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Technical Report **R 530**

PORTABLE TOTAL ENERGY PACKAGE FOR ADVANCED BASE FUNCTIONAL COMPONENTS

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NAVAL FACILITIES ENGINEERING COMMAND

NAVAL CIVIL ENGINEERING LABORATORY

Port Hueneme, California

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PORTABLE TOTAL ENERGY PACKAGE FOR ADVANCED BASE FUNCTIONAL COMPONENTS

Technical Report R-530

Y-F015-12-06-902

by

John S. Williams

ABSTRACT

Under consideration is the concept of a total energy package consisting of a gas-turbine-driven generator and a waste-heat boiler for use in the advanced base functional component system. The results of a survey show that a total energy package will probably not provide balanced heat and electrical energy demands, making the small gas turbine a poor logistic and economic choice for a prime mover. Suggestions are offered for the utilization of waste heat from diesel generators, where feasible. Included in the report as an Appendix is a literature study of high-temperature corrosion of turbine blading in a marine atmosphere.

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INTRODUCTION

The concept of a total energy package has received considerable attention during the past several years. The package is usually conceived as consisting of a gas-turbine-driven electric generator and a steam generator that uses the exhaust gas as a heat source. A popular application has been the furnishing of power and year-round air conditioning for commercial complexes, such as shopping centers and public schools.

In 1962 the Naval Civil Engineering Laboratory (NCEL) was directed by the Bureau of Yards and Docks (now the Naval Facilities Engineering Command) to award a contract for the development of a multipurpose mobile utility plant conforming to specifications furnished by the Bureau. Details of this effort and the subsequent evaluation of the prototype are contained in an NCEL report (Beck, 1965). The tests were suspended when the turbine failed, and the new Bureau instructions requested that a survey be made of the actual requirements including the total energy package in the advanced base functional component system. Procurement specifications for a new unit, based on the findings of the survey, were then to be prepared.

The unexpected and catastrophic early failure of the gas turbine, reported by Beck (1965), was tentatively diagnosed as due to a high-temperature corrosion generally termed sulfidation. NCEL made a literature study of high-temperature corrosion, its causes, and the research currently in progress to solve the problem. It soon became apparent that the problem is general where sulfur in the fuel and sodium ions (in this case from salt-air ingestion) can combine at temperatures of 1,200°F or greater to effectively remove the protective oxides inherent in high-temperature corrosion-resistant materials used for blading. No immediate and complete solution is foreseen, but a comprehensive study of all known aspects of the problem is included in the Appendix. Until the problem is solved, early failures of high-temperature blading can be expected in gas turbines operated in a marine environment.

SURVEY OF REQUIREMENTS

The survey was concerned only with determining the desirability of including the total energy package in the advanced base functional component system, which would require that a number of identical units be stocked for future use. In conducting the survey two approaches were used.

The first consisted of interviews with field personnel. The personnel included officers and enlisted men of Naval Construction Battalion units, staff members in the Functional Component Section of the Construction Battalion Center, Port Hueneme, California, and engineers at the Bureau. Their general response was that a total energy package was not needed in the advanced base functional component system. The reasons for this response are probably twofold: a failure to understand the principles of waste-heat recovery and a fear of the imagined complexity of waste-heat recovery equipment. Such misunderstanding points up the need for a thorough training period before something as novel as waste-heat recovery equipment is introduced. Since relatively untrained men may be operating the electrical equipment, the introduction of an apparently more complex system could result in operational problems.

The second approach was less subjective. The power and heat requirements of each major component in the advanced base functional component system were studied (U. S. Navy, 1966). At the same time, the size and type of equipment furnished with each component were also noted. By matching the power requirements of each piece of equipment with its thermal energy recovery potential, it was possible to ascertain the number of opportunities to combine the heat source and the power generator into one unit. It was discovered that there was in fact no component where power and heat demands were compatible in the sense that the heat generated from reject energy from the power source met the demand. This was true of the best possibilities, as is illustrated by the subsequent analysis of the hospital component.

The feasibility of furnishing the energy requirements of two or more components from a single source was also studied. A single source works quite well for electrical power, which can be distributed without undue difficulty. The distribution of hot water or steam presents a more formidable problem. In general, a central energy supply system is not considered to be practical for a functional component complex.

The best opportunity to utilize a total energy package would occur in a component which had power-generating equipment as part of the standard allowance. A good example of such a component is the G-5 component, a 100-bed hospital (U. S. Navy, 1966). Table 1 is a compilation of the various segments of the hospital, listing both power and heat requirements for each. Figure 1 shows the planned location of the buildings and power-generating equipment. The building numbers correspond to those in the second column of Table 1.

The heat demand has been broken down in Table 1 into space heating and water heating (or what is termed process heat). These loads are the maximum attainable with the equipment furnished and quite obviously do not reflect a true steady-state demand.

It is also obvious that the electrical load levels will not be constant. The demand in the X-ray, urology, and surgery areas will vary with the patient flow, which is almost certain to be cyclic. In times of reduced activity, the electrical load will be cut by as much as half. However, the heat load might remain fairly constant for days at a time as long as the wards are occupied and the galley and laundry are being used.

Table 1. Power and Heat Requirements of Segments of the G-5 100-Bed Hospital

Bureau of Yards and Docks Drawing Number	Building Number Shown in Figure 1	Description	Heating Devices	Btu Capacity		Electrical Load (kw-hr)
				Northern Climates	Temperate-Tropical Climates	
264134	1	galley	boiler water heater space heater	182,000 20,000 150,000	182,000 20,000 —	12
303610	2	laundry	boiler space heater	182,000 100,000	132,000 100,000	1.75
304040	3	ward	space heater 30-gallon water heater	800,000 20,000	800,000 20,000	19.66
304040	4	storage (general)	space heater	100,000	—	—
304040	5	storage (provision)	space heater	100,000	—	0.72
303604	6	laboratory	space heater	100,000	100,000	12.97
303587	7	storage hospital	space heater	200,000	—	0.72
303589	8	receiving ward	45-gallon water heater space heater 30-gallon water heater	30,000 100,000 20,000	30,000 100,000 20,000	12.93
303595	9	X-ray	space heater	100,000	100,000	32.45
816400	10	administration	space heater 45-gallon water heater	200,000 30,000	200,000 30,000	1.36
493993	11	pharmacy	space heater 45-gallon water heater	100,000 —	100,000 30,000	7.1
504572	12	E.E.N.T.1/ and urology	space heater boiler 45-gallon water heater	— 595,000 —	100,000 — 30,000	35.92
504584	13	surgery	space heater boiler	— 595,000	100,000 —	45.78
889753	14	head and shower	18-gallon water heater 18-gallon water heater space heater	15,000 15,000 100,000	15,000 — 100,000	1.16
			Space heat . . . . . 2,150,000 Process heat . . . . 1,704,000 3/ Total 3,854,000		1,800,000 2/ 539,000 2,339,000	184.52

NOTE: For an electrical output of 180 kw-hr, the generators (drawing number 816413) would have a Btu capacity of 1,000,000 in both the northern and temperate-tropical climates.

1/ Eye, ear, nose, and throat.

2/ Will vary with ambient temperature.

3/ Includes space heat for E.E.N.T. and surgery (240,000 Btu each).

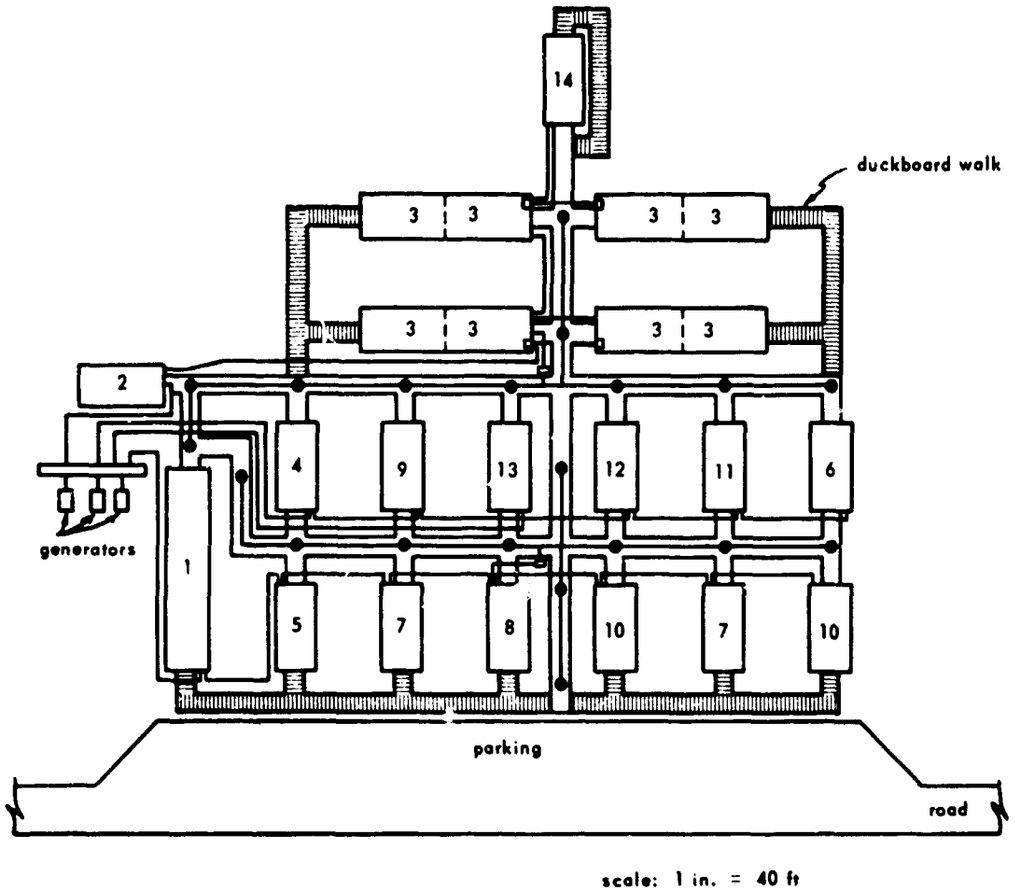


Figure 1. Plan of the G-5 100-Bed Hospital.

Based on these assumptions, it appears feasible to supply the galley and laundry with process heat from a waste heat recovery unit source at the power plant. The space heat would continue to be supplied by individual heaters.

The next question to be answered is how best to recover the waste heat. The following section attempts to analyze the procedure for selecting the best energy package.

METHODS OF RECOVERING WASTE HEAT FROM POWER-GENERATING EQUIPMENT

The common source of electrical power in the advanced base functional component system is the diesel generator. Waste heat is available from either or both of two sources: the engine jacket water and the exhaust gas.

Heat from the engine jacket may be obtained by a liquid-to-liquid heat exchanger, where the engine coolant is maintained at a maximum of about 200°F, or by a boiling-condensing system, where the engine coolant is boiled and the steam condensed at the point of heat use. The latter method requires less investment in recovery equipment. Either the exchanger or the boiling-condensing system can be used to replace the radiator, or with intermittent heat demand, they can be used with a bypass to the radiator.

Heat can also be readily recovered from the diesel exhaust gases in a simple shell-and-tube exchanger. The steam pressure that can be obtained from a boiling-condensing cooling system without an auxiliary exhaust gas boiler is limited. The jacket pressure can be safely held at or near 15 psig, which is adequate for most process and heating requirements, including air conditioning with lithium bromide refrigeration systems. For higher pressure steam, it is necessary to recover waste heat from the higher temperature exhaust of either the diesel or gas turbine engine.

Gas turbines are also being used to drive electric generators. Waste heat from the turbine is obtained only from the exhaust gas. The proponents for the gas turbine claim two advantages, namely, the reduced weight of the equipment and a large quantity of waste heat. The weight reduction is considerable, especially where a 400-cycle generator is used, but it is questionable whether the reduction is an advantage for stationary equipment under 100 kw. Excepting the 600-kw, 95,000-pound generator, the largest generating unit listed for the component system is the 500-kw, 56,000-pound, trailer-mounted generator. If air transportation of generators of this size is necessary, the C-141 cargo plane, and possibly the C-124, can carry this weight. The 8,000-pound, 100-kw generator can even be lifted by a helicopter.

The fallacy in placing so much importance on the dead weight of the generating equipment lies in the comparative fuel requirements of the turbine and the diesel. A 100-kw turbine-powered generator set will burn about 100 pounds more fuel per hour than will a 100-kw diesel-driven set. In 3 days the diesel would save enough fuel to equal its own weight. The additional fuel represents a continual logistic problem as well as a large additional cost, especially where it must be flown in.

The extra fuel consumed by a turbine is the reason for its large waste heat recovery potential. Recovery of this heat requires very large heat exchange surfaces or significant pressure drops. If an attempt is made to obtain the maximum recovery, pressure drops are unreasonably high and further reduce the economy of power generation by imposing an excessive back pressure on the turbine. Diesel engines are far less affected by high back pressure, so represent a more economical type of recovery equipment.

The heat recovered from the diesel engine is truly waste heat, whereas the extra fuel burned in the turbine could be more effectively used in a standard steam boiler, but only as needed. The electrical loads and heat loads must be very well balanced before the use of a turbine can possibly be justified.

To this point no consideration has been given to the comparative capital costs of the two systems. Currently, the turbine costs several times as much as the small diesel engine; it is competitive only in the 2,000-to-5,000-horsepower range.

Historically, maintenance of the smaller gas turbines has been a problem. In general, fewer mechanics are familiar with turbines than with diesels, except those in military air groups. Some difficulties which may be expected with turbines are discussed by Beck (1965) and in the Appendix to this report.

In reviewing the foregoing, it becomes apparent that several factors must be considered before deciding whether a total energy package might be satisfactory and desirable in advanced base functional components.

The first factor to consider is the effect of combining the heat source with the power generator on the mission of the component. To what extent will a simultaneous loss of power and heat jeopardize the operation?

A second potential factor is the requirement for a heat distribution system to operate from the central plant. Assuming hot water or steam lines will be used for space heating, the effect of the added costs and the complexity of installing and maintaining such lines must be considered.

Finally, potential fuel savings may be the controlling factor if supply is limited or difficult. Therefore, a comparison would have to be made of fuel requirements for the different power–heat combinations diesel generator and individually fired heaters; diesel generator with waste heat recovery and some individually fired heaters; and a gas turbine with waste heat and some individually fired heaters.

INTEGRATION OF POWER AND HEAT INTO AN ADVANCED BASE COMPLEX

It was pointed out in the example of the G-5 hospital unit that, in terms of a total energy package, there probably would be a mismatch between power demand and heat supply and heat demand. In spite of the apparent added complexities in using waste heat recovered from diesel engines, there is evidence of fuel savings and an increase in reliability which might well justify the small additional costs. For every 15 pounds of steam generated from waste heat, over 1 pound of boiler fuel can be saved. The most effective use of waste heat may mean a change in some of the advanced base planning and layout concepts, principally the location of generator stations.

The two largest and most consistent potential users of waste heat are the galley and the laundry. Other important heat loads are found in the showers, decontamination center, and water desalting plant. If the generator sets and the above units are placed close together, the waste heat can easily be utilized. Any space heating which can be accomplished by using hot water or steam radiators will eliminate or supplement the usual oil-fired heaters, and therefore should be considered in view of the potential fuel savings.

CONCLUSIONS

1. The concept of a multipurpose mobile utility plant consisting of a gas-turbine-driven generator and a combination waste-heat and direct-fired boiler is not considered desirable, because both flexibility and economy are adversely affected by the combination. A turbine-powered electrical generator with the capability of waste-heat recovery is attractive only when the power demand and the waste-heat demand are balanced. A study of advanced base functional component requirements indicates that this situation does not often exist. Even if it did, a diesel engine is probably more flexible and expedient for waste-heat recovery.

2. Waste-heat recovery should be utilized at every opportunity in order to reduce both logistic problems and costs. The extent to which utility facilities can be centralized is a matter of value judgment and beyond this study. It would seem to be axiomatic that the more permanent the base, the more sophisticated the utility system which can be justified, because of the probable longer period of life of the system available for cost write-off.

RECOMMENDATION

There is a disadvantage in substituting small gas turbines for diesel engines because of the greatly increased fuel consumption and the much greater first cost of turbines. It is therefore considered imperative that a complete comparative cost analysis of the two systems be made for any given installation before a gas turbine is chosen.

Appendix

A DOCUMENTED STUDY OF HIGH-TEMPERATURE CORROSION IN THE MARINE GAS TURBINE

By Layne E. Fuller

INTRODUCTION

The year 1926 saw the introduction in Great Britain of an aerodynamic theory for axial-flow gas turbines by Dr. A. A. Griffith of the Royal Aircraft Establishment. Twelve years later the U. S. Army Air Corps launched a modest program at Wright Field to perfect the gas turbine for aircraft, with a target date of 1943. More recently, the gas turbine's high power density and light weight has made it attractive for certain marine applications. The Navy presently uses, or plans to use, gas turbines in hydrofoils, hydroskimmers, advanced landing craft, and high-speed, destroyer-type, antisubmarine warfare ships. Some 17 years of marine gas turbine propulsion for naval service (Weinert and Carlton, 1965) has revealed special problems associated with the operation of gas turbines at sea.

In order to make the gas turbine more nearly competitive with conventional prime movers, low-cost residual fuels commonly used in boilers were sometimes burned. In 1950 the vanadium content of these fuels was identified as a cause of accelerated high-temperature corrosion of blades and vanes in gas turbines. Lamb and Duggan (1953) cite two forms of corrosion attack attributable to certain fuel ash constituents formed on combustion: (1) accelerated oxidation due to vanadium and (2) intergranular penetration of the metal due to sodium sulfate. It is with the second form that we are concerned in naval gas turbine operation, since vanadium has been largely eliminated by the use of refined distillate fuels.

Typical marine diesel fuel specifications (for example, distillate fuel) limit sulfur to 1% maximum. Salt concentrations of ocean atmospheres are believed to be about 0.5 ppm under typical operating conditions. It has been found that temperatures above 1,200°F and more commonly above 1,400°F enable a very corrosive slag to be formed by the combination of fuel sulfur and sea salt. The nickel and cobalt base superalloys commonly used for nozzle guide vanes and turbine blades are severely attacked by this slag.

The sulfur–sodium attack, termed sulfidation, is currently being counteracted by limiting temperatures, cooling hot section components, coating superalloys, filtering salt from the intake air, and controlling fuel supplies to limit the sulfur content. These will be discussed later in this Appendix.

SULFUR EFFECTS BELOW 1,300°F

The National Gas Turbine Establishment (NGTE) in England carried out laboratory tests, complementary to Marine Proteus trials, which suggested that the fluxing of protective surface oxides by salt mixtures at temperatures in the range of 1,200-1,400°F may play a significant part in what was called "sea-salt" corrosion.

Boilers have had similar problems. A common form of corrosion, caused by complex sulfates occurring in boilers operating below 1,300°F, was cited by Nelson and Cain (1960). They found that the following rapid liquid-phase attack reaction occurred between the melting point of the mixture of complex alkali sulfates present and their thermal-stability limit:

$$3\,Fe + SO_4^- \longrightarrow Fe_3O_4 + S^-$$

Tube metal	Molten complex sulfate	Iron oxide	Sulfide

The skin temperature range of 1,025-1,300°F for attack was established by investigations described in a second paper published in 1960. Figure 2 shows the rapid drop off of corrosion loss caused by molten sulfate complexes at about 1,300°F.

Cain and Nelson (1961) mentioned sulfidation in conjunction with the liquid-phase attack discussed above. They pointed out that sulfidation of a metal structure usually involved corrosion by either coal or oil ash, although rapid general corrosion sometimes destroyed any evidence of sulfide penetration. They claimed that extensive sulfidation occurs only in the presence of molten sulfate complexes, which in turn produce sulfides at the metal surface. The penetration of sulfides was said to be intergranular in nature and indicative of liquid-phase attack.

In a study which showed that sulfidation is thermodynamically predicted if oxygen is absent from the metal surface, Boll and Patel (1961) established a second important aspect of high-temperature corrosion. They found that at high temperatures, Na_2SO_4 (a stable liquid at about 1,600°F) in contact with high-alkali combustion gases allowed sulfidation to occur in marine gas turbines in which the temperature of the gas leaving the combustors is above 1,300°F.

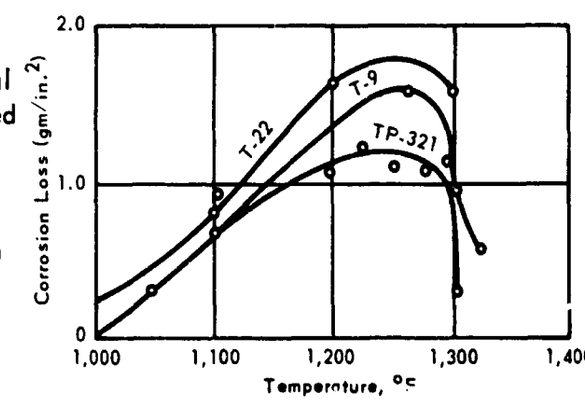


Figure 2. Effect of alloying constituents on corrosion rate. (Courtesy of ASME journal.)

EXPERIENCE WITH SULFIDATION ATTACK

Although the use of distillate fuels has eliminated vanadium corrosion as a prime problem in naval applications, sodium sulfate corrosion remains a major concern in marine gas turbine operations. Figure 3 clearly illustrates the advantage of distillate fuel over residual fuel in reducing the deposition of corrosive ash. The oxidation of high-temperature alloys under normal operating conditions (1,200°F and up) is accelerated in the presence of combustion products of sulfur-bearing fuel and air when either fuel or air is contaminated by sea salt (Stoeckly, 1965). Stoeckly indicates that this particular type of corrosion is referred to as "sulfidation," "green rot," and "the black plague" in England. As higher sulfur-content distillate fuels continue to be used in marine applications, the incidence of high-temperature corrosion becomes greater in frequency and severity.

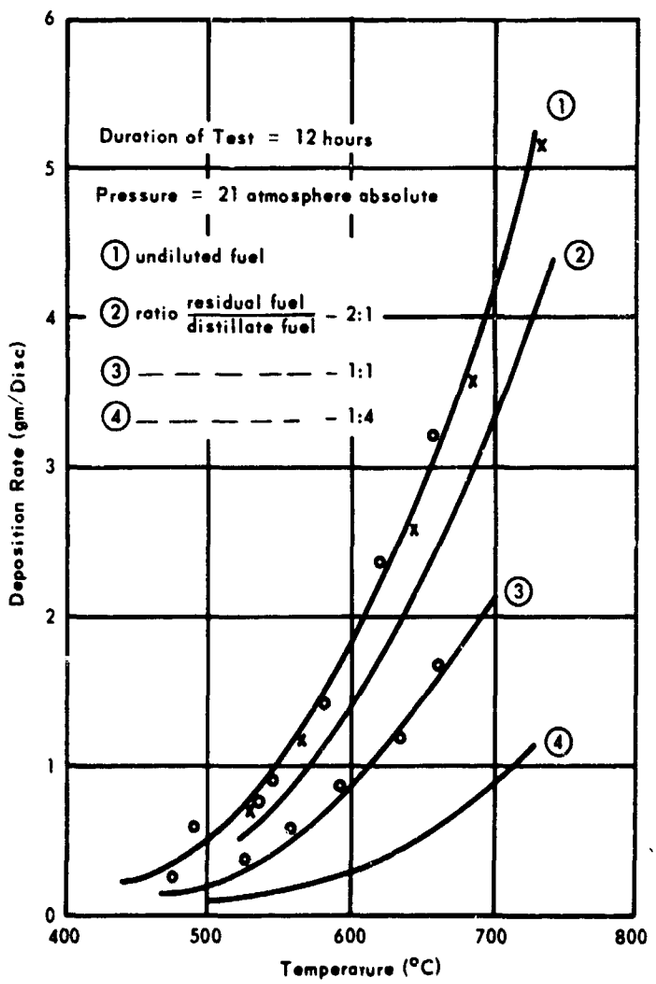


Figure 3.
Effect of ash content and temperature on deposition rate. (Courtesy of ASME journal.)

The failure which provided the impetus for this study occurred in a 300-horsepower gas turbine, shown in Figure 4. After operating in a seashore atmosphere for some 850 hours, the unit was shut down due to power loss attributed to corrosion of the high-temperature nozzle blading. This blading, operating at approximately 1,550°F, failed, as shown in Figures 5 and 6 (Beck, 1965). Danek (1965) reports that at temperatures above 1,550°F, fuel sulfur and salt from the fuel or intake air interact to form a very corrosive slag. Pierce (1965) observed failures at about 1,500°F in several gas turbines operated, but not in a marine atmosphere, by the Southern California Gas Company. Burwood-Smith (1965) reported tests on Marine Proteus turbines at the NGTE in which gas temperatures at the inlet blading ranged from 1,310 to 1,418°F with sea salt ingested at 0.5 ppm in the air. Severe sulfide penetration and oxidation of Nimonic 90 blades arose within 300 hours of operation. The fuel contained approximately 0.8% sulfur. Tyler (1965) described corrosion of Ni–Cr alloys of the Nimonic type at gas temperatures up to 1,400°F. Grandey (1965) found corrosion of Inco 713 in the General Electric Company's operating experience with nickel and cobalt base alloys at temperatures from 1,400 to 1,650°F. Clark (1965) points out that sulfidation usually is not severe at metal temperatures below about 1,400°F.

By October 1963 the U. S. Navy had compiled 188,000 hours of operating experience with a turbine-powered fleet of 298 vessels. The need for a lightweight gas turbine in the 20,000- to 30,000-horsepower range for hydrofoils and other ships resulted in the awarding of a contract by the Bureau of Ships for development of the present Pratt & Whitney Aircraft (P&WA) FT4A marine gas turbine (see Graves and Sawyer, 1963). In the final report on a 1,000-hour endurance test of the FT4A engine Carlton (1964) recommended that investigations be made to determine how to minimize erosion and sulfidation attack of the first-stage turbine blades. He and Weinert (1965) cite an investigation of the FT4A engine by White (1962), stating that sulfidation attack occurred at a temperature of approximately 1,600°F in this engine. Freeman (1965) furnished a recent Lycoming proposal to study sulfidation mechanisms. The proposal included Figure 7, which shows severe attack of Inco 713C uncoated gas-producer turbine blades. The engine had been operated in a marine atmosphere for 200 hours, of which 45 hours were with inlet temperatures to the blading above 1,700°F. Severe corrosion was observed in nickel and cobalt superalloy turbine vanes and blades operating between 1,600 and 1,900°F (Kearns, 1965). These vanes and blades were in ship and aircraft turbines operating in marine environments. Kearns attributed the corrosion to the effects of sea salt or to the combined effects of sea salt and fuel sulfur.

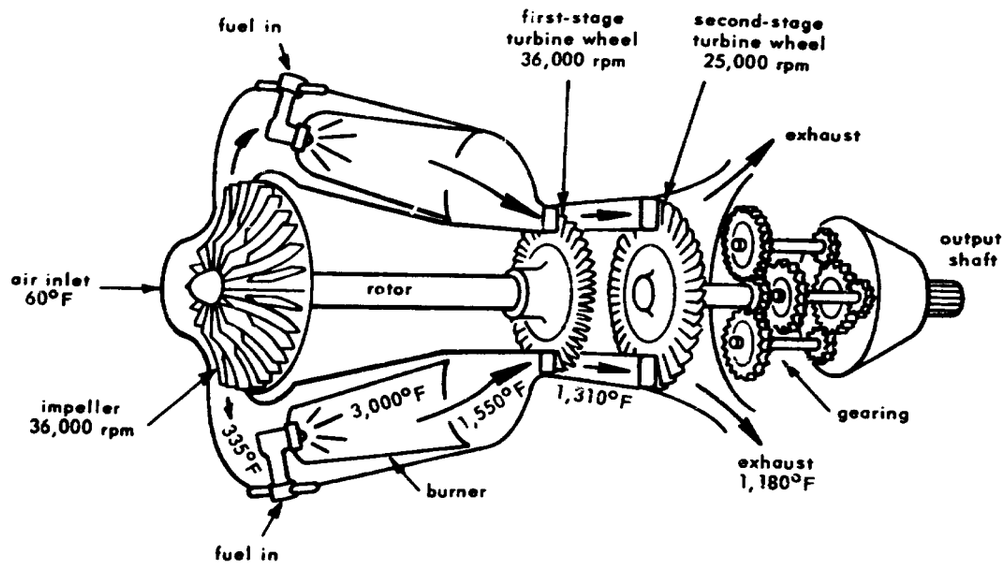


Figure 4. Basic operational features of the model 502 gas turbine. (Courtesy of Journal of Metals.)

Figure 5. Nozzle blading in Boeing turbine.

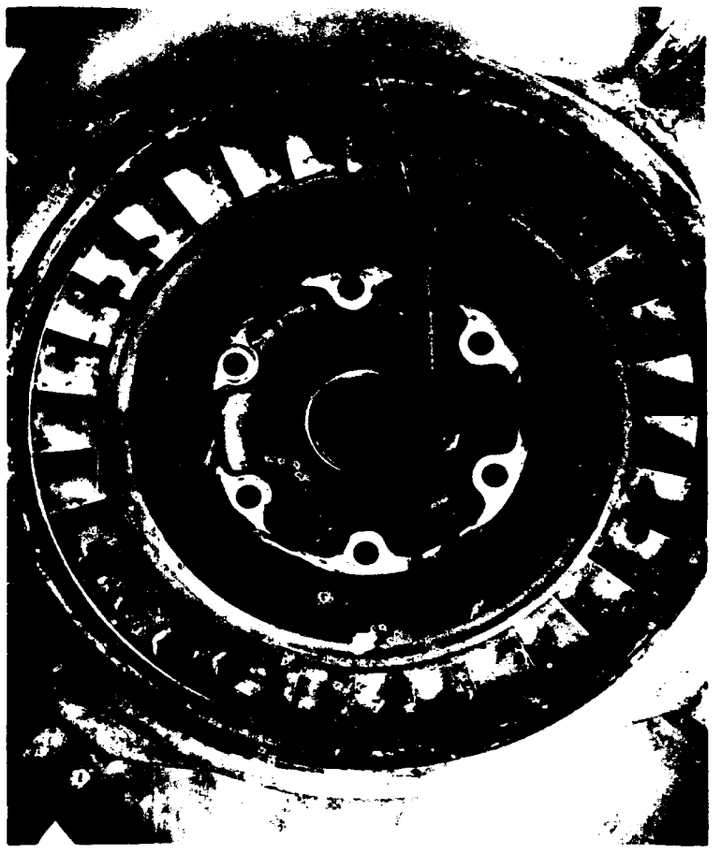


Figure 6. Trailing edge of nozzle blading.

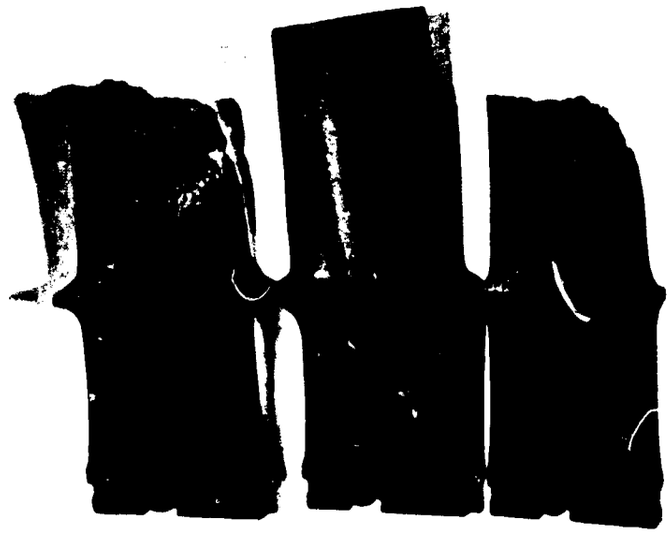


Figure 7. Gas-producer turbine blades of Inco 713C (uncoated) after 200 hours of marine operation, with 45 hours at turbine inlet temperatures above 1,700°F. Undamaged center blade included for purposes of comparison. (Courtesy of Lycoming Division, AVCO Corp.)

CHARACTERISTICS OF SULFIDATION ATTACK

Early gas turbines burned vanadium-bearing residual fuels for economy, and the practice continues in many applications. Early investigations of vanadium attack, such as the investigation by Frederick and Eden (1954), diverted attention from the sodium sulfate aspects of fuel-ash corrosion. As the role of Na_2SO_4 was recognized in accelerated oxidation studies (Monkman and Grant, 1953), illustrations of its effects began to appear, as shown in Figure 8. Further studies of both types of corrosion by Young, Hershey, and Hussey (1955) established temperatures of 1,200-1,300°F for attack by vanadium in the form of V_2O_5 and temperatures of 1,600-1,700°F for attack by Na_2SO_4. The metallographic characteristics of type 310 stainless steel corroded by this slag are shown in Figure 9. The nature of the accelerated corrosion which is characteristic of sulfidation was better understood when Shirley (1956) discovered that the addition of 0.5% sodium chloride to the slag increased the rate of corrosion of 18/11 stainless steel. Corrosion by chloride-contaminated slag on type 310 stainless steel at 1,600°F is clearly discernible in Figure 10. When similar occurrences of such catastrophic hot corrosion appeared in marine applications of gas turbine engines, the characteristic attack came to be commonly termed sulfidation.

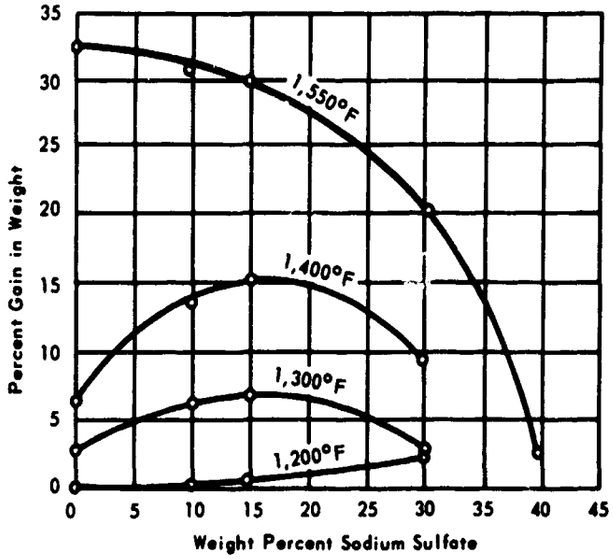


Figure 8.
Gain in weight of type 347 stainless steel in contact with various Na_2SO_4–V_2O_5 mixtures for 168 hours. (Courtesy of Corrosion magazine.)

The variation in sulfidation with blade location is shown in Figures 2 through 7 of the Lycoming proposal of 1964. The attack was shown to be most severe on the concave surfaces of the blading.

Danek (1965) describes sulfidation macroscopically as a voluminous and blistered dark-colored mass interspersed with small amounts of greenish material. As illustrated in Figure 11, from Lycoming (1964), sulfidation attack generally advances on a broad front. Figure 12, from the same source, shows the metallographic characteristics of sulfidation on an Inco 713C turbine component. Phase (A) is developed at the oxide–base metal interface in which a light gray phase (B) is formed. Danek (1965) describes this phase as composed of gray-lavender globular particles in a white matrix. He states that although this phase is randomly distributed within the grains, it appears to diffuse into the matrix material through grain boundaries. Bergman (1964), quoted by Danek, describes sulfur diffusion as a grain boundary mechanism and mentions a golden-colored phase in conjunction with the gray-lavender particles which appear to have been molten. Lycoming (1964) describes the matrix material as composed of "unattacked" metal areas (C) scattered throughout an oxide matrix (D) and containing finely dispersed particles (E). The completely oxidized outer layer (F) appears to Danek (1965) to be a loose and porous, but homogeneous, dark-gray scale. The composition of each of the materials indicated by letter is given in Figure 12.

These values are reported by the Lycoming Laboratories as precise within 5% of the amount present, except for the particles (E), which could not be discretely analyzed. The compositions are discussed on pages 3-5 and 3-6 of the Lycoming proposal.

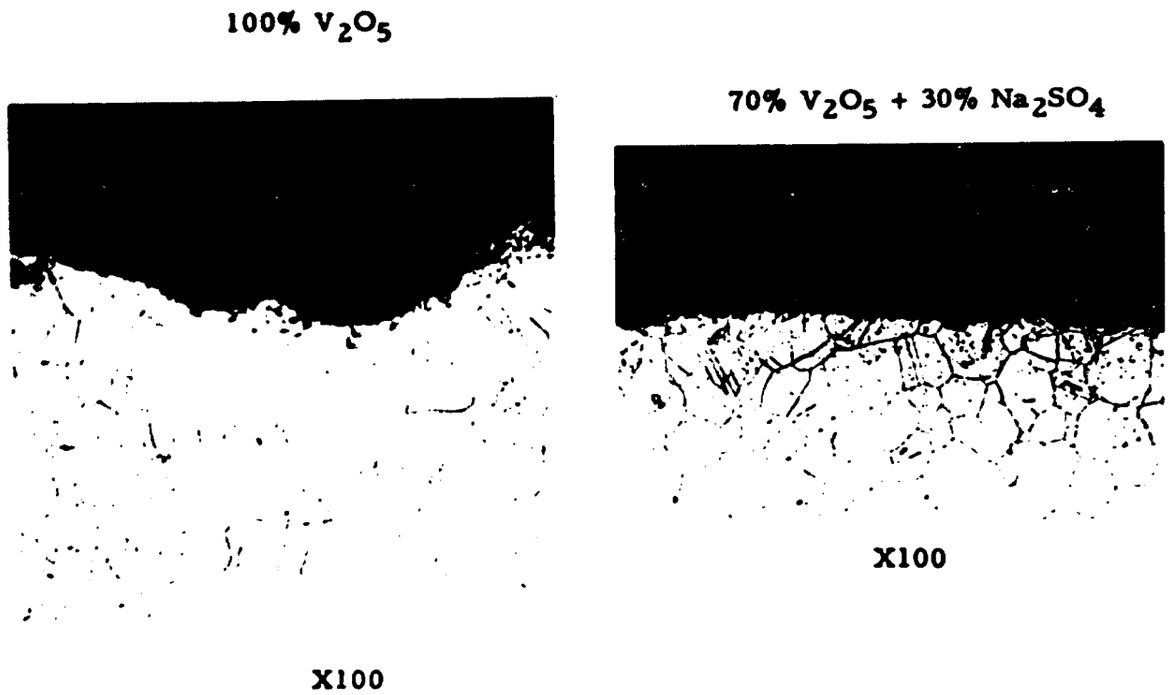


Figure 9. Metallographic characteristics of type 310 stainless steel corroded by V_2O_5 oxide and Na_2SO_4. (Courtesy of Corrosion magazine.)

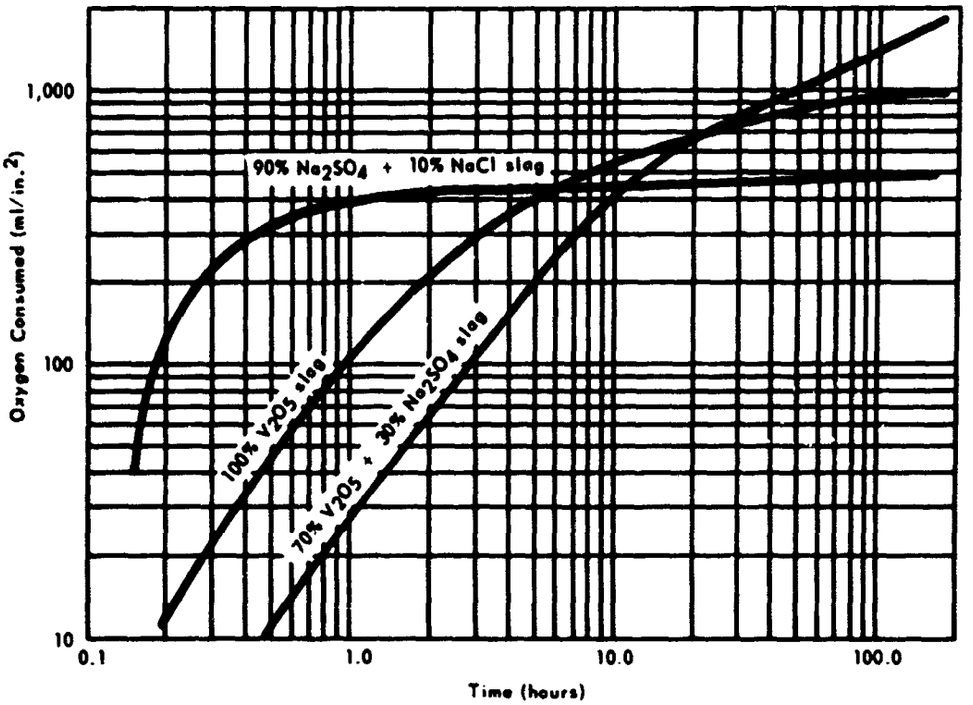


Figure 10. Corrosion of type 310 stainless steel by various laboratory slags. Temperature 1,600°F. (Courtesy of Corrosion magazine.)

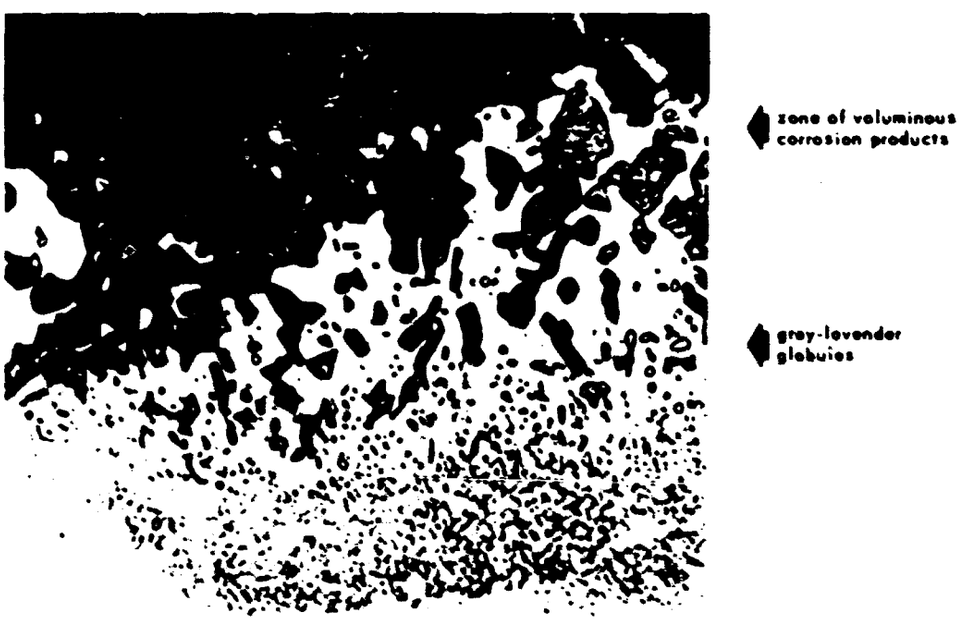
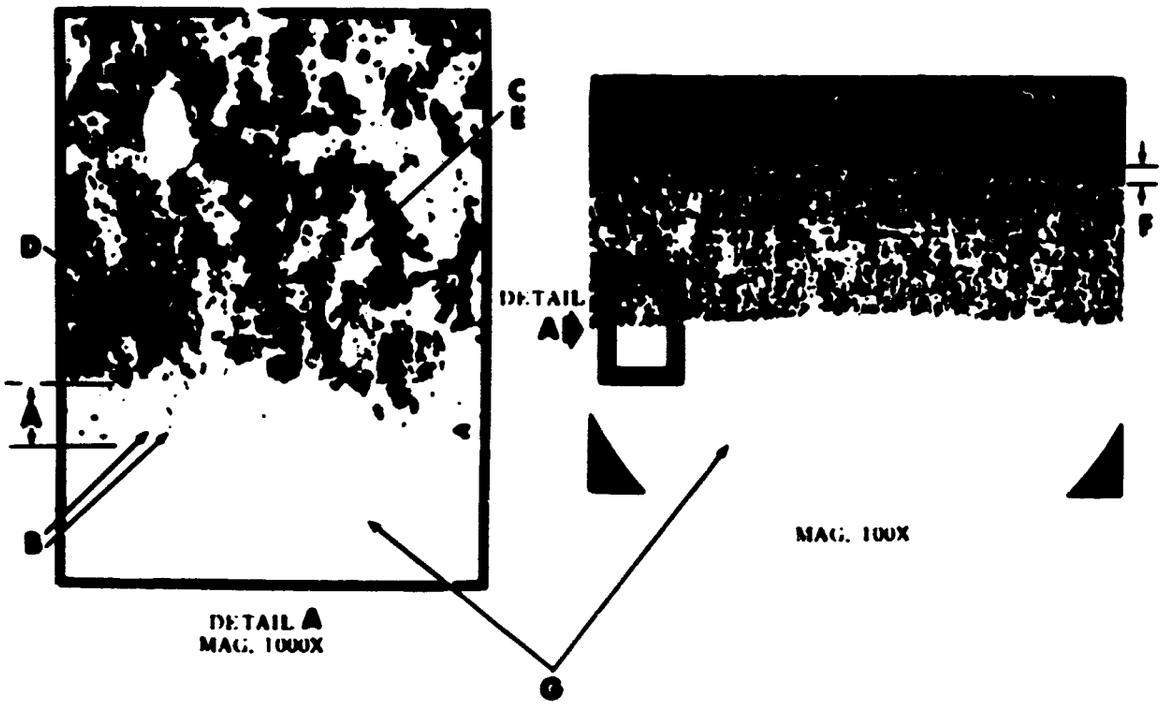


Figure 11. Sulfidation attack of U-700 turbine blade. Electrolytic etch in 10% CrO_3, 2 volts, 5 seconds (Courtesy of Lycoming Division, AVCO Corp.)



COMPOSITION - WEIGHT PERCENT

AREA	DESCRIPTION	Ti	Fe	Cr	Al	Ni	S	Mo	Cb
A	DEPLETED ZONE	0.1	0.9	2.9	1.7	91.0	-	3.2	0.1
B	Cr_xS_y PHASE	4.1	0.5	47.5	2.9	-	41.2	-	4.1
C	UNATTACKED METAL	0.02	0.9	1.4	1.2	93.3	-	2.2	0.9
D	OXIDE MATRIX	2-3	0.4	17-19	14-16	17-19	-	1-2	1-2
E	INTERNAL OXIDATION	0.2	0.9	3.4	5.8	84.2	0.1	5.8	0.1
F	UNIFORM SCALE LAYER	0.5	1-2	8-9	4-5	66-68	-	0.2	2-3
G	UNAFFECTED ALLOY MATRIX	0.70	<0.5	10.8	5.8	-	-	4-5	2-3
713C	NOMINAL COMPOSITION	0.75	0.5 max.	13.0	6.00	Bal.	0.015 max.	4.5	2.3

Figure 12. Characteristics of sulfidation attack in an engine-operated Inco 713C turbine nozzle vane. (Courtesy of Lycoming Division, AVCO Corp.)

MECHANISMS AND PARAMETERS OF SULFIDATION

There have been several attempts to explain the accelerated high-temperature corrosion observed in marine gas turbine engines. The lack of general agreement among the corrosion theories postulated to date indicates that the attack is not well understood. There is agreement, however, in three areas:

1. Sulfidation corrosion cannot occur until a molten slag, probably composed primarily of Na_2SO_4, is formed.
2. Attack begins when the normally protective oxides formed on superalloy surfaces are destroyed; the slag appears to act as a flux.
3. Rapid oxidation of the base metal proceeds as sulfur from the slag is absorbed by the fluxed metal.

The proposed mechanisms of corrosion are found to differ primarily in explaining the phenomena involved in areas 2 and 3.

The molten slag initiating sulfidation in marine gas turbines is formed by the reaction of sulfur in the fuel and airborne sea salts, and appears to be composed primarily of Na_2SO_4 and NaCl. Early investigations indicated that Na_2SO_4 alone is harmless. A study of sulfate-chloride effects in corrosion by Shirley (1956) indicated that chloride contamination of the sulfate was necessary for rapid attack. Contradictory findings by Bergman (1964), cited by Danek (1965), indicated that the chloride ion does not enter into the corrosion reaction. Bradley (1965), however, claims that chlorine must be present in the gas turbine atmosphere as a catalyst for the promotion of sulfidation. Danek (1965) states that current thinking ascribes a dual role to sodium chloride in the sulfidation process. Sodium is supplied to the fuel-sulfur reaction, yielding Na_2SO_4, and an excess of NaCl reduces the melting temperature of the slag. This effect causes reductions in turbine operating temperatures and thereby detrimentally affects engine efficiencies. Danek also constructed the Na_2SO_4–NaCl phase diagram shown in Figure 13 to illustrate the influence of NaCl on the melting characteristics of the mixture.

Considerable time has been spent conducting crucible tests to determine the reaction by which the protective oxide film on superalloys is destroyed. Before the development of superalloys to meet high-temperature strength and oxidation resistance requirements, stainless steels were widely used in high-temperature applications. The protective chromium oxide layer on these steels inhibits corrosion. Evans (1947), cited by McCullough et al (1951), expressed oxidation rate as a function of time.

The discussion in Lycoming (1964) of the effects of chloride compound on the breakdown of protective film points out that the corrosion rate changes from linear to parabolic, corresponding to total consumption of the chloride in particular oxide reactions. According to Dalton (1965), the protective oxide films on high-temperature alloys are normally in the form of spinels having the generic formula $X_2O_3Y_0$.

Dalton states that the corrosion is initiated by fluxes at high temperatures, which remove the protective film much as do brazing fluxes. The theory that the oxide film is fluxed off by the sodium sulfate slag is, in fact, most widely accepted as the initial destructive mechanism (Danek, 1965). Danek's discussion of film breakdown also includes explanations of penetration of films by chloride ions and the presence of the complex carbides $M_{23}C_6$ and M_6C in the grain boundaries (Bradley, 1965). A second theory postulates the oxidation of Cr_2S_3 along with nickel-matrix material, resulting in the release of sulfur, which is then available to enter into further corrosion as SO_2. A comprehensive discussion of the SO_2–NaCl interaction is given in Lycoming (1964). NaCl is found to be unstable in the presence of SO_2, which provides for the conversion of NaCl to Na_2SO_4 in an exothermic reaction with the oxide. A decrease in corrosion rates accelerated by chloride contamination is found to occur upon the addition of SO_2 gas. Schley (1965) states, however, that the hypothesis that the protective oxide layer is altered by the salt melting on the hot sections of the engine is supported by the best evidence to date.

Once the protective oxide film is penetrated, catastrophic corrosion of the base metal is initiated (Simons et al, 1955). Simons et al placed emphasis on their hypothesis that the attack mechanism is autocatalytic, and suggested that a liquid metal–metal sulfide eutectic forms and penetrates the alloy. The eutectic formation is brought about by an initial production of lower-than-valent sulfur in a reducing environment. The following successive reactions were suggested:

Triggering Phase: $Na_2SO_4 + 3R = Na_2O + 3RO + S$

(sporadic and unpredictable) $M + S = MS$

Autocatalytic Destruction: $Na_2SO_4 + 3MS = 4S + 3MO + Na_2O$

(rapid and violent) $4M + 4S = 4MS$

Simons et al also expressed doubt that any such simple set of reaction equations will adequately describe the complete process. Tyler (1965) describes the common "fluxing attack" on Ni–Cr alloys in which the presence of sulfur results in the formation of a $Ni–Ni_3S_2$ eutectic with a melting point low enough to maintain a liquid surface at gas turbine operating temperatures. In the discussion of this and other base metal–environment interactions, Lycoming (1964) points out that sulfidation attack is less rapid in cobalt base alloys than in nickel base alloys due to the melting point of $Co–Co_4S_2$ eutectic, which is higher than that of similar nickel compounds. The process involving N_3S_2 was not initially suspected due to the frequent but misleading occurrence of CrS on gas turbine alloys after shutdown. It is now known that N_3S_2 is converted to Cr_2S_3 as chromium diffuses from the cooling alloy upon engine shutdown (Bradbury et al, 1963).

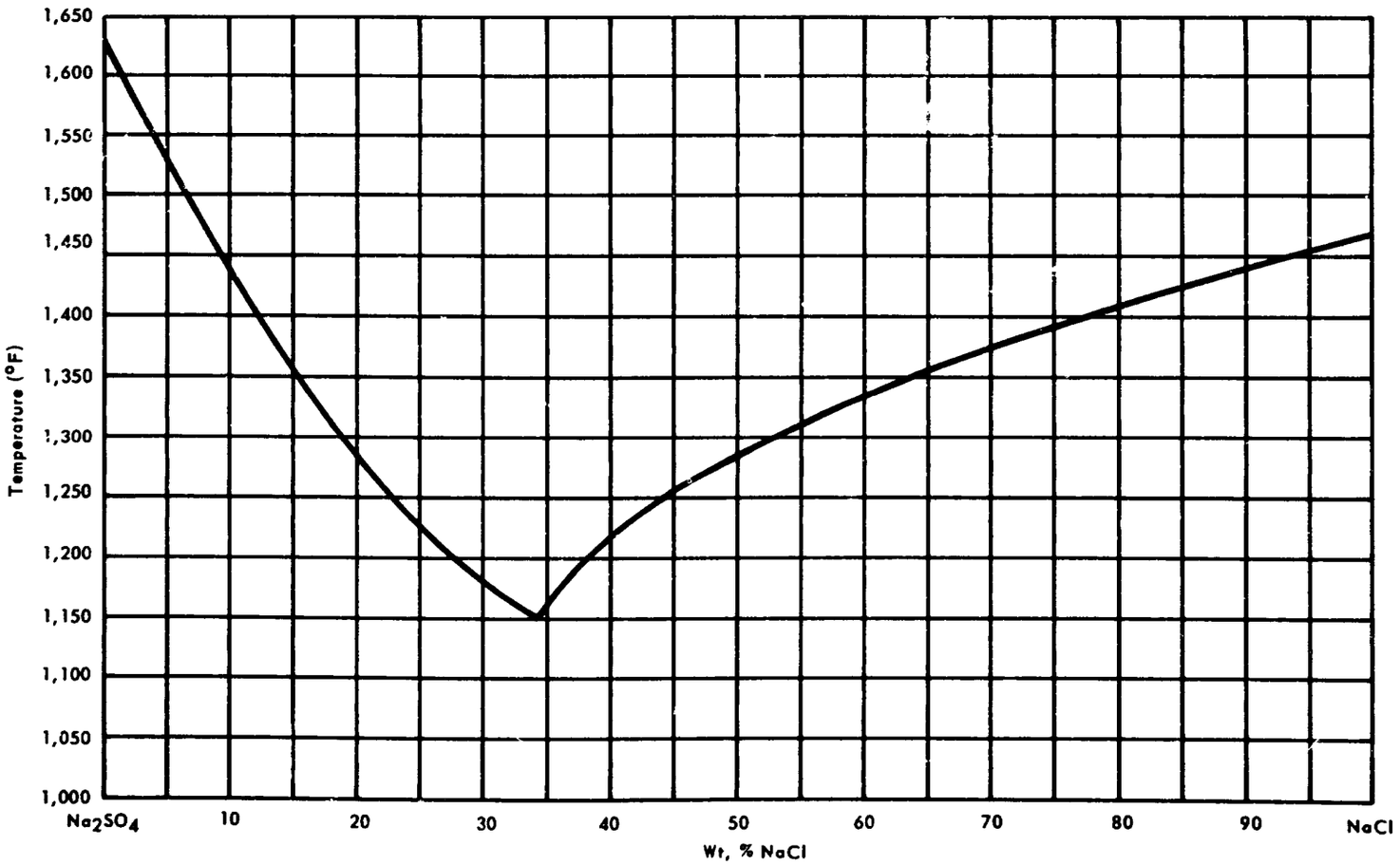


Figure 13. Phase diagram, Na_2SO_4–NaCl.

The effects of temperature, sea salt, sulfur, time, pressure and velocity are significant as parameters in the mechanism of sulfidation. Alloy composition parameters will be discussed in the next section of this report. Temperature receives considerable attention as a parameter causing weight loss in high-temperature alloys. Studies by Greenert (1962a, b, c) indicate a threshold temperature of approximately 1,560°F for 90% Na_2SO_4 plus 10% NaCl slag corrosion of type 310 stainless steel (Figure 14). Lycoming (1964) discusses the idealized curve shown in Figure 15. A considerable drop in the rate of sulfidation is indicated at 1,750°F. In a study of sea salt, temperature, and sulfur effects by Quigg et al (1965), increased exhaust gas temperature over the range 1,800-2,200°F is found to increase weight loss in 15 of 26 comparisons involving five alloys. Quigg et al indicate that metal loss increases with increasing temperature. Earlier, investigators of the Phillips Petroleum Co. (Aldrich and Schirmer, 1964), as cited by Lycoming (1964), found no sulfidation at 2,000°F, even though metal losses continued at a high level. Upon shifting their attention from temperature to the effects of ingesting sea salt in the air supply (60/1 air-fuel ratio) of the Phillips 2-inch combustor used in testing, Quigg et al (1965) found that any significant increase in sea salt led to increased weight loss. In 19 of 26 comparisons weight loss increased as salt concentration was increased from 0 to 10 ppm. When the fuel sulfur content is increased from 0.0002 to 0.4 weight percent while 10 ppm sea salt is ingested, increased weight loss in some comparisons is observed to be balanced by approximately the same number of decreased weight losses. The Phillips investigators concluded that a reduction from the 0.4% maximum sulfur content of JP-5 to a 0.04% maximum, in combination with a high ingested sea salt concentration, would be detrimental to some superalloys.

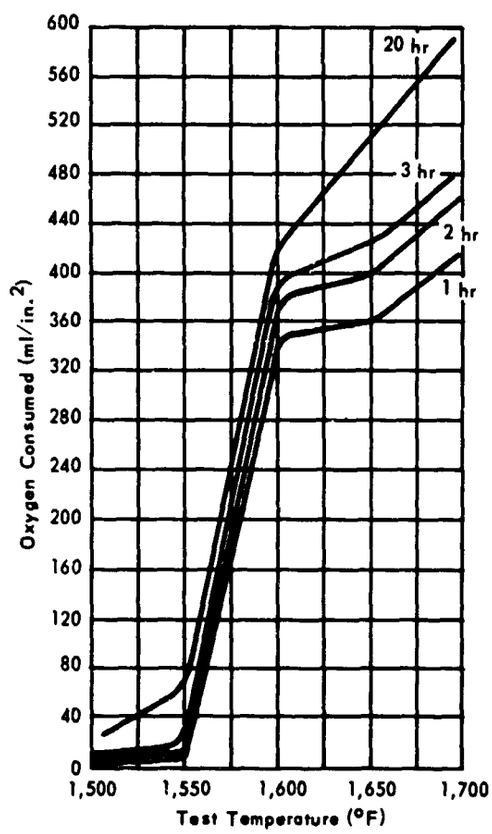


Figure 14. Effect of temperature on oxidation of type 310 stainless steel in 90% Na_2SO_4 + 10% NaCl slag. (Courtesy of Corrosion magazine.)

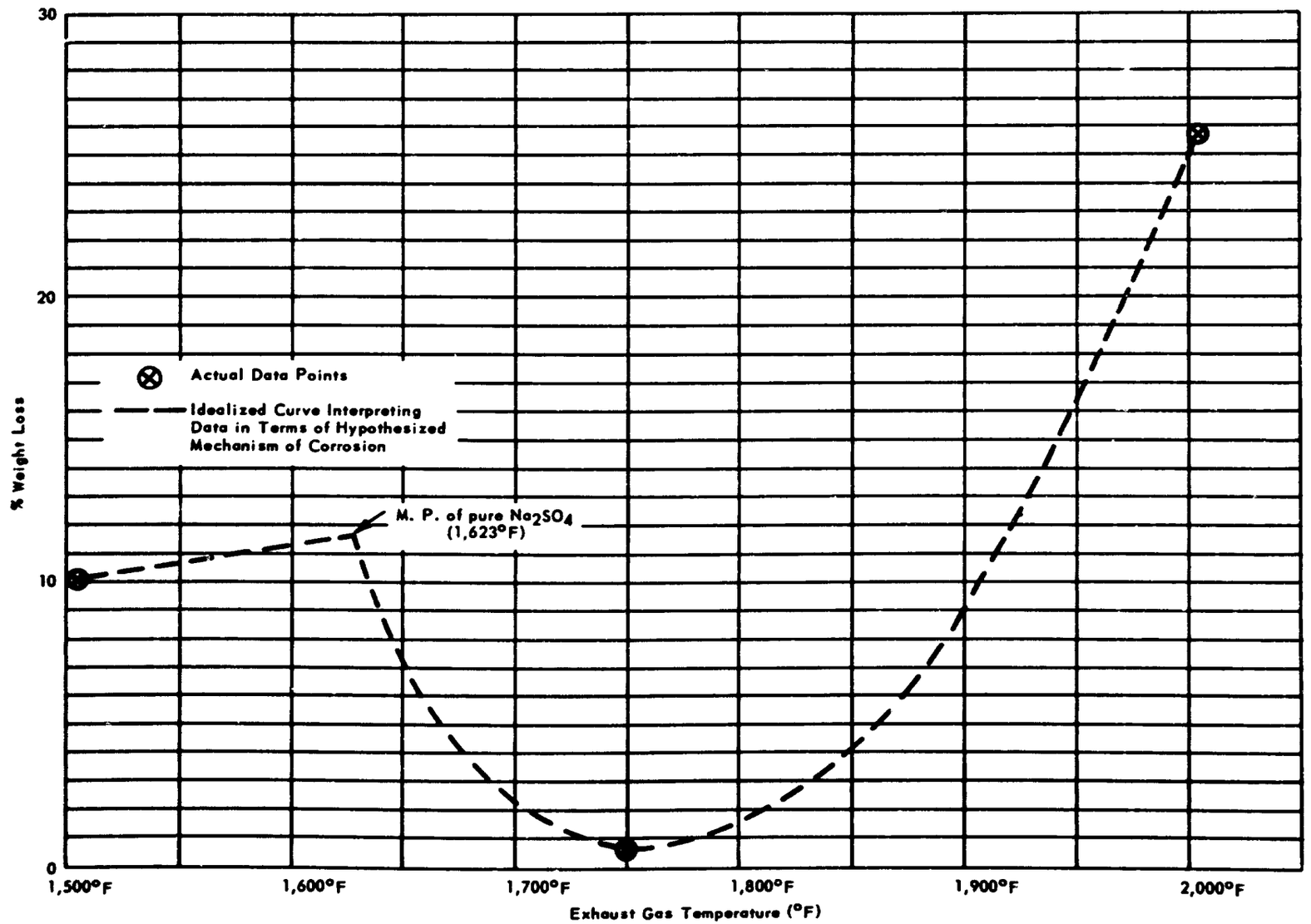


Figure 15. Variation of corrosion rate with temperature. (Courtesy of Lycoming Division, AVCO Corp.)

Danek (1965) pointed out a measurement of 3 ppm as the high observed for salt concentrations in ocean atmospheres under severe conditions. He cited a Russian study establishing that 0.05% sulfur fuel provides about 70 times the necessary sulfur to react stoichiometrically with 0.046 gm/min of ingested sodium chloride. He also cited a Pratt and Whitney study (Report PNA 2218) in which it was observed that low salt content (0.5 ppm) and long exposure (500 hours) caused the most severe attacks on gas turbine blading. The effect of time is emphasized by Simons et al (1955) in reporting the triggering reaction previously discussed. The effect of pressure on corrosion rates was studied as early as 1955 by Sulzer. The increased corrosion rates at higher pressures are illustrated in Figure 16. A large pressure effect between 5 and 15 atmospheres is demonstrated by Quigg et al (1965). At high temperature and low sulfur conditions, corrosion rate is accelerated with an increase in combustor pressure. As gas velocity is increased from 50 to 500 ft/sec under conditions of high temperature and low sulfur, a similar effect is observed. The higher velocity would be expected to play an important role in removing the liquid phase, which occurs during sulfidation of gas turbine vanes and blades. Results of studies at the Phillips Petroleum Co. suggest that changes in operating conditions primarily affect the penetration of the protective oxide film. The final phase of sulfidation, involving sulfur absorption by the metal, does not seem to be directly related to variations in operating conditions.

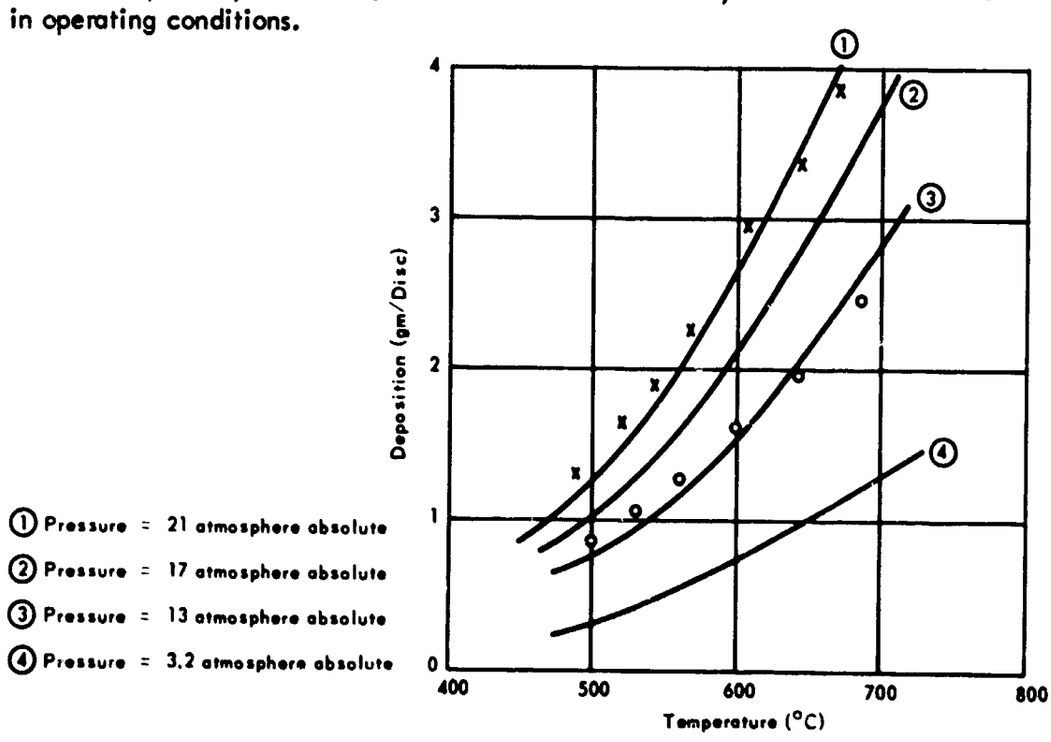


Figure 16. Effect of temperature and concentration on deposition rate. (Courtesy of ASME journal.)

GAS TURBINE MATERIALS DEVELOPMENT

Early evaluations of heat-resisting alloys were bent toward finding materials resistant to the corrosive conditions encountered in boiler atmospheres. As was the case then and now, no single material can be recommended as satisfactory under all the conditions. Further complications arise in developing alloys capable of withstanding the severe environment of gas turbine hot sections. Early work resulted in the development of Kentanium by Kennametal (1951). This alloy contains titanium carbide as its chief ingredient, with cobalt or nickel as the auxiliary metal. The alloy is said to have great strength at high temperatures (1,800°F and above) and to resist oxidation for long periods of time when heated to 2,200°F. In a study of infiltrated titanium carbide ceramets, Hoffman (1956) found that the impact resistance of nickel-base infiltrants was promising. He found that Hastelloy C and Inconel infiltrations had the best hot ductility and impact strength of those tried. A 64% titanium-carbide–25% nickel ceramet oxidized in tests run by Chiarito and Johnston (1959) at the Lewis Research Center. Solid Inconel and titanium were suggested (Marquette, 1965) as possible alloys to remedy the blading sulfidation problem encountered with the 300-horsepower turbine run by NCEL (Beck, 1965).

The high-temperature alloys now commonly used in gas turbines have a nickel or cobalt base. Recent developments in the United States brought a change from precision-cast cobalt-base alloys to nickel-base complex alloys for use in turbine blades (Dunlop, 1960). The air-reactive titanium and aluminum used in these alloys require that they be vacuum-melted and -cast (Cartwright, 1961). The cobalt-base alloys do not require these processes. Nimonic 80 and Nimonic 90 were developed to meet the early demands of gas turbine operation as aircraft prime movers. As the benefits of higher titanium and aluminum levels became apparent, Nimonic 95 was developed. Increased demands for better properties led to the development of Nimonic 100 and the appearance of a Widmanstatten type of oxide penetration traced to sulfur in the gas flame used in laboratory trials of this alloy. The chromium content was increased in producing Nimonic 105. This alloy was found to be more resistant to sulfur attack. The foregoing developments within the Nimonic family of alloys have not provided an alloy satisfactory for use with aero-gas turbines in marine atmospheres. The effect of chloride contamination of the gas turbine environment on Nimonic alloys is illustrated in Figure 17. Other nickel-base alloys with a high chromium content were found by Greenert (1962c) to be similarly attacked. Sulfidation corrosion is evident on both Hastelloy X and Inconel upon exposure to a 90% Na_2SO_4–10% NaCl slag.

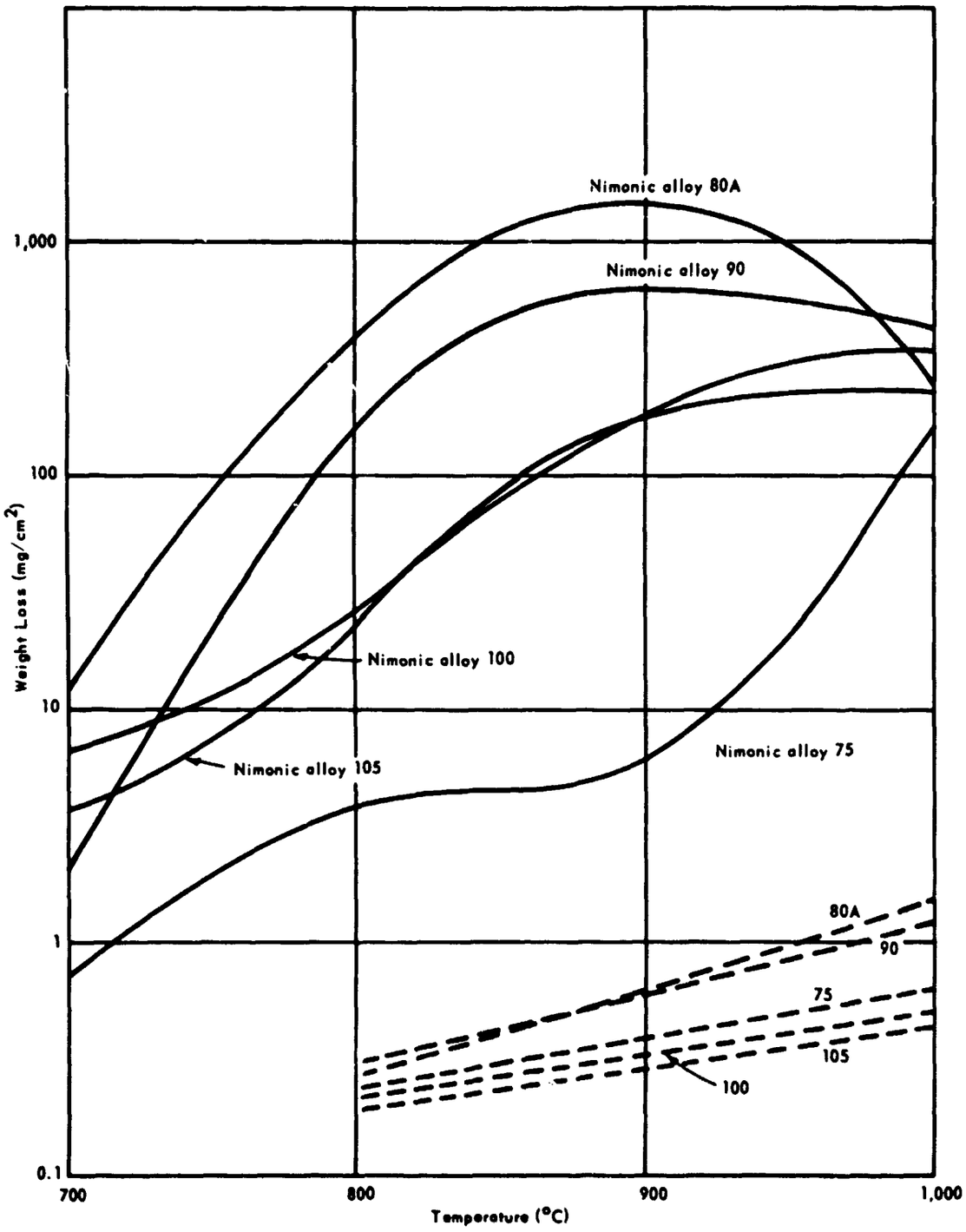


Figure 17. Effect of temperature on attack of Nimonic alloys by the corrosive Na_2SO_4–NaCl mixtures in 1 hour tests. (Courtesy of Lycoming Division, AVCO Corp.)

The Marine Proteus tests, mentioned earlier, revealed differences in the sulfidation resistance of cobalt and nickel base alloys. Burwood-Smith (1965) reported metallurgical examinations which showed severe sulfide penetration and oxidation of Nimonic 90 blades, whereas only slight corrosion and no sulfide penetration appeared in cobalt X40 blades. He expressed the opinion that cobalt-base alloys are generally favored over nickel-base alloys in England. Bowers (1965) stated that first-stage nozzles of cobalt-base alloys suffer less than do nickel-base alloys, but that the latter are satisfactory for the first-stage buckets of gas turbines. Rig-test results indicate that cobalt-base alloys as a class possess a high degree of immunity to sulfidation (Danek, 1965). Danek related that the superiority of cobalt–chromium alloys may be attributed to three facts:

1. Cobalt sulfide molecules have a smaller volume than do nickel sulfide molecules.
2. The diffusion of cobalt to the alloy's surface is slower than the similar diffusion of nickel.
3. The $Co-Co_4S_3$ eutectic melts at a higher temperature (1,616°F) than the $Ni-Ni_3S_2$ eutectic (1,193°F) mentioned previously in the discussion of sulfidation mechanisms.

The position of cobalt-base alloys is weakened, however, by the Pratt and Whitney observation (Report PWA 2218, 1962) that under their exposure conditions nickel-base alloys fare better than alloys with a balance of cobalt.

Intensive investigations on the effects of compositional changes on the sulfide resistance of superalloys is under way at several laboratories. No one disputes the beneficial effects of chromium in counteracting the corrosion of both nickel and cobalt-base alloys. Figure 18 gives the variation of weight loss with chromium percentages in nickel–chromium alloys exposed to a 90–10 sulfate–chloride mixture.

Two additional facts about chromium content are known:

1. The addition of chromium is made at the expense of strength.
2. The influence of chromium on the complex process of sulfidation cannot be prejudged for any particular composition.

Additions of aluminum and titanium were also found to be helpful in reducing sulfidation corrosion of nickel-base alloys. Lycoming (1964) suggested that titanium is about 1.5 times as effective as aluminum on a weight basis in suppressing severe corrosion. The superalloys with a proper balance of cobalt usually do not contain these elements. Lewis and Smith (1961), who suggested the foregoing relationship, suggest that carbon and silicon have an adverse influence on the resistance of superalloys to sulfidation. The detrimental effects of silicon were observed before 1961 by Caplan and Cohen (1959). They attributed periods of accelerated oxidation of three austenitic stainless steels to disruption of the protective scale <u>after</u> a silica

layer had accumulated at the metal—scale interface. The role of carbon in forming undesirable complex carbides at grain boundaries has been mentioned previously. Low percentages of carbon and silicon are typically found in superalloys of both nickel and cobalt base.

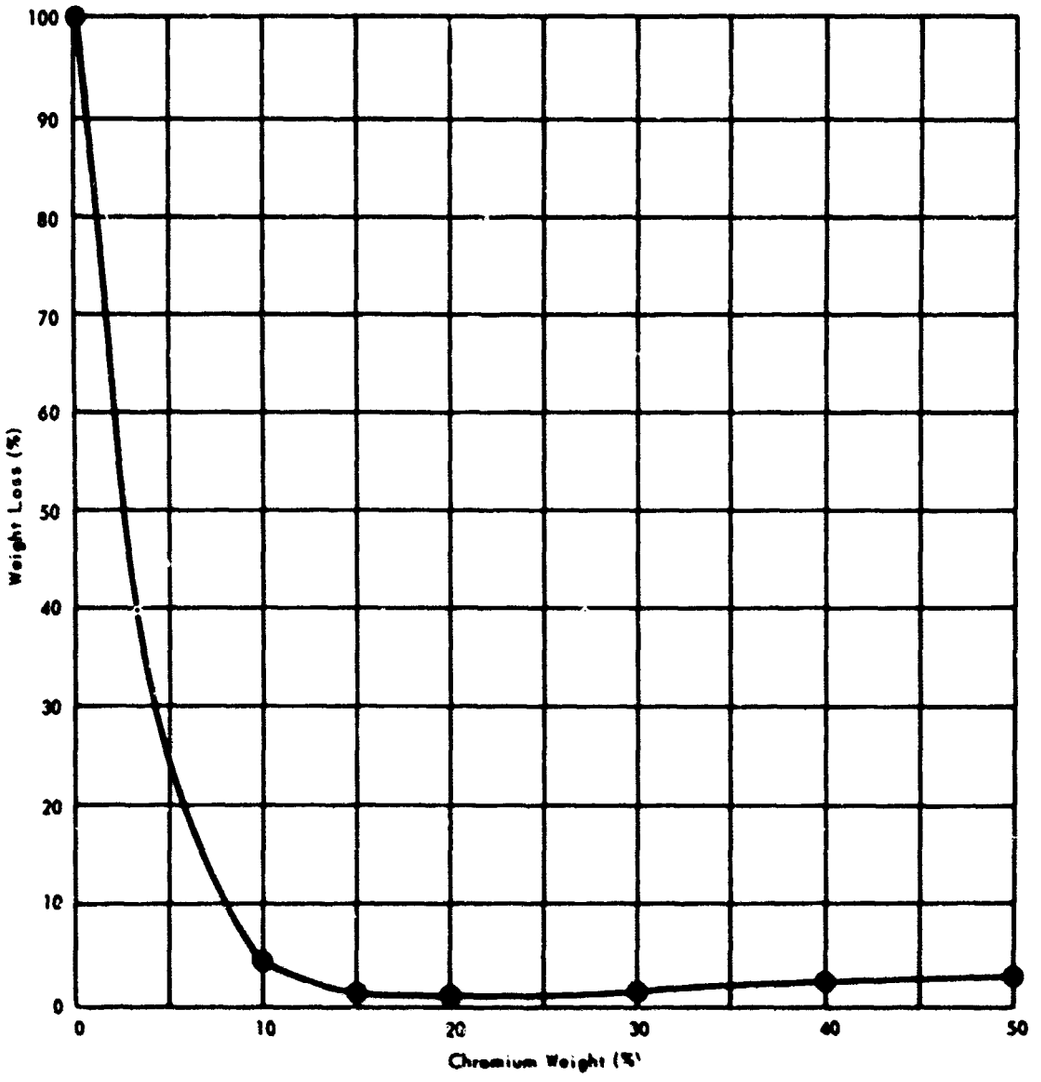


Figure 18. Corrosion rates of Ni—Cr alloys after 100 hours at 1,700°F in a 90% Na_2SO_4 ± 10% NaCl mixture in air. (Courtesy of Lycoming Division, AVCO Corp.)

Attempts to improve "hot section" durability of marine gas turbines resulted in the developments and discoveries discussed in the foregoing section. These works constitute a small portion of the continued search for an alloy immune to sulfidation attack. Interest in austenitic chromium–manganese steels exhibiting good high-temperature strength characteristics and substantial resistance to sulfate–chloride slag was generated by Greenert (1962c). He concluded that practical high-strength, high-temperature alloys exhibiting good resistance to fuel-ash corrosion may be obtained by the addition of copper and silicon to the chromium–manganese steels. Piearcey and VerSnyder (1965) reported the recent development by Pratt and Whitney of a "directional solidification process" for casting superalloys. This process results in longitudinal columnar grains with a preferred orientation, thereby eliminating the transverse grain boundaries believed to be a cause of high-temperature failure in gas turbine parts. Nickel base PWA 659 of PWA 664 composition and cobalt base PWA 653 cast by the "controlled conventional process" were compared to PWA 664 for blade and vane applications, respectively. The nickel base superalloy PWA 664 cast by the new process demonstrated superior strength and ductility as a blade and superior resistance to deformation and thermal shock as a vane.

Only one investigation is known in which a material clearly demonstrated immunity to high-temperature corrosion. Inconel 713C treated with a diffused aluminum coating designated as MDC-1* was tested under simulated marine conditions in the 2-inch combustor of the Phillips Petroleum Company. Quigg et al (1965) reported immunity of this combination to attack under the wide range of conditions investigated.

METHODS OF COUNTERACTING SULFIDATION

The most common method of protecting superalloys from attack in marine operation is the application of protective metallic coatings. The electrodeposit of a two-layer nickel-over-chromium plating made molybdenum steel turbine blades feasible in the late fifties. The plating prevented oxidation of molybdenum for over 1,000 hours at 1,796°F in aircraft installations (News item, 1958). Nickel is more commonly used in combination with cadmium in marinizing treatments of aircraft turbines. Cadmium, nickel, and nickel–cadmium platings have been suggested for use on materials subject to accelerated corrosion from seawater ingestion, according to reports on the marinization of the Pratt and Whitney FT4 (White, 1962) and FT12 (Nolte, 1965) gas turbine engines. Aluminum coating of both nickel- and cobalt-base superalloys was established as an outstanding method of deferring corrosion by Preston (1965) and Bowers (1965), both of whom used aluminizing surface treatments for counteracting sulfidation in British installations. Hanink (1965) reported the

* Proprietary company designation for a diffused aluminum coating.

development by General Motors of Alpak coating, which involves surface impregnation with aluminum and has proved to be a good corrosion preventive on Inco 713C. The Phillips observation of immunity to sulfidation of this nickel-base alloy when coated with Misco MDC-1 diffused aluminum coating was previously noted. Stoeckly (1965) reported on marinization tests by General Electric Company of MDC-1 and four other coatings for use in their Model LM 1500 gas generators. His conclusions were:

1. Since coatings can adversely affect the mechanical properties of alloys, the results of a coating's performance on one alloy are no indication of its performance on another alloy.
2. Coatings are usually brittle, so require careful handling.
3. The advisability of stripping and recoating used coated parts is doubtful at present.
4. Parameters affecting coating life are time, temperature, corrosive environment, and characteristics of erosive agents in the gas stream.

Bradley (1965) points out the sensitivity of the life of intermetallic nickel–aluminum diffused aluminum coating to other parameters, including technique of application, alloy surface preparation, coating thickness, and the diffusion cycle.

Erosion is produced primarily by small carbon particles, which are formed in the burners during combustion and are carried past the vanes and blades by the high-temperature, high-velocity gas stream. The loss of protective coatings by erosion leaves superalloys open to sulfidation attack. The carbon particles not only cause erosion of coatings and base metal, but may cause severe coke buildup, as shown in Figure 19. This coke may then become lodged in gas turbine vanes and abrade the leading edge of first-stage blades (Nolte, 1965; Beck, 1965), as shown in Figure 20. Unfortunately, erosive combustion products cannot readily be eliminated from the gas stream as can salt and dust particles from the intake air.

The problem of dust erosion encountered in land-based installations does not usually arise in marine gas turbine installations. Mund and Murphy (1963) gave a comprehensive treatment of dust erosion and its prevention. The problems arising from sea-salt ingestion by marine gas turbines are well appreciated. Kaufman (1965) related that the problems requiring solution in the reduction or elimination of air-ingested sea salt by naval gas turbines are:

1. The definition of a "maximum acceptable concentration," considering engine endurance.
2. The definition of a "maximum expected concentration" to be encountered in naval operations.
3. The importance of particle-size distribution, as well as sea-salt concentration, to the problem of separation.
4. The preparation of specifications for a full-scale separator system.

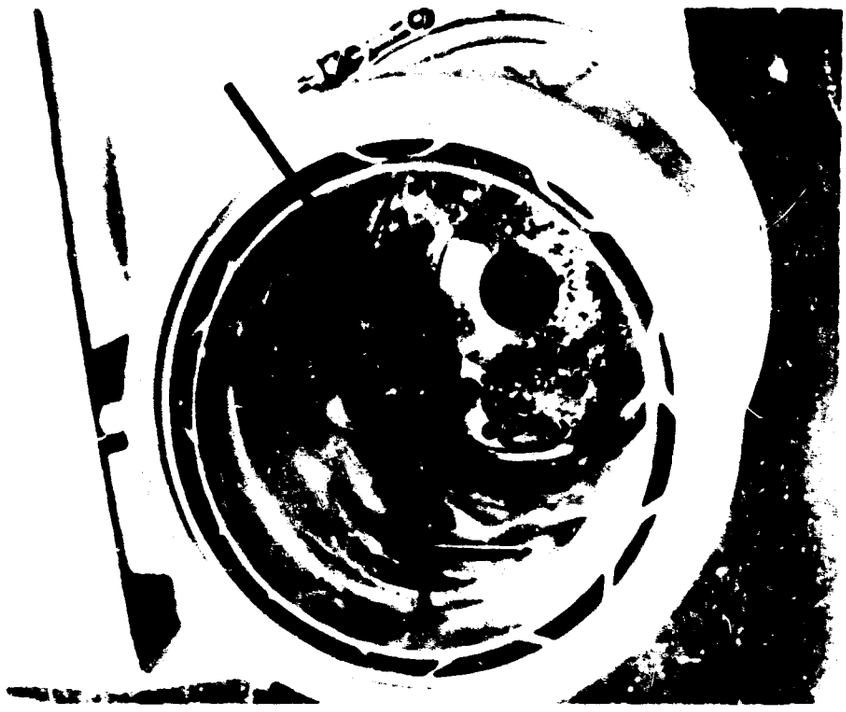


Figure 19. Severe coke buildup in area of igniter and crossover firing tube in Boeing gas turbine combustion liner.

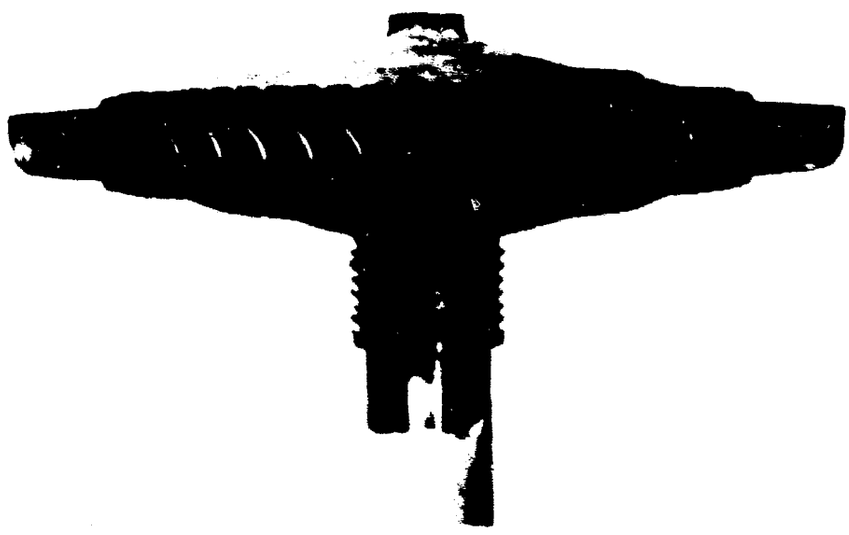


Figure 20. Worn leading corners of producer section turbine blading caused by coke lodged in nozzle blading.

He also discussed several techniques of separating particles from gas flows — each having an efficiency dependent on particle size and concentration. These included baffling, electrostatic precipitation, interpositional filtration, and inertial separation. Of these, inertial and precipitation techniques are readily applicable to marine gas turbines. In selecting a separator, high-pressure drops at the compressor with consequent power losses must be avoided. According to Kaufman (1965), if sea-salt particles below 5 microns in diameter are a problem, then separation must be accomplished in mechanical and electrostatic precipitators. Bowers (1965) stated: "Control of the atmosphere ingested by the gas turbine is of major importance, and we consider it essential to fit most eliminators of the knitted-mesh-type for this purpose."

Large land-based or marine gas turbines are made economically competitive with diesel engines and steam turbines by burning cheap fuel, the vanadium and sodium content of which can cause severe corrosion which must be inhibited. Methods of washing and centrifuging the fuel are available by which sodium can be removed from fuels. Vanadium cannot be removed by such techniques and, therefore, corrosion is inhibited with fuel additives. Figure 21 illustrates the effect of various additives in inhibiting corrosion (Bowden et al, 1953). Silicon dioxide is seen to be a superior performer.

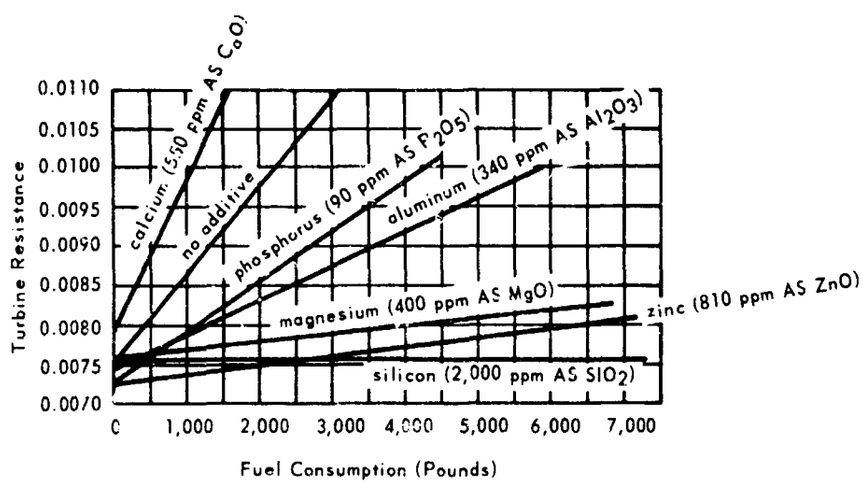


Figure 21. Effect of various additives on deposition. (Courtesy of Institution of Mechanical Engineers Proceedings.)

Scott (1965) reported the availability of a metal–organic silica additive called Perolin 602 GT. Its value in operating large gas turbines is stressed by Pfenninger (1965). The manufacturer believes his additive would inhibit sulfidation. A recent Phillips Petroleum report by Aldrich and Schirmer (1964), cited by Danek (1965), concludes that the fuel-additive approach merits further study as a means of reducing hot corrosion of turbine blading.

In naval boilers ash corrosion is effectively controlled by a lime slurry coating and water-washing treatment (Greenert, 1962c). Freshwater washing of compressor blading is also used where sea salt is ingested by naval turbines. Fouling of the compressor with salt deposits causes exhaust-gas temperatures to exceed those recommended in order to maintain power, increasing the probability of sulfidation. Cleaning solutions include water, kerosene, methanol, and water solutions of household detergents. Solid cleaning agents include crushed walnut shells, apricot pits, and coffee grounds. Weinert and Carlton (1965) pointed out, however, that salt washed from the compressor may be redeposited in the engine hot sections and solid cleaners may remove protective coatings as well as slag.

Gas turbine operating temperatures may be reduced to acceptable levels by cooling schemes employing both water and air. Water injection as applied to a Rover IS/60 gas turbine is described by McIlroy (1964). Water sprayed through twin nozzles into the air-inlet ducts depresses the air-inlet temperature and increases the weight of the charge. The resulting depression allows greater fuel consumptions and consequent increases in turbine output. The water evaporates to steam, an effective working medium.

Ainley (1956) described methods of reducing metal temperatures which allow operation of turbines at high gas temperatures without early blading failure. Cooling of the rotor blades is accomplished by applying liquid or air to the blade either internally or externally. Free and forced convection processes are used internally, although external surfaces are evaporatively cooled. Maximum gas temperatures are commonly established to avoid sulfidation in marine gas turbines. Severe reductions in fuel economy result. Danek (1965) lists references which recommend limitations of 1,550°F in the United States and 1,525°F in Great Britain. Joseph (1965) reports the derating of a sanitation plant turbine 30% to hold firing temperatures below 1,400°F to avoid sulfidation.

Between 1958 and 1960 the Central Electricity Generating Board in London, England, pioneered the restriction of excess air in the oil firing of boilers to limit oxygen concentration. Crossley (1964) reported the beneficial effects of oxygen reduction with respect to minimizing SO_3 in flue gases. The careful control of air–fuel ratios is as important in gas turbine operation as it is in boiler operation, with combustion control particularly important to gas turbines in marine atmospheres. Excessively high air-intake and firing temperatures in marine operation enhance sulfidation attack. Contamination of fuel in storage is described by Westwood (1965) as a source of corrosion in Air Force jet engines. Stored fuel frequently becomes

contaminated with condensation, which corrodes the tanks. Weinert and Carlton (1965) suggest that tanks be constructed of corrosion-resistant materials, such as aluminum and stainless steel, to minimize contamination from this source. Leakage of seawater into hull tanks and the supply lines of ships must, of course, be prevented. Digman (1962) calls attention to a requirement for the regular maintenance of filters, water separators, and storage tanks to ensure quality control in fuels.

RDT&E IN PROGRESS AND PLANNED

An operating time of 5,000 hours between overhauls is a goal set for gas turbines if they are to be competitive with other prime movers in general naval service (Danek, 1965). This goal appears to be attainable if intensive investigations currently under way are successful. A government–industry advisory group composed of 26 persons knowledgeable in the field of sulfidation corrosion met at the U. S. Navy Marine Engineering Laboratory in June 1964. A majority of the participants felt that efforts to develop improved alloys should parallel corrosion control. Program objectives included target dates of 1968 for 1,750°F firing temperatures and 1970 for 2,000°F firing temperatures.

A two-phase program initiated in January 1965 is in progress at General Electric facilities in Schenectady under contract from the U. S. Navy Marine Engineering Laboratory (Foster, 1965). Phase I involves a study of basic corrosion mechanisms and Phase II involves the development of more resistant cobalt- and nickel-base alloys.

Hanink (1965) describes laboratory and engine testing currently under way at the Allison Division of General Motors Corporation. Tests are conducted at about 1,800°F under simulated marine conditions.

An extensive program is in progress at the Lycoming Division of AVCO Corporation to:

1. Evaluate the sulfidation resistance of gas turbine blading materials.
2. Provide data for the future development of improved alloys.
3. Gain an increased understanding of hot corrosion mechanisms in gas turbines (see Freeman, 1965).

The Phillips Petroleum Company has been working in the problem area of marine gas turbine operations for several years under BUWEPS sponsorship (Reid, 1965). The final phase of an investigation to determine the merit of the 0.40% maximum sulfur content specified for grade JP-5 aero-turbine fuel is expected to be completed in the near future. At the June 1965 meeting of the ASTM Gas Turbine Panel headed by B. O. Buckland of General Electric, Schenectady, the Hot Corrosion Task Force headed by C. C. Clark of Inco was authorized to organize a symposium on hot

corrosion to be presented at the next ASTM annual meeting. Informal discussions were presented at the June 1965 Hot Corrosion Workshop of the Task Force by General Electric, Westinghouse, Lycoming, Allison, and the Navy.

CONCLUSIONS

1. The gas turbine at present is not a dependable prime mover for long-time operation in a marine atmosphere, because of potential early failures from high-temperature corrosion.

2. Gas turbines must be derated to reduce firing temperatures in order to reduce sulfidation in unprotected engines.

3. The sulfidation of marine turbine hardware is effectively retarded by coating base metals with aluminum impregnations and by separating salt spray from the intake air.

4. Cobalt- and nickel-base superalloys for nozzle vane and turbine wheel blades show the most promise in marine gas turbine applications.

5. Both laboratory and field testing indicate a great need for extensive investigations toward the understanding and prevention of sulfidation corrosion in gas turbines operating in a marine atmosphere.

RECOMMENDATIONS

1. Gas turbines should not be used in low-output installations in a marine atmosphere until problems of high-temperature corrosion are solved.

2. Progress in existing sulfidation research programs should be closely followed.

REFERENCES

Ainley, G. D. (1956). "Hot turbines; an NGTE engineers exposition of a crucial subject," Flight, vol. 69, no. 2640, Mar. 16, 1956, pp. 292-295.

Aldrich, E. W., and Schimmer, R. M. (1964). Inhibition of hot corrosion of superalloys by fuel additives. Phillips Petroleum Company, Research Division, Report no. 3823-64R, Bartlesville, Okla., Aug. 1964.

Beck, E. J. (1965). Laboratory experiences with a gas turbine powered power package. U. S. Naval Civil Engineering Laboratory, Technical Note N-746, Port Hueneme, Calif., Oct. 1965.

Bergman, P. A. (1964). Saline corrosion of aircraft gas turbine materials at temperatures up to 2,000°F. General Electric Company, Report no. R64SE10, Schenectady, N. Y., Apr. 1964.

Boll, R. H., and Patel, H. C. (1961). "The role of chemical thermodynamics in analyzing gas-side problems in boilers," American Society of Mechanical Engineers, Transactions, series A, Journal of Engineering for Power, vol. 83, no. 4, Oct. 1961, pp. 451-467. (ASME paper no. 60-WA-182)

Bowden, A. T., Draper, P., and Rowling, H. (1953). "The problem of fuel ash deposition in open-cycle gas turbines," Institution of Mechanical Engineers, Proceedings (A), vol. 167, no. 3, pp. 291-300.

Bowers, N. K. (August 20, 1965). Personal communication (letter). Commander, Royal Navy for Director General of Ships, Ministry of Defense, England.

Bradbury, E. J., Hancock, P., and Lewis, H. (1963). "The corrosion of nickel-base material in gas-turbine and boiler atmospheres," Metallurgia, vol. 67, no. 399, Jan. 1963, pp. 3-14.

Bradley, E. F. (August 9, 1965). Personal Communication (letter). Chief, Materials Engineer, Pratt & Whitney Aircraft Division, United Aircraft Corporation.

Burwood-Smith, A. (August 11, 1965). Personal communciation (letter). For Director of National Gas Turbine Establishment at Pyestock, Farnborough, Hampshire, England.

Cain, C., Jr., and Nelson, W. (1961). "Corrosion of superheaters and reheaters of pulverized-coal-fired boilers, II." American Society of Mechanical Engineers, Transactions, series A, Journal of Engineering for Power, vol. 83, no. 4, Oct. 1961, pp. 468-474. (ASME paper no. 60-WA-180)

Caplan, D., and Cohen, M. (1959). "High temperature oxidation of chromium-nickel steels," Corrosion, vol. 15, no. 3, Mar. 1959, pp. 141t-146t.

Carlton, G. A. (1964). Evaluation of Pratt & Whitney FT4A marine GT engine — 1,000 hour endurance run. Final Report on NBTL Project T-434, U. S. Naval Boiler and Turbine Laboratory, Naval Shipyard, Philadelphia, Pa., June 1964.

Cartwright, B. (1961). "Vacuum cast alloys for turbine blades," The Aeroplane and Astronautics, vol. 100, no. 2584, Apr. 27, 1961, pp. 467-468.

Chiarito, P. T., and Johnston, J. R. (1959). Experimental evaluation of cermet turbine stator blades for use at elevated gas temperatures. National Aeronautics and Space Administration, Memorandum no. 2-13-59E, Washington, D. C., Feb. 1959.

Clark, C. C. (August 6, 1965). Personal communication (letter). In charge, Aeronautical Section, International Nickel Company.

Crossley, H. E. (1964). "Marchwood and now — advancement of boiler operating conditions," paper presented at American Society of Mechanical Engineers Winter annual meeting, New York, Nov. 29-Dec. 3, 1964. (ASME paper no. 64-WA/CD-3)

Dalton, C. A. (1965). "Sulfur and sea salt attack of turbine blades," paper presented at American Society of Mechanical Engineers Gas Turbine Conference and Products Show, Washington, D. C., Feb. 28-Mar. 4, 1965. (ASME paper no. 65-GTP-7) also in: Marine Technology, vol. 2, no. 3, July 1965, pp. 243-247, 272.

Danek, G. J. (1965). State-of-the-art survey on hot corrosion in marine gas-turbine engines. U. S. Naval Marine Engineering Laboratory, R&D Report 32/65, Annapolis, Md., Mar. 1965. (AD 461181)

Digman, W. J. (1962). "Contaminant control curbs jet fuel tank corrosion," Society of Automotive Engineers, Journal, vol. 70, no. 12, Dec. 1962, pp. 56-58. (SAE paper 575A)

Dunlop, A. (1960). "High temperature alloys," Metal Industry, vol. 96, no. 19, May 6, 1960, pp. 378-382.

Evans, U. R. (1947). "The mechanism of oxidation and tarnishing," Electrochemical Society, Transactions, vol. 91, 1947, pp. 547-572. (Preprint no. 91-5 for meeting Apr. 9-12, 1947) also in: Corrosion, vol. 4, no. 4, Apr. 1948, pp. 149-171.

Foster, A. (August 26, 1965). Personal communication (phone call). Production Engineer, General Electric Company, Schenectady, N. Y.

Frederick, S. H., and Eden, T. F. (1954). "Corrosion aspects of the vanadium problem in gas turbines," Institution of Mechanical Engineers, Proceedings, vol. 168, no. 3, 1954, pp. 125-130.

Freeman, W. R., Jr. (August 6, 1965). Personal communication (letter). Manager, Materials Laboratory, Lycoming Division, AVCO Corporation.

Grandey, M. F. (August 9, 1965). Personal communication (letter). Materials Development Laboratory, General Electric Company.

Graves, G. L., Jr., and Sawyer, J. W. (1963). "Turbines go to sea," Machine Design, vol. 35, no. 25, Oct. 24, 1963, pp. 144-149.

Greenert, W. J. (1962a). "High temperature slag corrosion of metallic materials — Part I. Theoretical considerations of slag induced corrosion," Corrosion, vol. 18, no. 2, Feb. 1962, pp. 57t-66t.

Greenert, W. J. (1962b). "High temperature slag corrosion of metallic materials — Part II. Failed service parts and remedial treatments," Corrosion, vol. 18, no. 3, Mar. 1962, pp. 91t-95t.

Greenert, W. J. (1962c). "High temperature corrosion of metallic materials — Part III. Comparative resistance of materials," Corrosion, vol. 18, no. 3, Mar. 1962, pp. 95t-102t.

Hanink, D. K. (August 6, 1965). Personal communication (phone call). Chief, Materials Laboratory, General Motors Corporation, Allison Division, Indianapolis, Ind.

Hoffman, C. A. (1956). Investigation of a cermet gas-turbine-blade material of titanium carbide infiltrated with Hastelloy C. National Advisory Committee for Aeronautics, Research Memorandum RM E55H12, Washington, D. C., Jan. 1956.

Joseph, J. (1965). "At California sanitation plant — sludge gas fuels turbine," Diesel and Gas Engine Progress, vol. 31, no. 9, Sept. 1965, pp. 61-63.

Kaufman, R. E. (1965). "Salt water aerosol separator development," paper presented at American Society of Mechanical Engineers Gas Turbine Conference and Products Show, Washington, D. C., Feb. 28-Mar. 4, 1965. (ASME paper no. 65-GTP-9)

Kearns, T. F. (August 18, 1965). Personal communication (letter). Head, Metals Branch, Materials Division, Naval Weapons Support Activity, by direction of Chief of Bureau.

Kennametal, Inc. (1951). "Kentanium new heat-resistant titanium alloy, resists thermal shock, withstands oxidation, retains strength at high temperatures (1,800°F and above)," Latrobe, Pa., Oct. 1951. (Abstract in trade literature)

Lamb, J. and Duggan, R. M. (1953). "Operation of a marine gas turbine under sea conditions," British Motor Ship, vol. 34, no. 404, Nov. 1953, pp. 336-338.

Lewis, H., and Smith, R. A. (1961). "Corrosion of high-temperature nickel-base alloys by sulfate-chloride mixtures," in Proceedings, First International Congress on Metallic Corrosion, London, England, Apr. 10-15, 1961. London, Butterworths, 1962, pp. 202-214.

Lycoming Division (1964). AVCO Corporation. Technical Proposal no. LYP 2040.3: Corrosion mechanisms study. Stratford, Conn.

Marquette Coppersmithing Company. (July 15, 1965). Personal communication (letter).

McCullough, H. M., Fontana, M. G., and Beck, F. H. (1951). "Formation of oxides on some stainless steels at high temperatures," American Society for Metals, Transactions, vol. 43, 1951, pp. 404-425.

McIlroy, H. M. (1964). "Water injection applied to a Rover 15/60 gas turbine," The B. C. Professional Engineer, Aug. 1964, pp. 16-18.

Monkman, F. C., and Grant, N. J. (1953). "An investigation of accelerated oxidation of heat resistant metals due to vanadium," Corrosion, vol. 9, no. 12, Dec. 1953, pp. 460-466.

Mund, M. G., and Murphy, T. E. (1963). "The gas turbine-air-cleaner dilemma," paper presented at American Society of Mechanical Engineers Aviation and Space, Hydraulic, and Gas Turbine Conference and Products Show, Los Angeles, Calif., Mar. 3-7, 1963. (ASME paper no. 63-AHGT-63)

Nelson, W., and Cain, C., Jr. (1960). "Corrosion of super heaters and reheaters of pulverized-coal-fired boilers," American Society of Mechanical Engineers, Transactions, series A, Journal of Engineering for Power, vol. 82, no. 3, July 1960, pp. 194-204. (ASME paper no. 59-A-89)

News item (1958). Chemical Week, vol. 21, Nov. 22, 1958, p. 62. (On new National Bureau of Standards coating)

Nolte, G. H. (1965). "Sea experience with Pratt and Whitney aircraft FT12 gas turbine in LCM-8," paper presented at American Society of Mechanical Engineers Gas Turbine Conference and Products Show, Washington, D. C., Feb. 28-Mar. 4. 1965. (ASME paper no. 65-GTP-26) also in: Marine Technology, vol. 2, no. 4, Oct. 1965, pp. 370-379.

Pfenninger, H. (1962). "Operating results with gas turbines of large output," paper presented at American Society of Mechanical Engineers Winter annual meeting, New York, Nov. 25-30, 1962. (ASME paper no. 62-WA-188)

Piearcey, B. J., and VerSnyder, F. L. (1965). A new development in gas turbine materials (The properties and characteristics of PWA 664). Pratt and Whitney Aircraft Division, United Aircraft Corporation. Report no. 65-007, East Hartford, Conn., Apr. 1965.

Pierce. J. W. (July 26, 1965). Personal communication (letter). Supervisor, Engineering Standards, Southern California Gas Company.

Pratt & Whitney Aircraft Division. United Aircraft Corporation. Report PWA 2218: FT4A-2 laboratory sulfidation testing, laboratory component testing, including appendix A. Design report for FT4A-2 maintenance structure. East Hartford, Conn., 1962. (Contract NObs 84755)

Preston, C. E. M. (August 11, 1965). Personal communication (letter). General Sales Manager, Bristol Siddeley Engines Ltd.

Quigg, H. T., Fromm, E. H., and Schirmer, R. M. (1965). Effects of JP-5 sulfur content on hot corrosion of superalloys in marine environment, progress report no. 4. Phillips Petroleum Company, Research Division, Report 4123-65R, Bartlesville, Okla., July 1965. (AD 619656) (Contract no. NOw-64-0443-d)

Reid, J. A. (August 31, 1965). Personal communication (letter). Manager, Research Division, Phillips Petroleum Company.

Schley, J. R. (August 16, 1965). Personal communication (letter). Manager, Applic. Engineering Technology Dept., Union Carbide Corporation, Stellite, Div.

Scott, J. S. (July 27. 1965). Personal communication (phone call). Vice-President, Perobin Company, Inc., New York.

Shirley, H. T. (1956). "Effects of sulphate-chloride mixtures in fuel-ash corrosion of steels and high-nickel alloys," Iron and Steel Institute, Journal, vol. 182, pt. 2, Feb. 1956, pp. 144-153.

Simons, E. L., Browning, G. V., and Liebhafsky, H. Y. (1955). "Sodium sulfate in gas turbines," Corrosion, vol. 11, no. 12, Dec. 1955, pp. 505t-514t.

Stoeckly, E. E. (1965). "Marinization of the General Electric LM 1500 gas turbine," paper presented at American Society of Mechanical Engineers Gas Turbine Conference and Products Show, Washington, D. C., Feb. 28-Mar. 4, 1965. (ASME paper no. 65-GTP-20) also in: Marine Technology, vol. 2, no. 3, July 1965, pp. 273-281.

Sulzer, P. T. (1955). "The influence of some chemical and physical factors on the formation of deposits from residual fuels," American Society of Mechanical Engineers, Transactions, vol. 77, no. 10, Oct. 1955, pp. 995-1001. (ASME paper no. 54-A-171)

Tyler, J. R. (August 9, 1965). Personal communication (letter). Engineering Manager, Turbo & Allied Products Division, Ruston & Hornsby Ltd., Lincoln, England.

U. S. Navy. Bureau of Yards and Docks. NAVDOCKS P-103: Detailed catalog of equipment and construction material for advanced base functional components. Washington, D. C., revised Jan. 1966.

Weinert, E. P. and Carlton, G. A. "Salt-water problems in marine gas turbines," paper presented at the American Society of Mechanical Engineers Gas Turbine Conference and Products Show, Washington, D. C., Feb. 28-Mar. 4, 1965. (ASME paper no. 65-GTP-18)

Westwood, Captain. (August 25, 1965). Personal communication (phone call), and K. Kolsov (General Electric representative) Arnold Development Center, Tullahoma, Tenn.

White, W. E. (1962). An investigation of requirements for protecting an FT4 engine against the effects of seawater and high sulfur marine diesel fuel. Pratt and Whitney Aircraft, United Aircraft Corporation, Report PWA-2070, East Hartford, Conn., June 1962. (AD 473582L) (Contract no. NObs 84755)

Young, W. E., Hershey, A. E., and Hussey, C. E. (1955). "The evaluation of corrosion resistance for gas-turbine-blade materials," American Society of Mechanical Engineers, Transactions, vol. 77, no. 10, Oct. 1955, pp. 985-994. (ASME paper no. 54-A-215)

BIBLIOGRAPHY

Brown, T. W. F. (1954). "High-temperature turbine machinery," British Motor Ship, vol. 34, no. 407, Feb. 1954, pp. 498-499. (Abstract of 26th Thomas Lowe Gray lecture before the Institution of Mechanical Engineers).

Buckland, B. O. (1954). "Corrosion and deposit in gas turbines," Industrial and Engineering Chemistry, vol. 46, no. 10, Oct. 1954, pp. 2163-2166.

Carlson, C. L. (1964). "FT4 gas-turbine engine for marine and industrial applications," paper presented at American Society of Mechanical Engineers Gas Turbine Conference and Products Show, Houston, Texas, Mar. 1-5, 1964. Abstract in: Mechanical Engineering, vol. 86, no. 5, May 1964, p. 68. (ASME paper no. 64-GTP-8)

Colombier, L. (1955). "High temperature corrosion resistant steels and alloys (Les aciers et allaiges resistant a la corrosion aux temperatures elevees)" Métaux-Corrosion Industries, vol. 30, no. 359-360, July-Aug. 1955, pp. 294-303. Also available as Special Libraries Association translation no. 62-18741, from SLA Translations Center, John Crerar Library, 35 West 33rd Street, Chicago, Illinois 60616

Daish, T. G. (1964). "The sea experience of Bristol Siddeley marine gas turbines," paper presented at American Society of Mechanical Engineers Gas Turbine Conference and Products Show, Houston, Texas, Mar. 1-5, 1964. Abstract in: Mechanical Engineering, vol. 86, no. 5, May 1964, p. 70. (ASME paper no. 64-GTP-10)

The Engineer (1951). "Critical review of gas turbine progress 1950," The Engineer, vol. 191, Jan. 12, 1951, pp. 50-52.

Evans, U. R. (1960). The corrosion and oxidation of metals: scientific principles and practical applications. New York, St. Martins, 1960.

Foster, W. R., Leipold, M. H., and Shelvin, T. S. (1956). "A simple phase equilibrium approach to the problem of oil-ash corrosion," Corrosion, vol. 12, no. 11, Nov. 1956, pp. 539t-548t.

Hansen, W. A. and Kessler, G. W. (1965). "Fuel–ash corrosion and its effects on boiler design," American Society of Mechanical Engineers, Transactions, series A, Journal of Engineering for Power, vol. 87, no. 2, Apr. 1965, pp. 210-214. (ASME paper no. 64–Pwr-11)

Hardgrove, G. A. (1960). "Turboshaft power for marine propulsion," paper presented at American Society of Mechanical Engineers Winter annual meeting, New York, Nov. 27-Dec. 2, 1960. (ASME paper no. 60–WA-332) Abstract in: Mechanical Engineering, vol. 83, no. 6, June 1961, p. 91.

Hryniszak, W. (1956). "The present state of gas turbine development (Derzeitiger Stand der Gasturbinenentwicklung)," MTZ (Motortechnische Zeitschrift), vol. 17, no. 1, Jan. 1956, pp. 16-23; no. 2, Feb. 1956, pp. 53-58; no. 3, Mar. 1956, pp. 82-90. Also available as Special Libraries Association translation no. 62-18742, from SLA Translations Center, John Crerar Library, 35 West 33rd Street, Chicago, Illinois 60616.

Johnson, H. R. and Littler, D. J., eds. (1963). The mechanism of corrosion by fuel impurities; proceedings of the international conference held at Marchwood, near Southampton, Hampshire, England, 20th-24th May 1963. London, Butterworth & Company, 1963.

Kerr, W. A. (1964). "Installation and operation of the model LM100 turboshaft engine aboard the HS 'Denison'," paper presented at American Society of Mechanical Engineers Gas Turbine Conference & Products Show, Houston, Texas, Mar. 1-5, 1964. (ASME paper no. 64–GTP-26) Abstract in: Mechanical Engineering, vol. 86, no. 6, 1964, p. 66.

King, H. F. and Nutt, H. V. (1956). "Fuels for U. S. Navy gas turbines," American Society of Mechanical Engineers, Transactions, vol. 78, no. 1, Jan. 1956, pp. 185-196. (ASME paper no. 55–OGP-8)

Kubaschewski, O., and Hopkins, B. E. (1962). Oxidation of metals and alloys, 2nd ed. New York, Academic Press, 1962.

Markham, B. G. (1959). "Marine proteus engines for the brave class patrol boats," Institute of Marine Engineers, Transactions, vol. 71, no. 10, Oct. 1959, pp. 316-323.

Mund, M. G. et al (1962). "Turbines taken to the cleaners," Society of Automotive Engineers, Journal, vol. 70, no. 11, Nov. 1962, pp. 84-89.

Neville, L. E. and Silsbee, N. F. (1948). Jet propulsion progress; the development of aircraft gas turbines. New York, McGraw-Hill, 1948.

Palmer, I. (1962). "Hydrofoil seacraft with gas turbines," Mechanical Engineering, vol. 84, no. 7, July 1962, pp. 36-40. (ASME paper no. 62–GTP-4)

Rhodin, T. N. (1956). "Oxide films on stainless steels," Corrosion, vol. 12, no. 3, Mar. 1956, pp. 123t-135t.

Schirmer, R. M., Quigg, H. T., and Mengelkamp, R. A. (1964). Effect of JP-5 sulfur content and seawater ingestion on hot gas corrosion of superalloys, progress report no. 3. Phillips Petroleum Company, Research Division Report 3696-64R, Bartlesville, Okla., June 1964. (AD 602152) (Contract NOw-63-0406-d)

Shreir, L. L., ed. (1963). Corrosion, vol. 1, Corrosion of metals and alloys. New York, Wiley, 1963.

Slosson, W. L. (1953). "Metallurgical aspects of the development of small gas turbines," Journal of Metals, vol. 5, no. 11, Nov. 1953, pp. 1419-1426.

Uhlig, H. H., ed. (1948). The corrosion handbook. New York, Wiley, 1948.

Vickers, W. C. (1964). "The use of gas turbines as marine auxiliary machinery," paper presented at American Society of Mechanical Engineers Gas Turbine Conference and Products Show, Houston, Texas, Mar. 1-5, 1964. (ASME paper no. 64-GTP-9) Abstract in: Mechanical Engineering, vol. 86, no. 5, May 1964, p. 68.

Weintraub, M., Goldberg, S., and Orning, A. A. (1961). "A study of sulfur reactions in furnace deposits," American Society of Mechanical Engineers, Transactions, series A, Journal of Engineering for Power, vol. 83, no. 4, Oct. 1961, pp. 444-450. (ASME paper no. 60-WA-183)

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13. ABSTRACT

Under consideration is the concept of a total energy package consisting of a gas-turbine-driven generator and a waste-heat boiler for use in the advanced base functional component system. The results of a survey show that a total energy package will probably not provide balanced heat and electrical energy demands, making the small gas turbine a poor logistic and economic choice for a prime mover. Suggestions are offered for the utilization of waste heat from diesel generators, where feasible. Included in the report as an Appendix is a literature study of high-temperature corrosion of turbine blading in a marine atmosphere.

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