operational personnel with the special features of the shuttle, its mode of operation, and the peculiar cargos it may carry is required if they are to be ready for this responsibility. To make this point, this report displays the technical content of a few novel safety problems and some solutions which typify the shuttle and its mission. These problems though well understood by specialists in the separate fields have basic subtleties that are generally unknown or misunderstood. The selected problems relate to rocket engine durability, airbreathing engine life, fuel fires, structural integrity, and radioactive cargo.

Rocket Engine Durability

Control over the design and performance of the hydrogen-oxygen rocket is highly developed and excellent single flight reliability exists. Yet strong thrust perturbations in combustion chamber still stress engine components, and drive sustained oscillations in the propellant flow through vibrational coupling with the vehicle structure (POGO).

The rocket structure and machinery will be subjected to many cycles of high thermal and/or mechanical stresses in 100 flighrs which raise a serious fatigue and wear threat. Thrust chamber designs will be devised which have the potential for 100 flights, but the limited service experience with re-used motors will require heavy reliance on thorough inspection by nondestructive testing techniques. The accessibility of the thrust chamber components makes such inspection a relatively easy matter with fairly sophisticated inspection equipment.

Turbopump Bearings

However, the bearings of the propellant turbopumps, and more particularly, those of the hydrogen pump are vulnerable to failure within the interval of 100 flights. Major disassembly effort would be required to permit periodic visual inspection of the bearing. Heavy reliance will no doubt be placed on acoustical methods for assessing bearing health, since such methods are applied to the assembled machine.

A high degree of training is required of an operator of acoustical diagnostic equipment to enable him to distinguish that amount of bearing wear that requires bearing replacement from that which is tolerable.

To understand the limited life of the hydrogen pump bearing, it is necessary to recall that the liquid hydrogen which wets the bearing serves only to remove the frictional heat. Lubrication is provided by the subtle mechanism illustrated in Fig. 1(a) which is a sketch of a ball bearing typical of those used for hydrogen pumps. The feature of the bearing which suits it for hydrogen use is the ball retainer which is usually made of teflon reinforced with glass fibres within it. The teflon serves as a dry lubricant which transfers to the surface of the balls in rubbing contact with it, and from the balls to the bearing races. As long as the teflon film coats the races cold welding of the balls to the race metal is prevented and the bearing operates with acceptable coefficient of friction and wear. Unfortunately, the teflon coating on the races builds to a maximum thickness of several microns and then wears out. A typical history of the teflon film development and disintegration on the race is shown in Fig. 1(b). The profilimeter data in the figure show that the teflon film on the race builds for the first 284 minutes of operation. By 404 minutes of operation the teflon film is worn through and race surface damage has begun. These bearing operating times correspond to those one expects in 100 flights of the shuttle. Repair of this teflon film on the races by further transfer from the retainer via the balls is limited by the glass reinforcing within the retainer. Transfer of teflon to the balls from the retainer occurs until the surface teflon is worn away and the underlying glass fibre is exposed throughout the ball contact areas in the retainer (fig. 1(c)). Once bare metal is exposed on both the races and the balls cold welding between the two leads to progressive surface spalling which accelerates to bearing failure. The oxygen pump bearing spalls less readily when the teflon film is lost since the oxygen that wets the bearing oxidizes the surfaces of balls and races. The oxide film so produced serves as an anti-weld compound which slows the spalling rate. While bearings can run with some spalling, the remaining life becomes uncertain once spalling begins. For shuttle, the rule will probably be that no flight shall begin with known spalled bearings.

Since disassembly of the pumps for bearing inspection would be awkward and time consuming, the rocket engines may be designed for easy periodic replacement of the entire propellant turbopump or for application of diagnostic techniques which might be used to assess the bearing condition during turbopump operation. Diagnostic devices for monitoring bearings are usually acoustic pickups attached to the case of the turbopump adjacent to the bearing. Shuttle maintenance personnel must judge from the acoustic record made during a previous flight whether or not the bearing condition is adequate for the next flight. The ability to discern the necessary information from the record in spite of the accompanying high background nose level over a wide frequency range is yet something of an art. Considerable experience by maintenance personnel in this diagnosis technique should be obtained with the turbopump operating in the complete rocket engine during qualification runs if reliance on this diagnostic technique is to be part of the shuttle maintenance plan. Those experienced in this diagnostic technique apply it with considerable confidence; but let the novice beware.

Jet Engine Safety

The airbreathing turbofan for shuttle booster and orbiter is to be an advanced military engine having a turbine inlet temperature above 2000° F and to be powered by a conventional, or slightly modified, jet propulsion fuel. The high engine temperature makes turbine life sensitive to modest departures from optimum operating conditions and the flight profile of booster and orbiter requires special fuel system maintenance if flight fire with the jet propulsion fuel is to be avoided. A detailed understanding of both of these matters is important to effective safety surveillance.

Turbine Life

The turbine inlet gas temperature of the shuttle fan engine is to be several hundred degrees above the temperature (1750° F) at which the turbine vanes and buckets lose strength rapidly with further temperature increase. Air-cooling of the blades and vanes holds the metal temperature to 1750° F while the turbine inlet gas temperatures can rise above 2000° F with useful turbine life.

In typical cooled turbine, vanes and buckets contain air cooling passages, such as those shown in Fig. 2(a). Air drawn from the compressor enters the buckets at the root, or the vane at root or tip, blows through passages within the vane or bucket and is exhausted at the tip or the trailing edge as shown in the figure. A picture of a cooled blade, Fig. 2(b), shows the cooling air slots at the trailing edge.

Blade life is limited by stress rupture through long time application of tensile loads, and by thermal low cycle fatigue and oxidation from the hot turbine gas stream. Blade life declines rapidly with increasing metal temperature for all three threats to the blade. While the decline in stress rupture life with temperature is clearly related to the reduction in tensile strength, the reasons for more serious low cycle fatigue and oxidation problem with high temperature turbines are less obvious and merit some discussion here.

Failures by low cycle fatigue show as chordwise cracks on the leading and trailing edges of the turbine blade. Typical leading edge cracks are shown in Fig. 3. These cracks are the result of alternating compressive and tensile stresses produced by the more rapid temperature change of the leading and trailing edges as compared with the rest of the vane or bucket when turbine inlet gas temperature is changed. The more rapid edge heating during engine acceleration places the leading edge in compression since it is constrained from its normal expansion by the cooler bulk of the vane or bucket. At the high blade temperature permanent plastic deformation of the edge occurs under the force of this compressive load. When the engine is decelerated the leading edge cools more quickly than the rest, but it is kept from shrinking by the warmer bulk of the remainder of the blade. This places the edges in tension. Such compression-tension cycling is responsible for the thermal (low cycle) fatigue cracks in Fig. 3. The higher the turbine inlet air temperature, the greater the transient temperature differences between the edges and the rest of the blade are apt to become. Also, small departures from normal conditions of blade cooling can increase the thermal gradients on the blade and aggravate the thermal fatigue problem.

As turbine inlet gas temperatures are raised, the more complex do the cooling channels within turbine blade become to minimize temperature gradients. For blades which must operate at turbine inlet gas temperatures above 2000° F, one approach for cooling the vulnerable leading edge employs slots or holes around the leading edge through which air issues from the blade interior to provide cool films along the adjacent exterior surfaces. Application of the cool-film principle to a turbine vane is shown in Fig. 4. These slots have narrow flow passages, which raise anxieties about clogging and consequent excessive local metal temperatures and its adverse effect on stress rupture, low cycle fatigue and blade oxidation. Likewise, these slots and holes, representing discontinuities in the blade material, can serve as sites for crack initiation.

With regard to blade oxidation, the key to blade life is the oxidation resistant coating which protects it. While many forms of coating are studied experimentally, those in use for high temperature blades are formed on the blade surfaces by chemical reaction of the blade material with the ingredient that confers oxidation resistance. For nickel base blade alloys, for example, the coating can be nickel aluminide formed by chemical reaction of the blade metal with an aluminum salt to produce a coating 0.003 in. thick, as shown in the photomicrograph of Fig. 5. The photomicrograph shows the coating to be an integral part of the blade metal since it is formed from it. All surfaces, including those which form the internal cooling air flow channels, must be coated uniformly to resist oxidation. Achieving quality coatings requires highly refined techniques.

Unfortunately, the coating is itself vulnerable to oxidation through the formation of Al_2O_3 which flakes off the surface. The marked dependence of the coating life on metal temperature is shown in Fig. 6(a). These data, taken from realistic tests of blade coating which simulate blade temperature histories and surface erosion by high velocity gases, show that coating life halves for each 60° F increase in surface temperature. Since blade failure follows shortly after coating failure, one can judge that the desired 500 hour blade life requires that metal temperature must not exceed 1850° F anywhere on the vanes or buckets. This rise in metal temperature to 1850° F can occur quite easily if blade cooling effectiveness is lost, or a combustor failure produces zones of excessive temperature in the turbine inlet gas. The characteristic progressive deterioration of a surface coating of CoAl on cobalt super alloy is shown in Fig. 6(b). The change from a tight coating impervious to oxygen penetration to a porous and fractured film is evident in the figure.

Ironically, the very coating devised to protect the blade from embrittlement by oxidation can itself threaten the blade with failure by embrittlement. This embrittlement appears as the progressive precipitation of sigma phase needles in the basic blade material immediately below the coating, as shown in Fig. 6(c). While the metallurgy of the sigma phase formation is poorly understood, it is believed to be due to the diffusion of constituents of the protective coating into the adjacent base material. Since the rate of this diffusion increases rapidly with metal temperature, the requirement to maintain fine control over blade temperature is emphasized again.

Flaw Detection

These considerations of the sensitivity of blade life to small departures from normal engine conditions suggest that careful inspection of the engine at frequent intervals should be practiced, particularly during the early days of their use. Because of the high cost of the intricate cooled turbine blades and their replacement time, the urge to maintain them in service following inspection will be great. For this reason, a nondestructive testing technique is desired which gives an estimate of the remaining blade life. Since no testing method is available now, estimates of remaining life will have to be made on the basis of visible blade damage, particularly cracks. For uncooled blades, which are usually solid, most cracks show on exterior surfaces and a judgment based on experience can be made as to whether or not the blade may be restored to use by simple repair. The cooled blade may develop cracks which run to internal surfaces and require X-ray inspection for detection.

Fortunately, a marked improvement in crack detection by X-ray is available through the use of an optical separation technique for analyzing radiographs, which are heavily exposed to reveal fine detail. The detail that is lost to the eye viewing a dense radiograph is made visible by the optical process which differentiates the various degrees of grey on the radiograph with far greater resolution than is possible by eye.

In this technique, a set of pictures, derived from the radiograph, is made on high contrast film. Each picture of the set contains the portion of the image on the radiograph whose intensity (depth of grey) lies between narrow limits. A separate picture is made at each intensity level of the image. The high contrast film exaggerates small differences in the depth of grey of the image on the original radiograph to reveal details that cannot be detected by eye on the original. A comparison of the original radiograph of a portion of wing spar, Fig. 7(a), with a separation made from the same radiograph, Fig. 7(b), shows a clear crack in one of the holes in the separation that is barely suggested in the original radiograph. Flaw discrimination advantage provided by the method is far greater than is illustrated here. The ability of the eye to detect flaws is enhanced if each separation picture is printed in a different color and a composite multicolored print is produced from them. The flaws show more readily because they have colors which contrast with the surroundings. NASA is cooperating with USAF to develop a convenient device which provides these inspection advantages. The device is useful for reading information from any radiograph regardless of the radiation used to produce it.

Jet Fuel Problems

The recent decision to power the turbofan with jet fuel rather than hydrogen suggests the value of reviewing some salient safety problems that relate to the choice of fuel tank system. The following remarks on fuel system safety are made on the assumption that the desire to minimize the weight of the shuttle will ultimately dictate a fuel system along conventional airplane lines, modified to the extent that a fuel tank vent closure will allow penetration into space while the tank pressure is maintained at several pounds per square inch absolute to suppress fuel boiling. If this proves to be so, then the subjects of fuel tank fires and fuel loss hazards explored for the supersonic transport have meaning at this time to guide the system design, since both airplanes are designed for high altitude flight and are subject to aerodynamic heating.

Ignition of fuel vapors in the tank vapor space by aerodynamic heating was indicated in laboratory studies simulating flight conditions of Mach 3 and above. In these studies tank fuel (JP-4, 5, etc.) was heated to 450° F to simulate the fuel temperature in near-empty tanks that were subject to many minutes of aerodynamic heating. Air in the tank ullage contained fuel vapor which varied from well within the combustible range to well beyond the normal rich combustible limit for hydrocarbon-air mixtures. With mixtures in the normal combustible range fires occurred at temperatures of about 450° F and above for all classes of jet fuels. Beyond the rich limit for hydrocarbon-air mixtures "cool" flames were observed in the tank at the same temperature. These "cool" flames are luminous manifestation of low grade oxidation reaction of the hydrocarbons. They produce pressure changes in the tank that vary from negligible to several times the initial tank pressure if the initial pressure exceeded 4 psia (fig. 8). For fuel tank designs typical of aircraft, this pressure rise imposes serious stresses on the tank structure.

Transition from "cool" to normal flames occurred in these experiments when air entered the tank vent at a rate which simulated an emergency descent of 8000 ft a minute or more. The extreme danger presented by such flames needs little comment.

If the fuel tanks in the shuttle booster and orbiter will be so located that the temperature of all the tank surfaces will be held below 450° F, then the fire threat just described does not apply. However, fuel-tank sealants may have limited life if they are allowed to cool to temperatures which shrink or embrittle them after cold soaking in space and then to be warmed on entering the earth's atmosphere. The fuel leakage problems that plagued the B-70 may reappear for the shuttle. If fuel leakage into uninsulated bays of the airplane occurs, then each fuel-wetted bay could be the site of ignition of the type just described during descent through the atmosphere.

A further fuel system anxiety relates to the release of gases dissolved in the fuel during the rapid climb from launch. Since oxygen dissolves preferentially in hydrocarbon fuels, the oxygen and nitrogen mixture evolved from solution during climb are richer in oxygen than is air. Because of this oxygen enrichment, the tank ullage contains fuel-vapor-air mixtures that are in the combustible range to higher altitudes than would normally exist without such enrichment. The combustible mixture fuel-air which flows from the fuel tank vent is vulnerable to ignition by lightning strikes to the vent area for a long period of the climb.

Also, the oxygen and nitrogen evolved from solution during climb from launch may cause the loss of substantial volumes of jet fuel from the tank vent. This undesirable prospect stems from the tendency for the fuel to delay the release of dissolved gases in climb until the fuel is highly supersaturated with respect to the air pressure in the tank ullage. A violent evolution of dissolved gas occurs throughout the fuel volume when desorption from the highly supersaturated state begins. The accompanying expansion of the gas bubble-filled fuel may overflow the tank through the vent. Unless a large initial ullage is provided, the fuel loss may be critical. The magnitude of this fuel foaming-over problem cannot be judged from airplane experience because the shuttle will climb far faster and attain higher altitudes (lower tank pressures) when desorption occurs. Fuel tank pressurization to levels high enough to avoid this problem might impose an unacceptable tank structure weight penalty.

The danger that incendiary electrostatic sparks within the tank may accompany violent fuel foaming remains a nagging uncertainty. Oxygen enrichment of the evolved gases improves the probability that a combustible atmosphere may exist. Control over electrostatic generation under these conditions is poorly understood. Each year one or more airplanes experiences a fuel tank fire laid to electrostatic sparks generated within the fuel system.

In order to eliminate all fuel tank fires threats it is recommended that shuttle designers and operators consider inerting the fuel and tank ullage in the following way. First, strip the dissolved gases from the fuel in a ground-based facility just prior to loading on the shuttle. One of the several types of facilities for doing this is shown schematically in Fig. 9. In the figure the fuel to be stripped is contained in a tank which is connected to a suction source. A manifold is installed at the tank bottom for distributing finely divided bubbles of nitrogen gas uniformly across the tank. Means for providing such uniform distribution with simple nitrogen manifolds are available from the aircraft accessory industry. During the stripping operation finely divided nitrogen gas bubbles are caused to rise through the fuel while the tank pressure is lowered by the suction source. The nitrogen bubbles stimulate the early release of dissolved gases by providing a dense population of desorption centers (nuclei). The tank pressure is decreased gradually to a value equal to or slightly less than the minimum pressure of the ullage during flight. The oxygen and nitrogen that remain in solution are in equilibrium at this pressure and will not come out of solution at higher pressures. The fuel so treated may now be loaded on the shuttle shortly before flight using nitrogen as a cover gas to prevent further contact with oxygen. Since the solution of nitrogen into fuel is slow, the benefits from the stripping treatment will be preserved for a useful time.

It is recommended further that a small quantity of nitrogen, perhaps as liquid, be carried on the shuttle to control the fuel tank pressure without the need for ingesting air during descent and when fuel is withdrawn for the engines in the flight back to land. All anxieties about fuel tank fire would be resolved by maintaining an atmosphere of nitrogen in the tank.

Miscellaneous Anxieties

Aluminum Oxygen Tanks

The liquid oxygen tanks for shuttle will be aluminum, according to present plans. While most compatibility tests show aluminum to be safe with liquid and gaseous oxygen, aluminum oxygen tanks do burn occasionally. A recent fire and explosion of an aluminum truck-mounted oxygen dewar is shown in Figs. 10(a) and (b). The wall thickness of the tank is about 3/4 in., designed for a working pressure of 200 lbs/in.^{2}. That a fire preceded the explosion is evident from the material burned and melted from the once near-circular baffle from the dewar shown in Fig. 10(c). The oxygen carried was of high purity used for hospital breathing oxygen. This accident occurred just after a hospital liquid oxygen tank was filled and the truck was beginning to draw away. This was a new tank which was filled about 25 times in service, well within the 100 projected uses of the shuttle booster. The cause of this fire has not been determined, but since it did not occur on first use, repeated use probably contributed to developing the condition that led to the fire. This accident suggests that the techniques used to ensure freedom from fire danger in one-shot systems must be augmented for multiple use systems. Accordingly, it is recommended that the shuttle oxygen tank be designed to permit:

1. Careful cleaning following assembly.
2. Periodic inspection of internal tank components for structural integrity and cleanliness.
3. Quality repair, inspection and cleaning by man access into the tank through manways.

Space Radiation

While the danger from space radiation to men and materials is the subject of careful study, the effect of this radiation on certain classes of safety instrumentation is sometimes overlooked. Recent estimates show that in some regions of the orbit desired for the shuttle the radiation within the vehicle can be high enough to introduce spurious signals into monitoring systems. Radiation produces these signals by stimulating electron emission in sensing equipment, by ionizing the space between instrument electrodes, or by exposing photosensitive plates. A partial list of the types of common sensing elements which can be stimulated by radiation includes photomultiplier tubes, ion chambers, Geiger tubes, and scintillation crystals.

For some instrumentation systems such stimulation may increase the system noise to the point where the signal-to-noise ratio is unacceptable. For others, such as ultraviolet fire detectors, the signal stimulated in the detector could produce a false fire warning. Likewise, smoke detectors which measure the change in the electrical conductivity of the atmosphere under surveillance, can be upset by levels of ionizing radiation which might prevail. Means for radiation protection or methods for cancelling radiation induced spurious signals are an essential part of the instrument development. Failure to cope successfully with this problem can render useless an otherwise desirable instrument.

Likewise, transistors, initially in marginal health, may degrade rapidly to a useless condition. Vital standby circuits which are rarely used, and which may contain marginal transistor, should be checked periodically for assurance that all is well.

Orbiter Reentry

The operation of the turbofan engines and associated accessories on entry into the atmosphere following a period of several weeks soaking in the vacuum of space will require considerable study to ensure performance reliability. Fuel regulators, engine accessory bearings and gears, and oil scavenge pumps are particularly vital machine components which must operate satisfactorily from a dry state without hesitation as soon as the engines are started. Failure of the fuel regulator to respond quickly may produce hot engine starts that could over-temperature combustors and turbines to limit their reliability and life severely. While lubrication can be provided to main bearings rapidly on engine start, since the oil will be carried in pressurized tanks and the oil pressure pump can function immediately, the bearings and gears of accessories, particularly the engine starter, may operate dry at high load for a period long enough to wear unduly. Likewise, the engine oil scavenge pump will be required to operate dry and unprimed at the low pressure of 40 000 feet altitude when the engines are being started. Unless special provisions are made to ensure that the scavenge pumps operate quickly oil might be lost to the engine airstream by leakage through bearing and sump seals. Since these oils are synthetic and may contain chemically active additives, their appearance in the main engine stream may raise corrosion problems in the hot section of the engine.

Radioactive Cargo

Highly radioactive spent reactor fuel elements and radioactive isotopes sometimes will be part of the shuttle cargo in logistic support of an orbiting space base. Means must be devised to contain these radioactive materials should the shuttle experience a violent crash. Current experiments on containment of nuclear materials are proving the point that such containment is possible with reasonable structures which withstand the maximum credible crash impact.

One of several successful spherical vessels is shown in Fig. 11(a). The outer shell, having a diameter of 2 feet, is made of 5/8 in. thick steel. A solid sphere about 1 foot in diameter, concentric with the outer shell, represents the radioactive cargo. The space between this sphere and the outer shell is filled with saddle-shaped metal chips. Water fills the voids between the chips. Impact tests of the containment vessel are conducted by supporting the vessel in the path of a sled-mounted concrete block which is rocket propelled to impact speeds. The progressive deformation of the vessel upon impact with the concrete block is shown in Fig. 11(b) for an impact speed of 480 feet/second. The vessel deforms without failure of the outer shell. The reinforced concrete block is heavily damaged.

Because radioactive materials generate heat continuously, cooling loops may have to penetrate the containment vessel to maintain safe temperatures. The design of penetration arrangements which do not detract from the crash resistance of the vessel is the next step in the development of this technique for safe transport of radioactive materials. The work is presently being conducted by those who are exploring the feasibility of a nuclear airplane.

Auxiliary Power Units

Present plans call for several auxiliary power units to be operating on the orbiter and booster when they land. These power units burn hydrogen in oxygen, with hydrogen in excess to limit flame temperature. When this excess hot hydrogen is exhausted to the air it may produce a barely visible flame characteristic of burning hydrogen. Either the hydrogen should be consumed with a large excess of air in an afterburner to provide a hydrogen-free exhaust of moderate temperature, or the burning hydrogen should be made visible by additive injected into the hydrogen as it is released to warn those operating close by.

Concluding Remarks

Many of the safety issues raised in this report will be attended to in the shuttle design and some may not be pertinent to the final configuration. However, those charged with the maintenance and safety of the shuttle operation need to understand the novel features of the shuttle and its operation that must claim their attention now. If short turn around times of a few weeks are to be a shuttle requirement, then maintenance and safety may require special accommodation in the basic vehicle design which permits rapid assessment of its condition in all respects, and easy correction of deficiencies. Now is the time for maintenance and safety to become aware of their future problems in operating the shuttle and make their needs known to the designer. This paper attempts to foresee some of these problems. Their total scope cannot be listed until a design is finalized.

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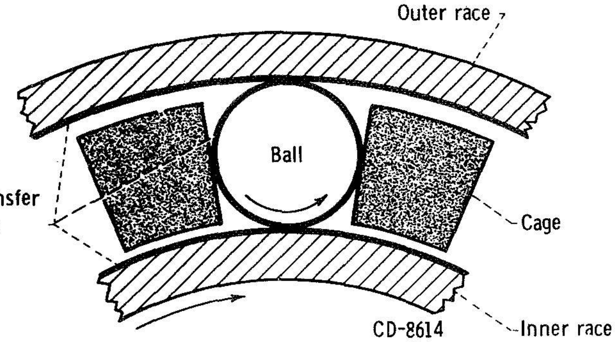
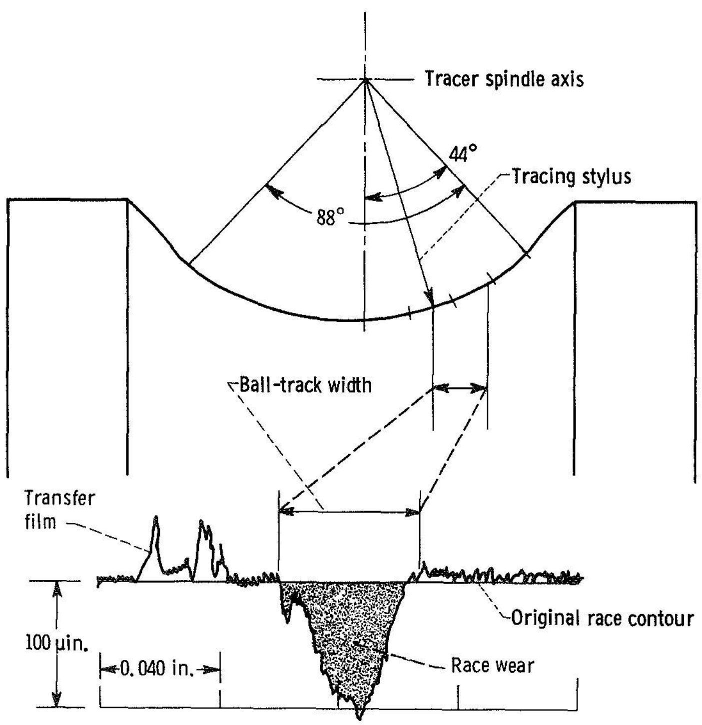
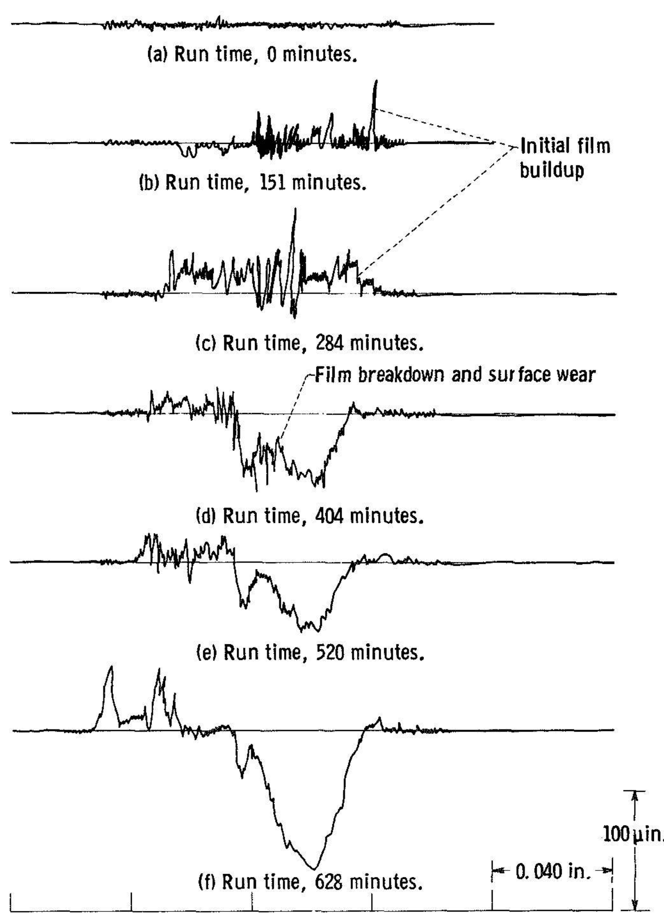


Figure 1(a). - Teflon lubricated bearing.



Profile trace of bearing inner race normal to ball-rolling direction.



Progressive profile traces of inner-race groove (normal to ball-rolling direction). Cage material, 38 percent glass-cloth with 62 percent Teflon binder; shaft speed, 20 000 rpm; thrust load, 200 pounds; coolant, hydrogen gas at 60° R.

Figure 1(b). - Inner race surface history.

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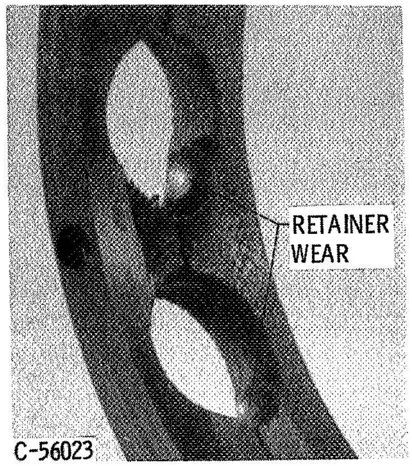

Figure 1(c). - Retainer wear.

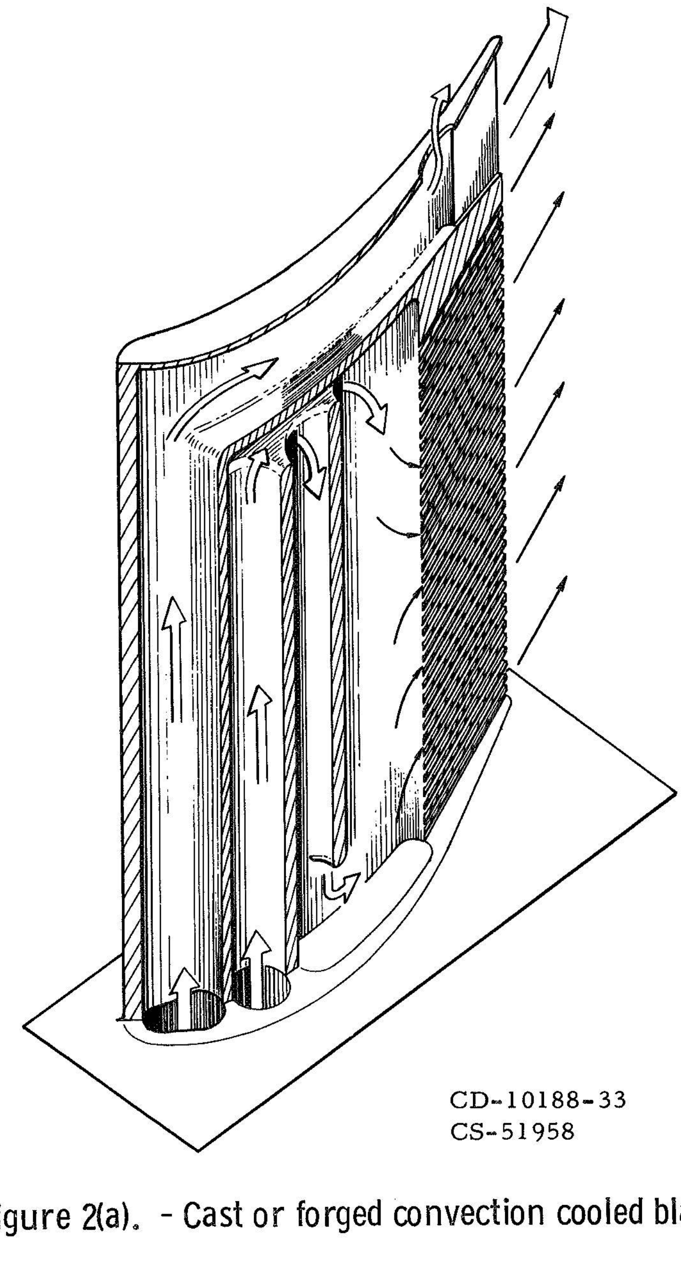

Figure 2(a). - Cast or forged convection cooled blade.

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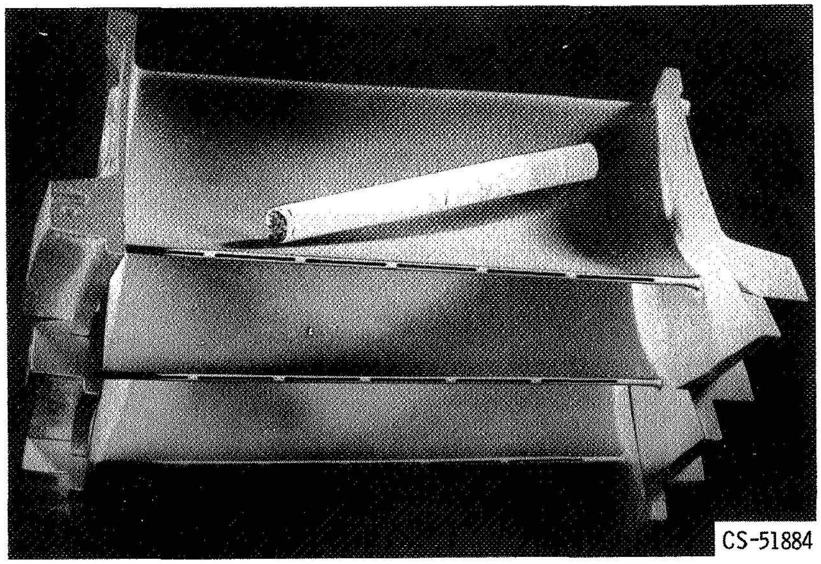

Figure 2(b). - Trailing edge cooling air exhaust slots on turbine blades.

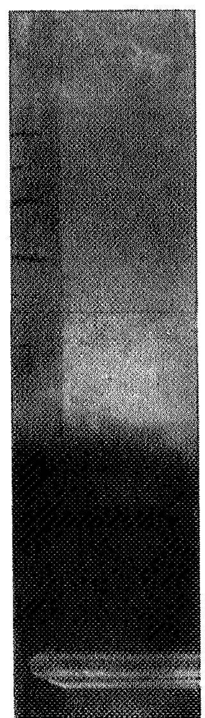

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Figure 3. - Thermal fatigue cracks on turbine blade leading edge.

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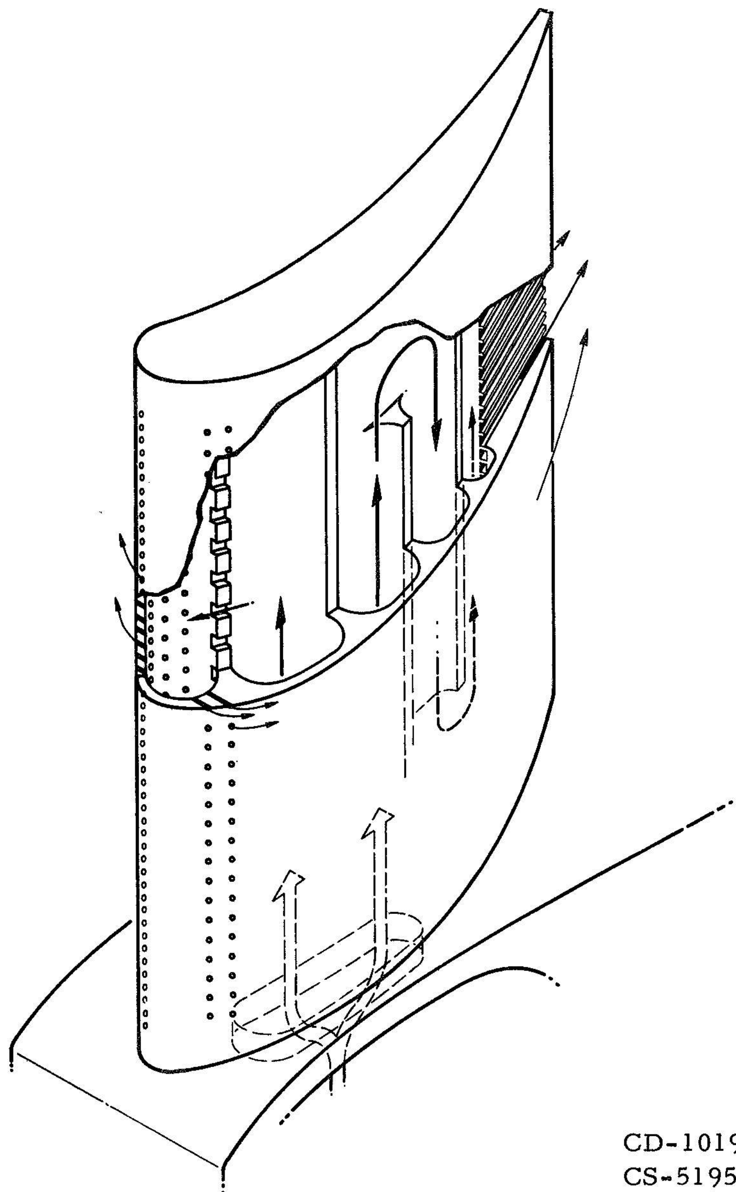

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Figure 4. - Film and convection cooled blade.

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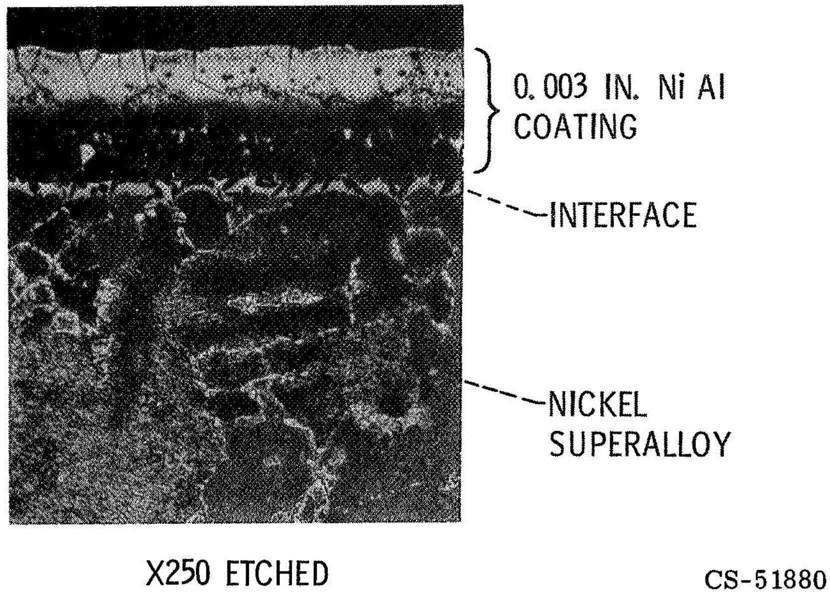

Figure 5. - Cross section-aluminide conversion coating.

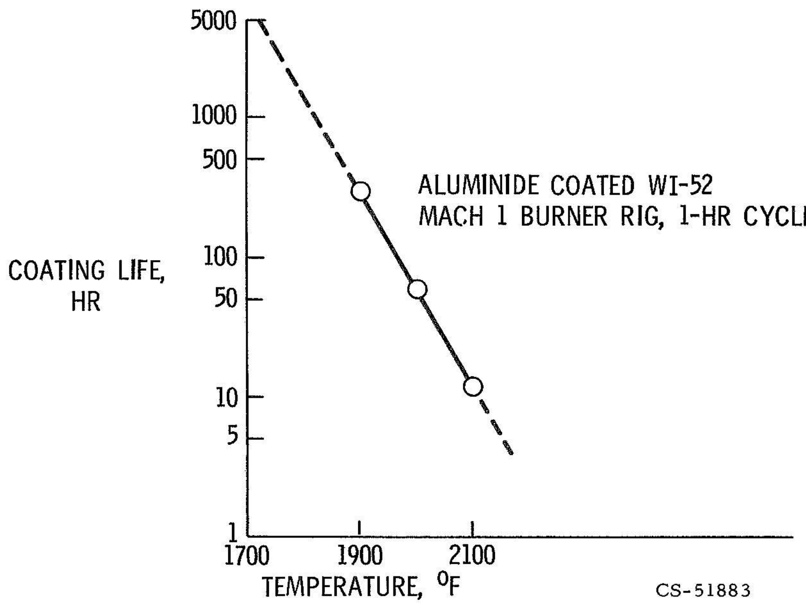

Figure 6(a). - Coating life, 1 hour cycles.

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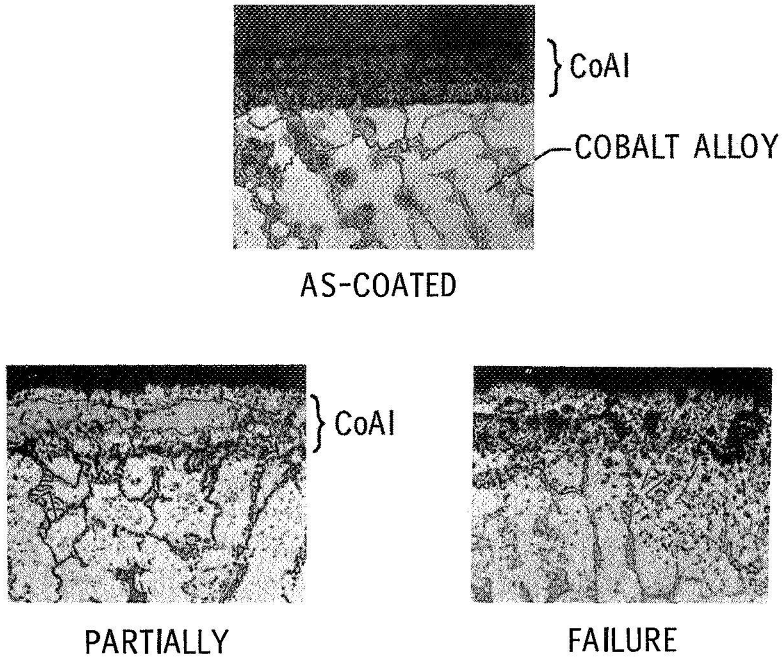

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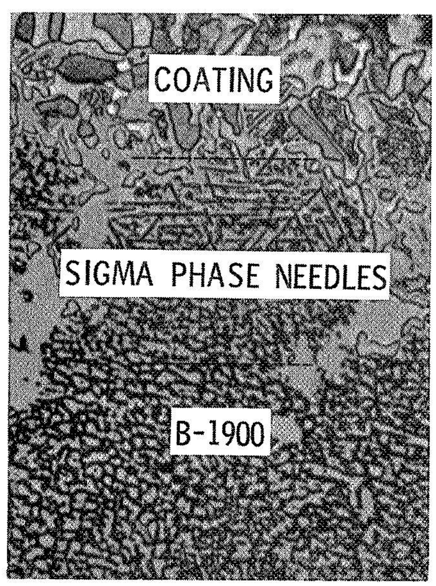
Figure 6(b). - Coating degradation.



SIGMA PHASE PRECIPITATE BENEATH AN ALUMINIDE COATING ON B-1900: 100 HR AT ~1850^{0} F (X1400)

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Figure 6(c). - Blade embrittlement by sigma phase precipitate.

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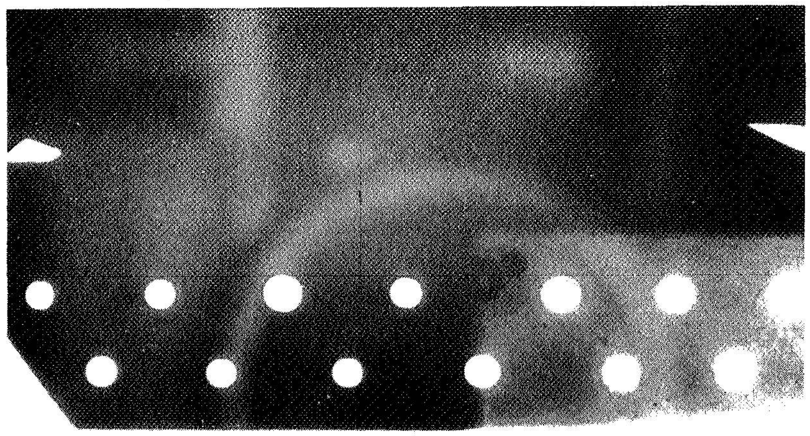


Figure 7(a) Radiograph of wing spar.

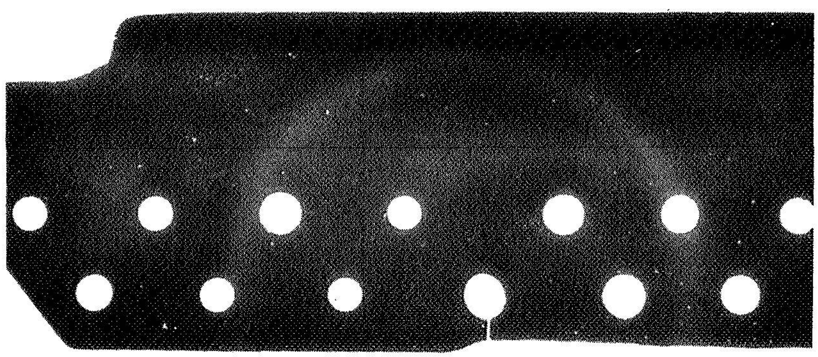


Figure 7(b). - Optical separation radiograph reveals clear crack.

E-6166

FUEL TANK PRESSURE BEFORE IGNITION, LB/IN.^{2}	FUEL TANK PRESSURE RISE DUE TO "COOL" FLAME, LB/IN.^{2}	$\frac{P_{final}}{P_{initial}}$
1	0.1	1.1
2	.4	1.2
3	1.7	1.6
4	6.0	2.5
4.8	10.0	3.1

Figure 8. - Fuel tank pressure rise produced by "cool" flames.

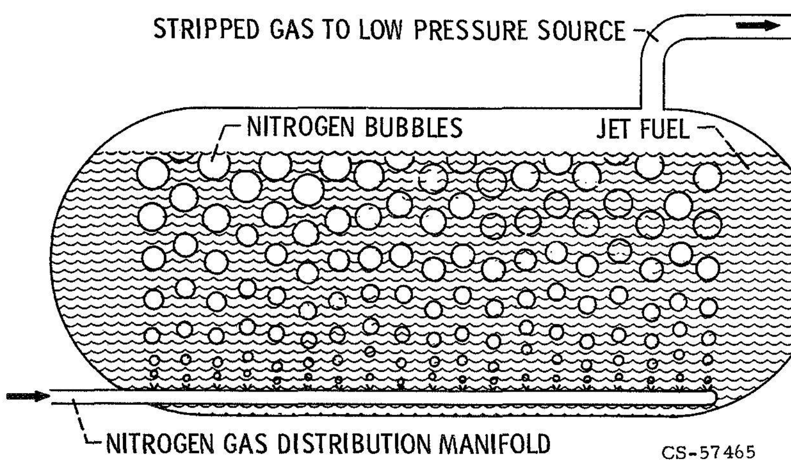
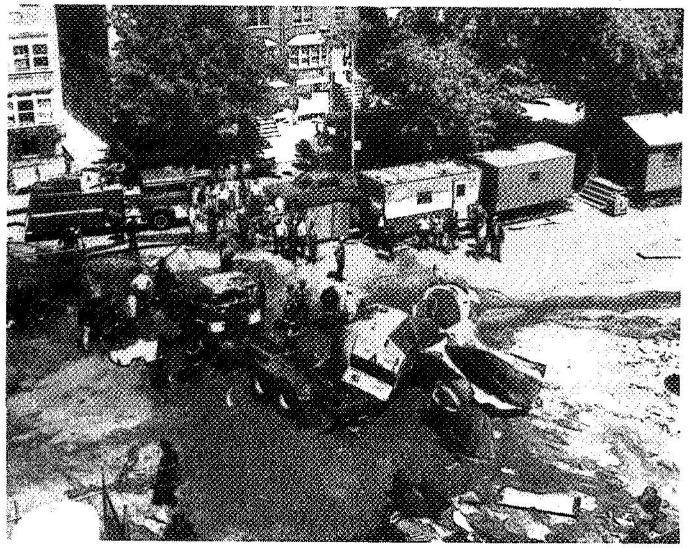
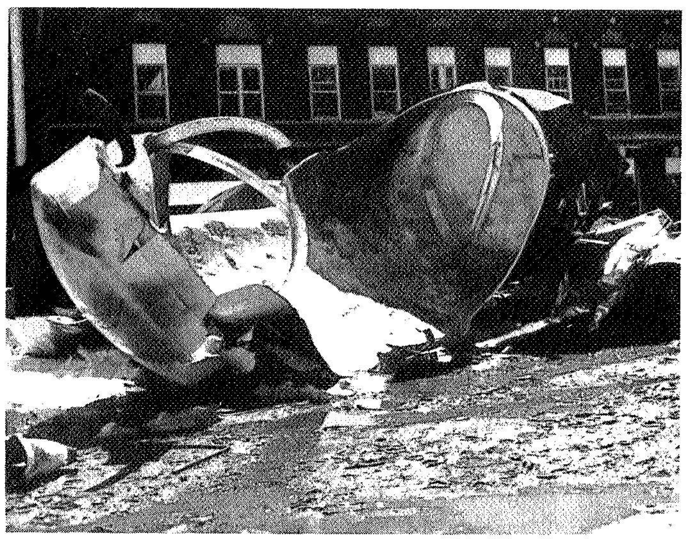


Figure 9. - Dissolved gas stripper for jet fuel.

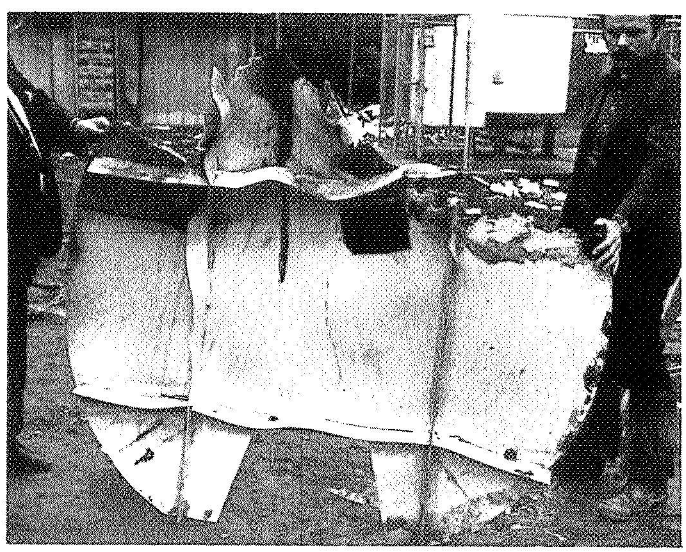
E-6166



(a) Long view. C-57452



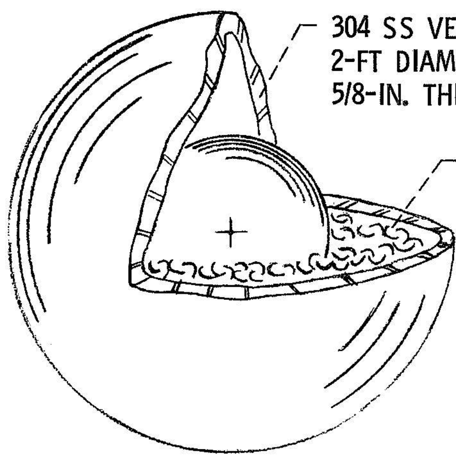
(b) Close-up. CS-57453



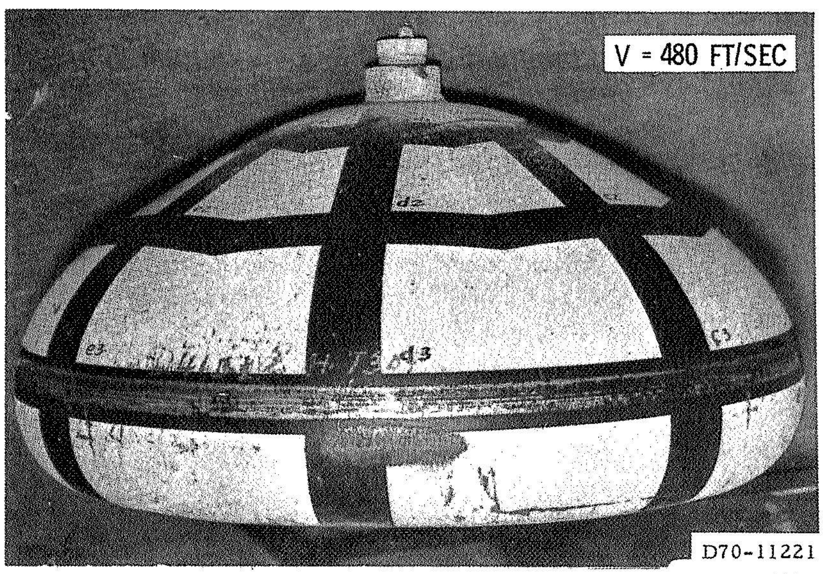
(c) Burned baffle. CS-57461

Figure 10. - Aluminum tank explosion.

BEFORE



AFTER



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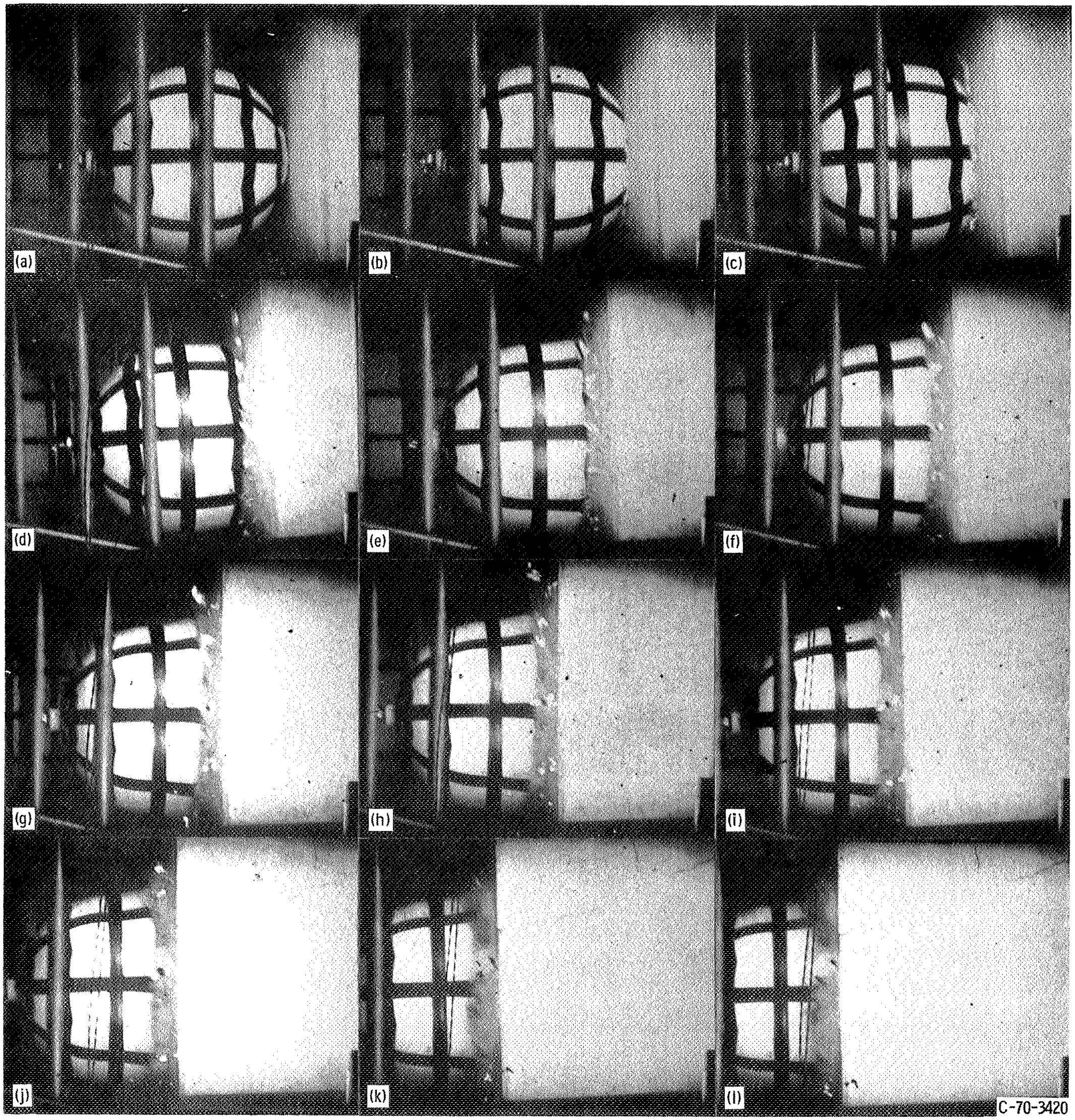
CS-57463

Figure 11(a). - Crash resistant containment vessel structure.

E-6166



CS-57464

Figure 11(b). - Sequence photographs at impact of containment system model.