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The Potential Danger of Fire in Gas Turbine Heat Exchangers

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Increased emphasis is being placed on the regenerative gas turbine cycle, and the utilization of waste heat recovery systems, for improved thermal efficiency. For such systems there are modes of engine operation, where it is possible for a metal fire to occur in the exhaust heat exchanger. This paper is intended as an introduction to the subject, more from an engineering, than metallurgical standpoint, and includes a description of a series of simple tests to acquire an understanding of the problem for a particular application. Some engine operational procedures, and design features, aimed at minimizing the costly and dangerous occurrence of gas turbine heat exchanger fires, are briefly mentioned.

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INTRODUCTION

To improve the thermal efficiency of the gas turbine for military, industrial, and vehicular application, increased emphasis is being placed on the regenerative cycle and the utilization of waste heat recovery for total energy systems. One area that does not appear to have been reported in any depth is the potential danger of heat-exchanger metal fires occurring as a result of a combination of the following: fouling deposit accumulation, foreign body ingestion, excess fuel trapped in the core, material oxidation, and engine overtemperaturing as a result of control malfunction.

For the simple cycle turbo-shaft, or turbojet engine, the occurrence of transient overtemperaturing, as a result of a prolonged hot start say, often results in damage to the combustor liner and the first-stage nozzle. Extreme cases of course result in the failure of the turbomachinery rotating parts with the result that the complete engine may be gutted. For the regenerative cycle, with an exhaust heat exchanger, the problem is aggravated by the fact that the matrix tends to act as a flame trap. One obvious danger is that of unburnt fuel becoming trapped in the ducts and matrix after a series of aborted starts. If a thorough purge procedure is not adopted, there is a distinct possibility that this fuel will be ignited on a subsequent successful engine light off, and burn with sufficient intensity in the confined space to start a metal fire in the thin metal foil structure. Also, during periods of compressor surge, it is possible for the over-rich flame to actually impinge on the heat-exchanger gas inlet face.

The problem of metal fire prevention has become more important with the use of metals in supersonic flight, and such high-temperature systems as gas turbines, furnaces, gas-cooled nuclear reactors, and missile propulsion, but very little published literature is available giving details of actual fires in heat-transfer systems. The use of metal fuels in propulsion has stimulated research on metal ignition and burning processes, particularly for metal powders, but this information is of very little help for the type of hardware systems used in gas turbines. The purpose of this paper is not to closely examine the metallurgical aspects of metal oxidation and ignition close to their metling or burning temperature, but rather to outline the likely hazards which could cause a fire to start in a practical heat-exchange system operating at temperature levels well within the materials structural capability.

A brief summary of heater fires reported in the literature is included, not all of which are actual gas turbine exhaust heat exchangers, but they are in related regenerative systems. This paper is intended as an introduction to the subject in an endeavor to stimulate interest leading to a full understanding of the problem. A series of very simple tests were carried out on a representative recuperator platefin module, in a simulated gas turbine environment, to get a preliminary understanding of the conflagration boundaries for a particular application. Although insufficient work was carried out to give many general recommendations, a series of suggested design features and operational procedures are included to minimize the costly and dangerous possibility of fires in gas turbine exhaust heat exchangers.

METALLURGICAL ASPECTS

Although the main emphasis in this paper is on the engineering rather than metallurgical aspects of heat exchanger fires, some metallurgical considerations are briefly discussed as follows. With current industrial engine temperature operating levels, the main danger of heat exchanger fire results from an excess of fuel or an accumulation of fouling products in the matrix, but mention should also be made of metal oxidation and ignition. For components such as the recuperator, where extended life is economically essential, the material strength determines the maximum safe operating temperature. For some systems metals have been known to ignite and burn at what would normally be structurally safe temperatures. In some cases then, failure by ignition and burning precede failure by structural weakening with temperature, and that the possibility of ignition must be considered in the design of many high temperature metal systems.

Obviously, beyond the scope of this introductory study, there are many metallurgical factors which enter into the problem of metal ignition and burning. Ignition is brought about by the exothermic oxidation reaction between the solid metal and its gaseous environment, and is believed to be closely related to the relatively slow oxidation ("rusting") that occurs on most metals at low temperatures. Burning, on the other hand, may proceed by any of several mechanisms. It may be a surface reaction resulting from an extension of the rusting process, and it is conceivable that a metal could ignite but not burn, the rise in temperature simply leading to melting. A great deal is known about oxidation and, from the metallurgical standpoint, a study of the various mechanisms gives considerable insight into the ignition and burning problem. Most of the metallurgical data in the literature is of a theoretical nature regarding ignition and burning mechanisms. In the literature the effects of varying environmental conditions as regards type of atmosphere, flow velocity, gas pressure and temperature, heat-transfer rates, and so forth, have been reported to see how these influence the oxidation rate and temperature at which failure of a metal sample occurs under ideal controlled laboratory conditions. Detailed accounts of metal combustion, oxidation, and ignition are given in works by Markstein (1),[1] Hill (2), and Reynolds (3).

Under certain circumstances, the ignition temperature depends on the thickness of the oxide scale covering the surface, and obviously any factors which might tend to reduce the scale thickness are important. For high-temperature systems without the presence of fuel or fouling deposits, the metal oxidation can be considered from the viewpoint of possible ignition and combustion due to the exothermic heat release from the accelerated oxidation. It seems logical that, if the oxidation occurs sufficiently rapidly, the heat of oxidation will exceed the heat dissipated in various ways and ignition and combustion will result. One of the main factors that tends to inhibit the oxidation of metals is the formation of an oxide film which separates the air from the base metal. Although most materials from which exhaust heat exchangers are manufactured are combustible if heated sufficiently, current cycle temperatures are way below those associated with the rapid oxidation outlined in the foregoing.

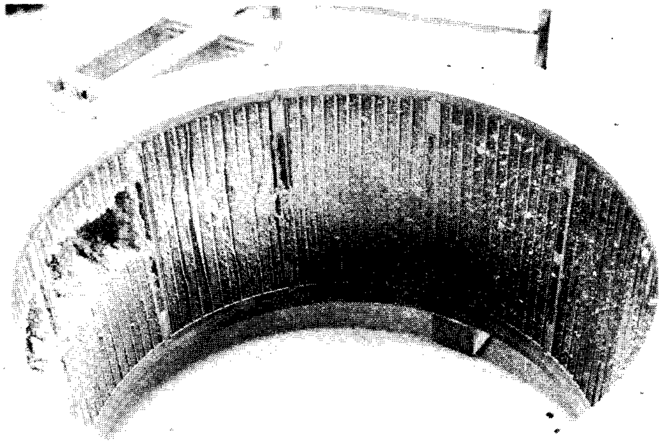

Fig.1 Fire damage to drum type rotary regenerator matrix (S0891)

Some experience with the combustion of metals has been obtained in connection with oxygen cutting torches for a variety of industrial uses. Most nonstainless steels cut rapidly; however, for chrome bearing steels the speed of cutting decreases, and the cutting temperature necessary increases as the chrome content of the steel increases. Data have been reported in which a series of tests in air, oxygen and nitrogen atmospheres, in wind tunnels and under static conditions, indicated that carbon steels were found to have spontaneous ignition temperatures in the solid phase (below melting) and melted very rapidly while burning. The 18-8 series stainless do not appear to have a spontaneous ignition temperature in the solid phase, nor can they be made to ignite at or close to melting.

There appears, at the present level of gas turbine recuperator inlet temperatures, to be no need for concern regarding the ignition of uncontaminated stainless-steel cores, where the material temperature is well below the structural limit and melting temperature. The effect of a typical nickel-manganese-silicon-boron brazing alloy might be expected to reduce the melting temperature of the parent material slightly. The problem we are faced with is not so much a metallurgical oxidation process, but rather metal fires being initiated by the combustion of excess fuel, and fouling deposits on the very thin foils. Some very simple tests on a thin foil plate-fin recuperator module will be outlined in the following.

SUMMARY OF FIRES IN GAS TURBINE HEAT EXCHANGERS

(a) In Fig.1 the damage to a regenerator drum matrix as a result of a metal fire can be

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[1] Numbers in parentheses designate References at end of paper.

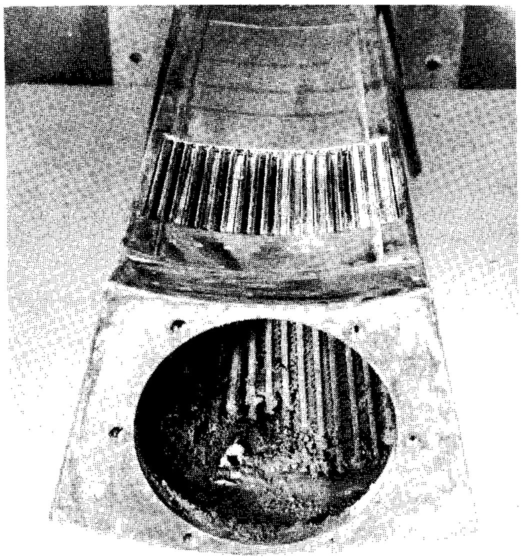

Fig.2 Fire damage to plate-fin type modular recuperator matrix (V860)

clearly seen. The fire occurred during a performance test on a development rig. A series of aborted starts were experienced, and because a thorough purging procedure was not adhered to, the resultant diesel fuel trapped in the matrix started a metal fire after a subsequent combustor light off was achieved. The compact matrix was made from 321 stainless steel.

(b) As outlined by McDonald (4), a fire was experienced in a thin foil plate-fin recuperator module manufactured from 347 stainless steel. The fire occurred during a rig test in which the unit was being thermally cycled, and it appeared that the matrix structurally collapsed allowing a large internal leakage. This caused a reduction in the air flow through the natural gas combustor, and for the fixed natural gas fuel flow schedule, excessively high burner outlet temperatures were experienced. This resulted in failure of the upstream flow straighteners, and these disintegrated and impinged on the core face. This particular fire was related to the test rig design and operation, and such a failure would be unlikely in engine operation. During the thermal cycling, the immediate upstream baffle temperature during a simulated engine acceleration period was in excess of 2000 F. A subsequent analysis of the resultant slag in the matrix indicated that an aluminum particle might have initiated the fire. A view of the damaged core can be seen in Fig.2.

(c) As shown in Fig.3, a fire was experienced in a full-size plate-fin recuperator (347 stainless steel) as a result of excess fuel becoming trapped after a series of aborted engine starts. It was found that a considerable quantity of diesel fuel had become trapped in the matrix and ducting as a result of an inadequate fuel draining system and lack of a thorough purging procedure. A CO_2 fire extinguishing system was activated after the fire had started, and although this prevented damage to the rest of the engine, the response time of the exhaust overtemperaturing sensor was too slow to prevent severe damage to the recuperator.

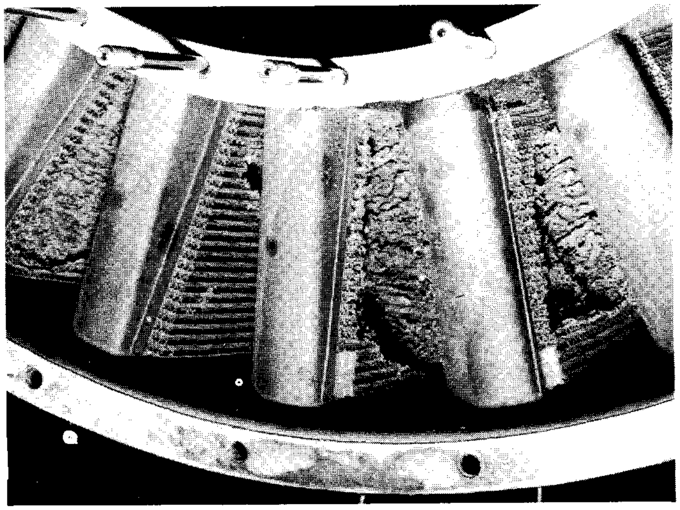

Fig.3 Fire damage to recuperator gas inlet face (67-1756)

(d) The damage to the recuperator, shown in Fig.4, occurred in a development engine as a result of a control malfunction during engine deceleration. During the engine speed reduction, a compressor surge was experienced and this, associated with the control malfunction, resulted in an excessively high turbine exhaust temperature. During periods of compressor surge, an excessively poor combustion efficiency would of course result in, either unburnt fuel passing through into the recuperator, or propagation of the flame front to the point of impingement on the recuperator gas inlet face. Again, as in the previous case, the response of the exhaust overtemperature sensor was not sufficiently rapid to prevent damage to the recuperator. During the engine run down, 50 lb of CO_2 were introduced into the compressor intake and, when the engine stopped rotating, a further 20 lb of CO_2 were injected into the recuperator from the exhaust duct. The engine was cranked on the starter for a minute to aid cooling, and as a result of these procedures, the damage was localized to the recuperator gas inlet face. In all the failures outlined in the foregoing, the emergency procedures adopted resulted in localized recuperator damage only; in no cases did the fire result

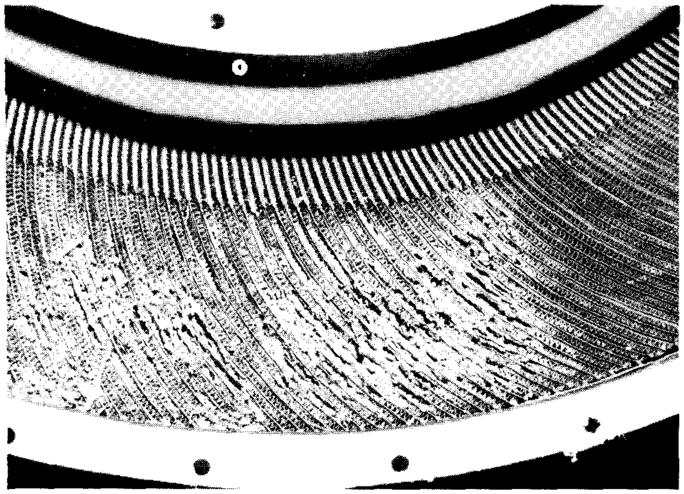

Fig.4 Local fire damage on recuperator gas inlet face as a result of excess fuel during engine start (W4812)

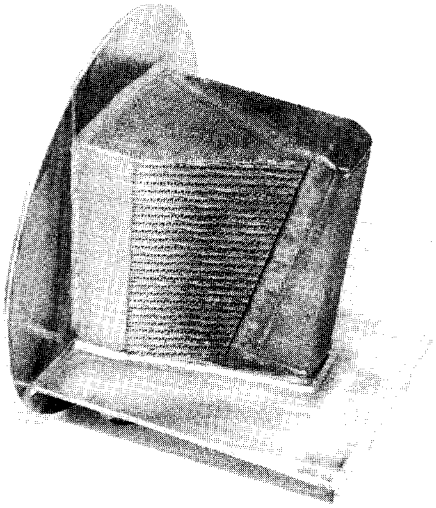

Fig.5 **View of basic plate-fin test module** (67-7691)

in failures of the turbomachinery rotating components.

Possible methods of minimizing the heat exchanger fire hazard in gas turbines will be discussed in a later section.

DETAILS OF TEST MODULE AND RIG

Details of Test Module

The fire test modules were manufactured from sections removed from a typical full-size plate-fin recuperator which had previously been used on a development engine. The small matrix sections were manifolded and sealed to form a module capable of withstanding the full internal pressure differential as that experienced in the full sized engine recuperator. To facilitate rapid installation in the rig, the matrix was welded to a plate which formed part of the duct and flange arrangement. Details of the basic module can be seen in Fig.5. Details of the module surface geometry are given in Table 1.

Details of Test Rig

The simple test rig was constructed in such a manner that the modules could be quickly installed and removed from the flow system. A view of the test rig used to get a preliminary understanding of the heat-exchanger fire hazard is shown in Fig.6. To simplify the rig, it was decided to flow hot gas only through the matrix and to pressurize the air side, no provision being made to simulate air side flow conditions. The rig consisted of a radial blower, an electrically actuated flow restrictor valve, a flow metering orifice section, a natural gas burning combustor to heat the air, a flow straightening tube bundle, and the specimen section. The specimen section was mounted in a square duct with a water-cooled viewing port and a rear access port for visual observation of the matrix upstream and downstream faces. The ducting incorporated mounting bosses for the temperature and pressure probes, and provision in the duct upstream of the matrix face was made for injection of fuel and the various solid contaminants.

The size of the ducting, the flow entrance arrangement, and selection of the fan were made such that the gas flow conditions into the matrix simulated those experienced in the full-size recuperator at engine operating conditions. Provision was also made in the plumbing for preheating

Table 1 Surface Geometry Details

Fluid stream	Air	Gas
Passage height, in.	0.100	0.125
Corrugation, fins/in.	25.78	16.96
Hydraulic diameter, ft	0.00391	0.00576
Surface compactness, sq ft/cu ft	384.0	339.0
Void fraction	0.375	0.488
Fin thickness, in.	0.004	0.004
Plate thickness, in.	0.006	
Plate and fin core density, lb/cu ft	70.0	
Module weight, lb	10.0	
Matrix material	430 Stainless Steel	
Braze alloy	Solar IXI (nickel-manganese-silicon-boron)	

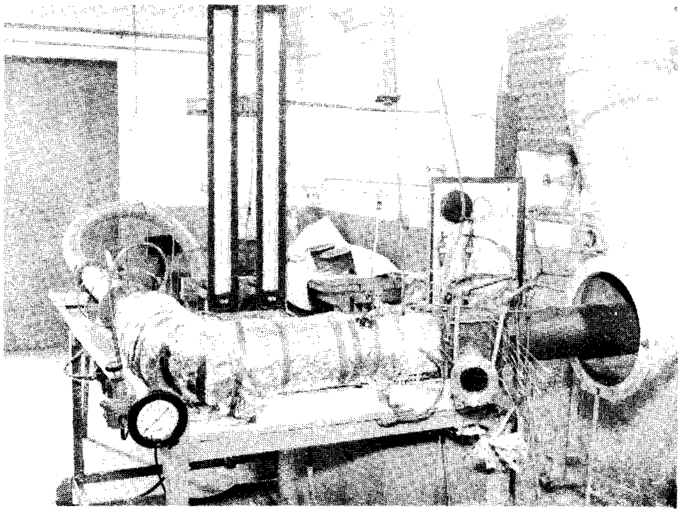

Fig.6 View of heat exchanger fire test rig (68-0679)

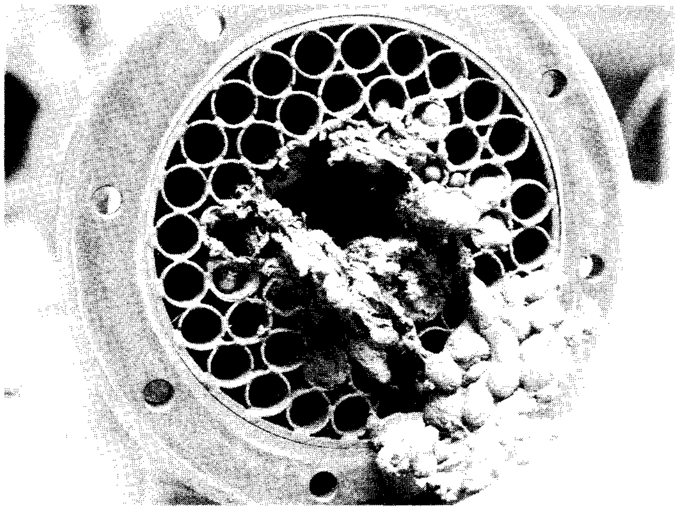

Fig.7 Fire damage to tubular flow straightener (67-6462)

the pressurizing air on the nonflow side of the module. Five thermocouples were attached to the matrix gas inlet face, three to the rear face, and four were used for recording the gas inlet temperature. Minneapolis Honeywell Brown self-balancing potentiometer temperature indicators were used to monitor all the temperatures. Specimen and gas temperature data were continuously recorded on a Honeywell Brown instrument and on a Sanborn recorder.

DESCRIPTION OF MODULE TESTS

During the initial run to calibrate the rig, the gas temperature was increased to about 2000 F, at which point a fire started in the upstream tubular flow straightener, causing severe damage as shown in Fig.7. The rig had been constructed from Hastelloy material, but by mistake the tube bundle had been made from 410 stainless steel. Prior to replacing the flow straightener, this time made from 713 C, a test showed that the flame from the natural gas burner was actually extending downstream and must have actually been impinging on the tube bundle during the initial test. After modifications to the combustor hole pattern, it was found that the rig could be operated up to temperature of 2500 F without damage to the ducting, and with a representative flow distribution into the matrix.

All the test modules were made from sections of a full-sized recuperator matrix which had been used on a development engine, and while free from contamination, the plates and fins did have an oxide film, although no evidence of scale or flaking was apparent. The modules were subjected to a series of tests to simulate, as closely as possible, an actual engine operating characteristic, bearing in mind, of course, the no flow situation on the air side of the module, although it was pressurized with heated air. Since the initial tests showed that the gas inlet temperature required for metal ignition, without the presence of excess fuel, fouling contaminants, or foreign body ingestion, was well above current engine operating temperature levels, the bulk of the tests were carried out with injection of various liquids and solids as described briefly in the following.

Tests were carried out with intermittent and continuous injection of Diesel oil through a hypodermic tube (located in the center of the duct about 12 in. upstream of the specimen) onto the matrix face to simulate engine conditions with a poor combustor efficiency, flame out at surge, and with excess fuel present as a result of an aborted start.

To simulate an engine bearing seal failure, similar tests were carried out with a representative lube oil. These tests were extended by actually baking lube oil onto a module and going through a series of runs to simulate engine operation.

A range of tests were carried out by injecting solid carbon particles into the gas stream, and further extended by actually packing the core with fuel soaked carbon, and undergoing simulated over temperature starts. Other solid foreign body particles considered were aluminum chips and a representative gasket material.

A fairly comprehensive range of tests were carried out with all the foregoing contaminants over a representative engine operating spectrum. In several of the modules, deliberate leakage holes were drilled in the core to examine the effect of varying leakage which might occur as a result of local cracks in an actual recuperator core. Prior to the installation of each module in the rig, a leakage test was carried out over a range of pressures.

As mentioned previously, the rig was constructed such that the upstream and downstream faces of the matrix could be observed, and during the initial tests, a radiation pyrometer was used as a further means of checking the matrix metal temperature. The actual burning of the core was usually preceded by a visible change in color, followed closely by a series of sparks, and finally a flame. In some cases, a front burn out was evidenced, while in others molten metal was noticed on the back face. Metal and gas temperatures throughout the tests were monitored continuously, and from the Sanborn traces the actual point of ignition could be seen, and these will be discussed in the next section. Once it was obvious that failure of the module had occurred, the natural gas burner was cut off and CO_2 was introduced into the duct for a few seconds to limit the damage to the specimen only, and minimize the risk of distortion to the ducting and flanges in the working section.

DISCUSSION

In retrospect it might be said that the tests described in the previous section were not carried out on a very scientific basis to give meaningful graphical data. With a limited number of modules, it was impossible to encompass all the variables that could lead to a fire situation in a compact plate-fin matrix, particularly since several of the tests were deliberately repeated with differing specimens to try to demonstrate repeatability of results.

The first question that must be asked is with regard to the module validity, and the interpretation of the data as applied to conditions in the full size heat exchanger under engine operating conditions. The convective heat input to the matrix was representative, but with only a 10-lb module, with a relatively large external surface area, a radiant heat out flow was in existence which would not occur on a well-insulated engine assembly. At 1200 F, the core was visible as a dull red color, but when the gas temperature was rapidly increased to 1450 F, the gas side fins could be seen to "light up" (to a bright cherry red color) almost immediately, rather like an electric light bulb filament. The air side surfaces had a slightly lower response time, but did not seem to be significantly influenced by air side temperature. The ducting and flows were selected such that the velocity upstream of the matrix face and the Reynolds number in the matrix were the same as in the full-size engine recuperator at the engine design point. It was felt that, for the initial tests outlined in this paper, the module was fairly representative and that data recorded would be equally true for engine recuperator conditions.

Another questionable area is that regarding the gas composition entering the rig module, compared with that in the engine. In Appendix 2 a comparison of the exhaust gas composition for ideal conditions is given assuming a combustion efficiency of 100 percent. It can be seen from Fig.15 that, for the same heat exchanger inlet temperature, there is a slight oxygen deficiency in the rig compared with engine conditions. This situation could have been improved by either, preheating the air before the natural gas burner, or by adding oxygen to the system between the combustor and matrix. Since the initial findings from the rig were in fairly good agreement with data taken from engines, it was decided, that for the preliminary tests outlined in this paper, not to alter the oxygen content of the gas mixture.

A summary of the findings from the module test program are outlined in the following.

(a) Metal Ignition and Combustion. Without the influence of fuel or any foreign body ingestion, two of the modules were heated until a metal fire was experienced and both units started to burn and melt at a temperature of 2300 F. The fire seemed to start in the center of the core and rapidly burn out the rear as shown in Fig.8. From work by Reynolds (3) the ignition temperature of 430 stainless steel in air is given between 2670 and 2720 F, but in our case, it appears that the alloying action of the silicon-boron-manganese components in the braze metal reduced the ignition temperature to the lower value of 2300 F obtained from the rig.

(b) Effect of Carbon in Matrix. An attempt to ignite a module by injecting carbon particles made from Diesel No. 2 fuel was unsuccessful. A module was packed with fuel-soaked carbon and subjected to a simulated engine over temperature condition without a trace of conflagration. The carbon glowed but did not start a metal fire even with subsequent diesel fuel injection with temperatures up to 1750 F.

(c) Effect of Aluminum Chips in Matrix. It is conceivable that failure of an engine component during operation could result in aluminum chips becoming lodged in the recuperator gas inlet face. With small pieces of aluminum inserted into the

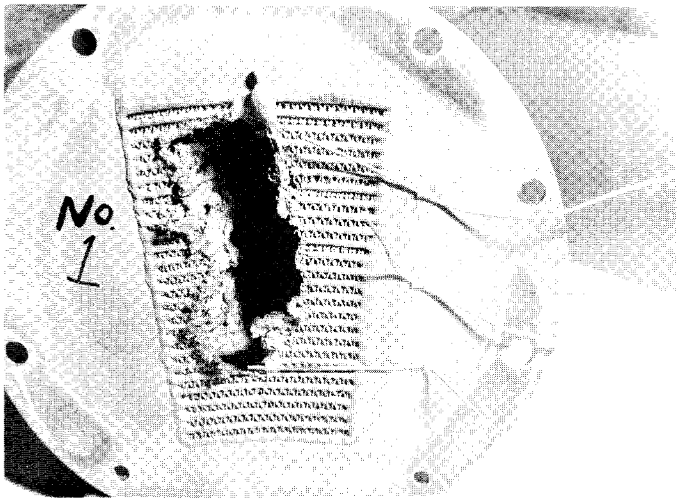

Fig.8 Rear burn-out damage to first test module
(67-7642)

gas side passages of one module, the gas inlet temperature was gradually increased to 1900 F, and no local glowing, sparks, or evidence of fire was apparent. From work by Hill (2), it appears that aluminum melts before igniting, and this must have been the case since only a gray ash deposit was seen in the local areas of aluminum insertion. No damage to the fins or plates could be seen.

(d) Effect of Gasket Material in Matrix. There is always the possibility that gasket material could become lodged in the matrix gas inlet face, and this was evaluated. Small pieces of a representative Raybestos A56 gasket material were inserted into the gas side passages and the gas temperature gradually increased to 1900 F with no signs of matrix conflagration.

(e) Effects of Internal Pressurization. The structural integrity of the small modules was evidenced by the ability to withstand temperatures up to 1950 F with a 40-psi internal pressure differential for a period of an hour. Although distortion and fin embrittlement were apparent, no drastic structural failure of the core occurred. A range of modules with varying leakage rates were tested over a range of air side pressures. To make conditions more realistic the pressurized air was heated, but there was no evidence to suggest that the pressure or temperature had significant influence on the temperature at which the metal fire actually started. Once the fire was initiated, the matrix burn out was more rapid with the higher internal pressure differentials creating an increased oxygen supply to the fire zone.

(f) Effect of Lube Oil Impingement on the Matrix Face. To simulate a bearing seal failure in an engine, tests were carried out using a representative lube oil, SATO 6256 heated to 150 F. Initially, this oil was inserted into the air side of the module, and even with pressurization, no fire was experienced during a simulated over temperature start to 1500 F. The module was then completely immersed in lube oil and oven baked prior to an over temperature start to 1600 F, and although a lot of smoke was evidenced, no fire was started. No burning of the oil on the matrix face, as a result of direct impingement, was observed below 1600 F, although hot spots could be seen on the rear face. The tests indicated that, for lube oil injection, the matrix leakage was not an influencing factor. Using oil flow rates corresponding to the worst oil consumption experienced in an engine in which a seal had failed, the lowest temperature at which a fire was started was 1650 F. The spontaneous ignition temperature for an oil of this type is in the order of 800 F, but injection of this oil into the gas stream with a velocity of about 100 fps produced no continuous burning on the face of the core below 1600 F. The work reported by Bell (5) has shown that for oil trapped in marine air preheaters, of the rotary Ljungstrom type, the thickness of the baked oil deposit has a significant influence on the ignition temperature. To date, only minor internal malfunctions have resulted in excessive engine oil consumption and this has not represented a fire hazard; however, it could become an increasing danger if deposits were allowed to build up in the recuperator air and gas passages.

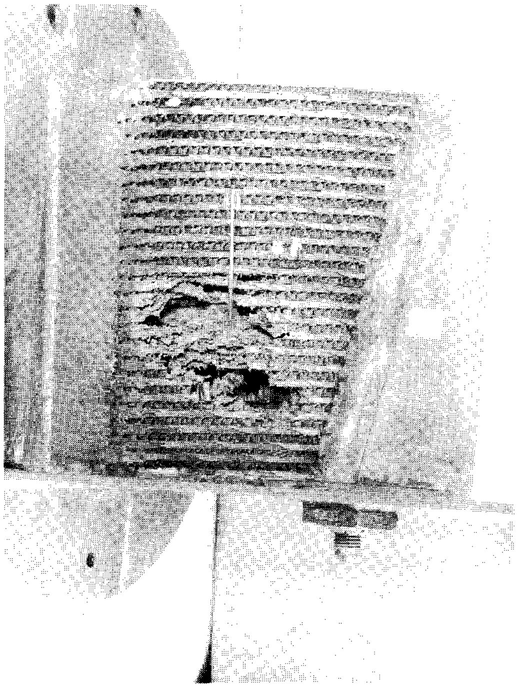

Fig.9 **Typical front burn-out damage with diesel** fuel injection (68-0695)

(g) Effect of Diesel Fuel Impingement on the Matrix Face. To simulate over rich or poor combustion characteristics, a series of tests to find the effect of diesel fuel impingement on the hot matrix were carried out. An approximate computation was made of the amounts of fuel which could be present for cases such as an aborted start with a hot and cold recuperator and high-speed surge. With an intermittent, and continuous injection of diesel in varying amounts, it was found that core leakage did not significantly influence the matrix burning temperature. For certain fuel flows, it was noticed that at temperatures up to about 1350 F no burning or flame was experienced, but above 1400 F, a continuous flame could be seen, and under these conditions, the matrix seemed to act as a flame holder, and local hot spots could be seen on the rear face. Some modules were tested in which a pickling process had been carried out to remove all the oxide film from the plates and fins prior to installation in the rig. The temperatures at which these modules burned were not significantly different from the rest of the modules tested. The lowest temperature at which a module burned was 1550 F, and a view of a typical failure is shown in Fig.9. From the Sanborn temperature trace shown in Fig.10, it can be seen that burning of the fuel on the front face took place, and that a rather violent front burnout was experienced. With the design gas flow, the amount of diesel injected represented an air-to-fuel ratio in the order of 185, which is a little lean for expected combustion to give direct flame impingement onto the matrix. A module was thoroughly saturated with diesel oil and a light off to 1500 F resulted in a lot of smoke but no evidence of fire. This test simulated an engine cold start where poor combustion efficiency at low speeds had resulted in unburned fuel passing into the recuperator. Based on the module tests carried out, it can be concluded that one of the main matrix fire hazards is that associated with unburned fuel being deposited on a hot recuperator face. On the units which burned out the rear, little evidence was seen of oxidation of the leading edge of the fins at the inlet face. Without more scientific tests to study the actual mode of ignition, it would appear that the gas side corrugations act as flame holders and burning starts on the fin just inside the core within the laminar boundary layer, some fuel being carried over into the center of the matrix where combustion is completed. Proof of the fact that the metal combustion starts inside the core was evidenced on one module in which the fuel flow was cut and the CO_2 turned on after a few sparks had been observed, and a rapid increase in outlet temperature noted.

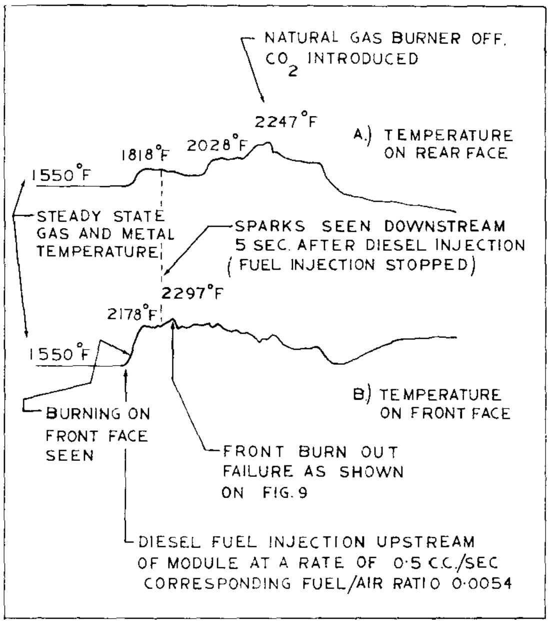

Fig.10 Typical matrix metal temperature traces during fuel injection test

On removal of the module, no external damage was visible, but when sectioned, it could be seen that metal combustion had occurred internally, an inch or so in from the gas inlet face.

An interesting extension of this preliminary work would be the evaluation of fusion-bonded metallic, ceramic, or cermet coatings, to provide high-temperature oxidation and corrosion resistance, **and perhaps transient over-temperature fire protection. For future high-temperature recuperative gas turbines, there will be a big economic incentive to utilize the lower grade alloys suitably coated for oxidation and corrosion resistance.**

CONCLUSIONS

This paper is presented at a stage when only conclusions of a general nature can be made, but the data shown does indicate that a preliminary understanding of the fire hazard, for a particular case, has been realized. The experimental investigation was carried out for only one metallic secondary surface of a given material type and thickness for a particular cycle condition, and must be regarded as more of an exploratory test of a qualitative nature.

Without the presence of diesel fuel or lubricating oil, a matrix fire could not be promoted below the metal ignition-combustion temperature of 2300 F. Up to temperatures of about 1900 F, matrix fires could not be promoted by foreign bodies such as carbon, aluminum chips, or Raybestos gasket material, in contact with the core. For the limited range of tests carried out, the lowest temperature at which a matrix fire started was 1550 F. There appeared to be little difference in burning characteristics between Diesel No. 2 fuel and SATO 6256 lubricating oil; although matrix fire temperatures in the order of 100 deg lower using the diesel fuel were experienced. The effect of continuous liquid injection lowered the fire temperature only slightly compared with the intermittent injection. Because of the random nature of the modules, no direct fire correlation with matrix leakage could be made. The units with a high leakage rate did not appear to fail at a significantly lower temperature. No fire or core failure in the local area of the drilled leakage holes was visible. The failure temperature did not seem to be significantly influenced by the internal pressure differential or by the temperature of the pressurizing air. Up to simulated engine over temperature start conditions (1500 F), fires could not be started in cold matrices saturated with diesel and lube oil. On several occasions, extreme hot spots were observed on the core face well below the fire temperature, and it is assumed that local structural failure would have occurred with prolonged running. On several occasions, there was evidence that the fire started in the center of the module, some inch or so from the front face, and this raises doubt as to whether a protective ceramic or refractory coating on the face of the matrix would prevent heat-exchanger fires.

The data taken is only relevant to 430 st.st. with fins and plates of 0.004- and 0.006-in. thickness, respectively, and with a surface compactness of around 720 sq ft/cu ft. Type 347 stainless steel has slightly superior resistance to oxidation and scaling at elevated temperature, but this would have only a small effect on the potential fire hazard. From the structural standpoint, an upper gas inlet temperature limit of approximately 1400 F has been imposed for recuperators made using the 300 and 400 series stainless steels. For temperatures above this level, materials such as Hastelloy X or Incoloy 800 would have to be used. In the thin foil form these are several times more expensive than stainless steel and could only be justified for military use, or on a one or two off basis for special application. This might mean that for some designs, in the interest of economy, the heat exchanger could be split into separate units, and the high-temperature portion made from a nickel or cobalt alloy, and the remaining section made from a 300 or 400 series stainless steel.

With the heat exchanged gas turbine, the danger of damage from over temperature, due to prolonged period of surge, excess fuel being trapped in the matrix, or control malfunction is more severe than for the simple cycle engine. When a hot matrix is suddenly exposed to flame under conditions where unburnt fuel could be present, because of over rich combustor conditions, there is a danger that a metal fire could start for temperatures above 1500 F. Even with fast response over temperature thermocouples and the introduction of CO_2, a matrix fire hazard exists for metallic exhaust heat exchangers. With poor combustion efficiencies at low engine speed, one must expect that during the engine start some unburnt fuel will pass through into the heat exchanger and will vaporize there, probably resulting in smoke in the exhaust for a few seconds.

To eliminate any possibility of a fire in a development engine, for instance, where bearing seals have failed resulting in oil deposition in the recuperator air or gas side, or where poor combustion has resulted in sooty conditions in the recuperator, the heat exchanger should be removed from the engine and thoroughly degreased and steam cleaned before being used again. It is for cases where fouling deposits have been repeatedly baked in the core, that an extreme fire hazard exists when an over-temperature condition with unburnt fuel in the exhaust occurs.

From the fires outlined in the literature, and the work carried out in this study, there appears to be two main causes for heat-exchanger fires. With the large, heavy oil burning gas turbine plants, the main danger of fires results from the ignition of soot deposits in the heat exchanger. This now seems to have been resolved by the intermittent use of steam soot blowers. With the smaller industrial and vehicular gas turbines, burning lighter fuel oils, careful attention to the combustor design has more or less eliminated the heat-exchanger fouling problem. The main danger of fire here seems to be caused by excess fuel becoming trapped in the matrix and ducting after a series of aborted starts. For all types of gas turbines, there still exists the possibility of high-speed surge, where transient over-rich combustion conditions result in either unburnt fuel passing through into the heat exchanger, or actual flame impingement on the matrix gas inlet face. A heat-exchanger system capable of withstanding direct flame impingement for, say, five seconds during compressor surge would be extremely desirable.

To minimize the risk of fires in new gas turbine heat exchangers, during the engine development period, a combination of the following should be observed. A relay in the starter system should be provided to prevent repeated start attempts, until some of the excess fuel had drained

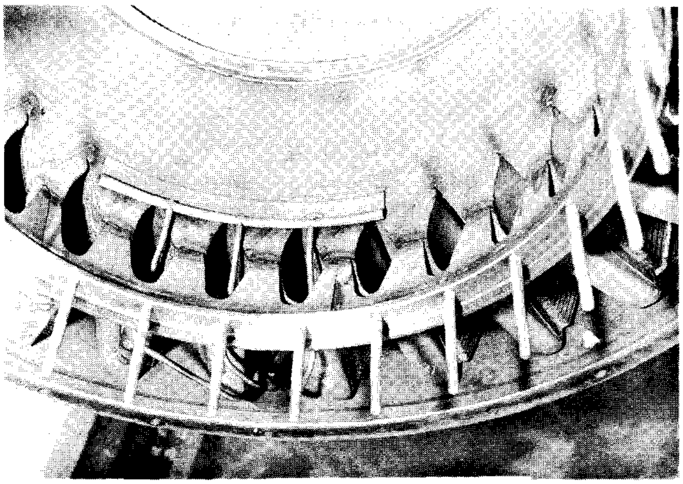

Fig.11 An example of an effective recuperator fuel drain system (67-6020)

away or vaporized. A good drainage system, such that fuel cannot become trapped in the combustor, ducts, and matrix for all engine attitudes, should be incorporated. A typical fuel drain arrangement is shown in Fig.11 in which the recuperator drain valve remains open during the starting procedure until the compressor discharge pressure reaches about 5 lb/sq in. to insure that any excess fuel is bled overboard. As a further precaution after an aborted start, the system should be purged thoroughly by motoring the engine over on the starter for 20 to 30 sec. Rapid over temperature sensors should be installed, which would actuate a CO_2 injection system, hopefully to prevent an actual metal fire from starting, even though the excess fuel may ignite locally in the ducts. In Fig.12, a development engine is shown in which CO_2 injectors were installed in the compressor inlet ducting and exhaust ducting. In Appendix 3 the details of a CO_2 injection system to smother any fire that might start are described. Any visible fouling deposits should be removed by steam or water washing and by fitting nozzles at the recuperator gas inlet plane; this can be done during engine operation.

For the next generation of heat exchanged gas turbines, it is likely that gas temperatures into the recuperator, or regenerator, will be considerably higher as a result of emphasis being placed on increased specific power to give smaller packages and reduced hp/lb and dollar. For most commercial applications, utilization of the nickel and cobalt alloys is economically prohibitive, and this fire hazard may well be one of the influencing factors dictating the use of ceramic heat exchangers for future high temperature, low sfc engines.

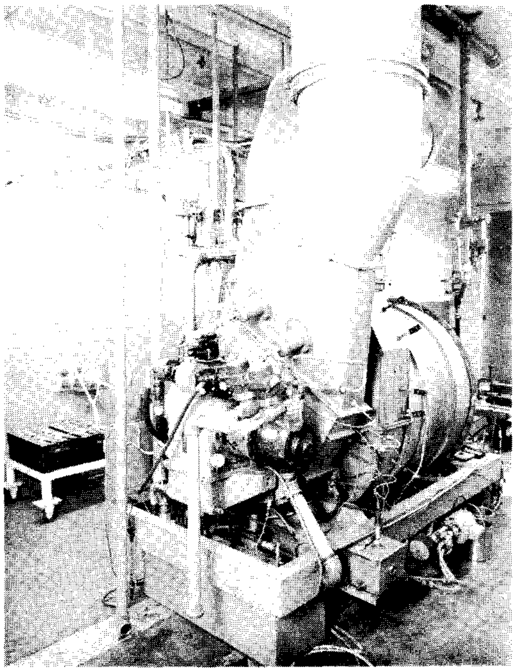

Fig.12 Development recuperative engine with CO_2 injectors installed in the ducting for over temperature protection (W5382)

In future extremely high-temperature gas turbines there are, of course, related areas where metal fires could be experienced. Loss of cooling air in a nozzle or blade row, or perhaps a local failure in more advanced fuel cooled turbines, could result in a metal fire starting. Another possible area is that of a metal fire initiated as a result of a high-speed rub between a turbine rotor and the fabricated sheet metal tip seal.

In this paper only the surface has been scratched as regards a fundamental knowledge of heat exchanger metal fires, and it is hoped that this will simulate an interest as regards a program of work leading to a better metallurgical understanding of oxidation and metal ignition-combustion in practical gas turbine heat-exchanger configurations. Such a program would be carried out under a controlled laboratory environment for a wide range of materials and operating conditions, hopefully leading to the adoption of a protective coating to inhibit fire initiation.

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APPENDIX 1

SUMMARY OF FIRES REPORTED IN THE LITERATURE

(a) A brief account of a fire experienced in an early gas turbine locomotive is discussed by Pfenninger (6). The fire occurred in a large cross-flow recuperator and details of the damage are shown in Fig.13. The Brown Boveri locomotive was being used by British Railways, and after an express run from London to Bristol, it was left standing in the yard, and, when two hours later the return journey should have started, a fire was discovered in the recuperator. A heavy fuel oil had been used in this turbine, and it was concluded that the fire was caused by soot deposits, probably ignited by a spark. The locomotive was back in working order very quickly as only the recuperator tube bundle had to be replaced. As a result of this accident, a recuperator washing procedure was regularly adhered to after a certain number of running hours, to remove any soot deposits and exclude recuperator fires with certainty.

(b) Details of a recuperator fire in a 27,000-kw gas turbine plant are also reported by Pfenninger (6), and the resultant damage is shown in Fig.14. The gas turbine was fired using a heavy fuel oil, and after an unsuccessful starting attempt, a fire was discovered in one of the large tubular recuperators two hours after the machine had come to rest. It was found that soot deposits had ignited, practically destroying three of the ten recuperators. The remaining seven recuperators exhibited only a slight soot coating. In five of the recuperators there had probably been no fire, while two seemed to have been on fire though no damage could be seen. With the installation of soot blowers, actuated regularly during operation, the danger of such recuperator fires was eliminated. After this experience, all the other gas turbine installations with recuperators were fitted with soot blowers.

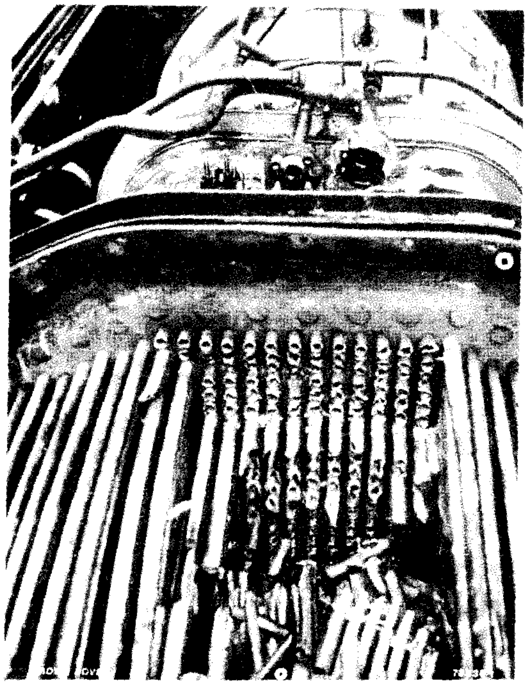

Fig.13 Fire damage in gas turbine locomotive tubular recuperator (by courtesy Brown Boveri) (68-4742)

(c) Although no actual details of the fire are given, mention is made by Lamb (7) of a fire in a 1200-hp marine gas turbine recuperator. The heat exchanger was a large single-pass plain-tube counterflow recuperator made from 1 1/16-in-od mild steel tubes. Apparently, a minor fire occurred causing no damage, but this, together with a serious fire in another turbine of a different type, served as a warning of the possible consequences of neglect. It, at once, became routine to wash the heat exchanger with water at every port. As soon as possible, three steam soot blowers were fitted and these were operated once every 24 hr. For a subsequent 5500-hp marine gas turbine, the fitting of steam soot blowers made it practical

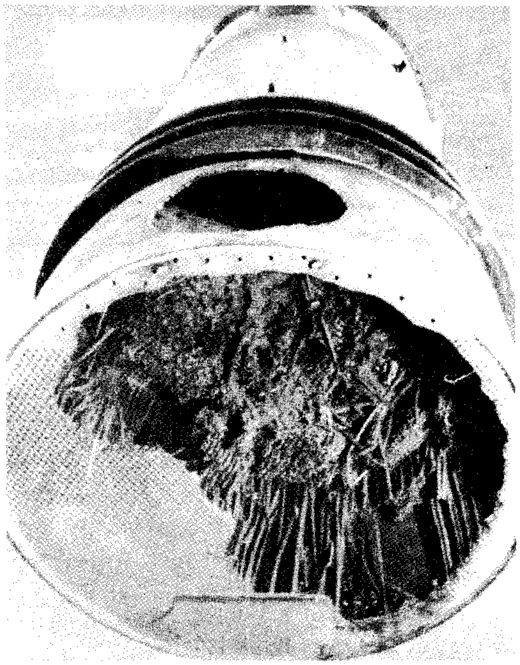

Fig.14 Fire damage in 27,000-kw plant gas turbine tubular recuperator (by courtesy Brown Boveri) (68-4743)

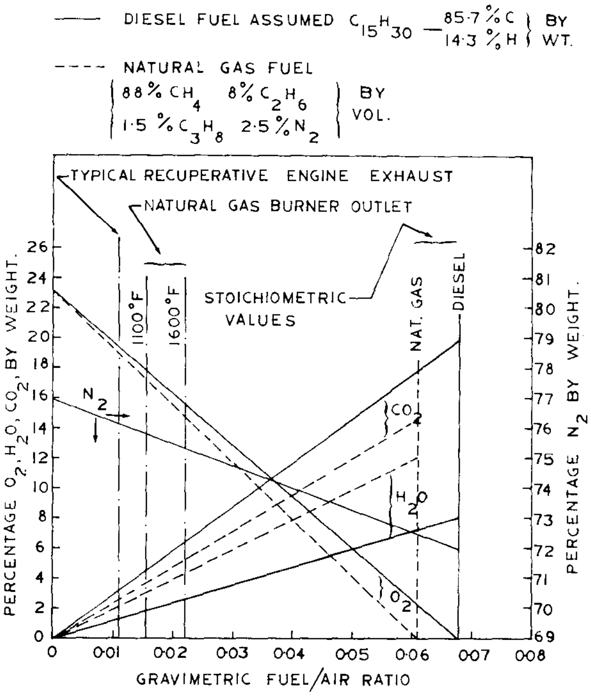

Fig.15 Theoretical exhaust gas composition

to keep the recuperator clean whatever the fuel or combustion conditions. A deciding feature in using steam, rather than air-operated blowers, was the value in extinguishing any fire which might occur, although it was felt that proper use of an efficient soot blower installation makes a heat-exchanger fire most unlikely.

(d) . The work by Bell (5) is a useful reference, although it does not specifically deal with the gas turbine engine, but rather fires in marine boiler air preheaters with particular reference to the Ljungstrom rotary regenerative type. The nature and ignition temperature of inflammable deposits, possible methods of ignition of these deposits, and recommended precautions against fires are discussed. In the majority of cases, fires have occurred shortly after lighting off or shutting down, and most of these have been due to accident or maloperation. The steel of which the air heater is constructed will itself burn, but the temperature to which it must be raised to ignite is so high that it cannot occur in normal boiler air preheater practice. Some other combustible material with a lower self-ignition temperature must, therefore, be present before an air heater can catch fire. This material is found in the deposits which, if not removed by efficient soot blowing, build up on air heater matrix surfaces. These deposits consist of soot, corrosion products, and unburnt oil. A survey of various fires is outlined, and an interesting account is given of a fire in an uncontaminated regenerative air preheater element which was observed at 1391 F. Many of the reported contaminated cores burnt well below 500 F. It is reported that, in several cases, the baked oil deposits in the air preheater ignited, resulting in a shower of bright sparks during the light-off procedure without causing any damage to the heater elements. It is concluded that, in view of the high ignition temperature found for oil free deposits, it is probable that marine boiler air preheater fires will not occur unless oil or soot is present.

(e) Although no so detailed as the foregoing work, Bergonzi (8) outlines the increasing use of Ljungstrom rotary regenerative air preheaters for improved marine boiler efficiency. Several fires are briefly mentioned, and, in general, the fires had in common the fact that during the time preceding the fire there was a period of poor combustion, which caused the depositing of unburned fuel oil in the air preheater.

APPENDIX 2

EXHAUST GAS COMPOSITION AT HEAT EXCHANGER INLET

To get a comparison between the estimated exhaust gas composition of a typical recuperative gas turbine and the conditions in the rig using a natural gas burner to heat the air, the following calculations were carried out.

Typical Engine Exhaust Composition Using Diesel No. 2

Considering a hydrocarbon liquid fuel, say $C_{15}H_{30}$, with 85.7 and 14.3 percent carbon, the theoretical air/fuel ratio and exhaust gas composition can be computed by assuming a combustion efficiency of 100 percent, and with the large percentage of excess air, it is assumed that all the H_2 is burned to H_2O, and all the C is burned to CO_2. From Fig.15 it can be seen that the theoretical stoichiometric fuel/air ratio is 0.0677, but this is of academic interest only since with secondary air, typically in excess of 500 percent, the fuel/air ratio at the recuperator inlet is of a considerably lower value. By assuming a representative value of 0.011, it can be seen that the exhaust gas consists of 19.3 percent O_2, 76.1 percent N_2, 3.3 percent CO_2, and 1.3 percent H_2O, by weight for ideal combustion conditions. In actual gas turbine practice, of course, the combustion efficiency is less than 100 percent, and this results in small amounts of unburned hydrocarbon, carbon monoxide, and oxides of nitrogen, being present in the gas entering the heat exchanger.

Typical Exhaust Composition Using Natural Gas

As mentioned in a previous section, a natural gas-fired combustor was used to preheat the air upstream of the small recuperator module in the fire rig. A check on the utility supplied natural gas at the time of the tests showed the composition to be 88 percent methane, 8 percent ethane, 1.5 percent propane, and 2.5 percent nitrogen. Again, under ideal combustion conditions, the estimated combustion products for a range of fuel/air ratios can be seen from Fig.15. At the lowest temperature levels at which matrix fires were experienced, the burner fuel/air ratio was in the order of 0.022, this corresponding to a theoretical gas outlet mixture of 14.8 percent O_2, 75.4 percent N_2, 5.3 percent CO_2, and 4.5 percent H_2O.

From the foregoing it can be seen that the conditions in the rig did not exactly simulate engine operating conditions, particularly with regard to oxygen concentration. The oxygen deficiency at the matrix inlet face in the rig could have been improved by either preheating the air, thus reducing the burner temperature rise, or by the introduction of bottled oxygen downstream of the burner. For the initial series of tests outlined in this paper, no oxygen enrichment was carried out to exactly simulate engine operating exhaust composition.

APPENDIX 3

FIRE EXTINGUISHING BY CO_2 INJECTION

As a safeguard, to minimize engine damage during the testing of a new heat-exchanger engine, it is desirable to install a system which would inject CO_2 into the compressor inlet in the advent of a fire starting in the heat exchanger. If a heat-exchanger fire occurred, an exhaust over temperature sensor would detect the sudden rise in gas temperature, actuate a control device which would cut the fuel flow, and inject CO_2 into the inlet as the engine coasted down. Initial discharge rates and system capacities for each particular application can be simply calculated by making the following assumptions.

In general, it is safe to assume that a mixture of 50 percent CO_2 and 50 percent air will not support combustion of any hydrocarbon regardless of the fuel ratio. It can be assumed that the CO_2 in the bottle behaves as an ideal gas, and while this is not strictly true, because the gas is very near the vapor dome and may even be inside it, it is sufficiently close since an exact solution is not required. The initial discharge rate is entirely dependent on the system, and can be calculated by assuming an adiabatic expansion of an ideal gas, again this is not strictly true because there will undoubtedly be some condensation. Assuming the CO_2 bottle remains choked throughout the entire discharge time, the maximum rate of discharge can be calculated for a choked compressor inlet condition to ensure that 50 percent volume flow of CO_2 will be maintained at the engine inlet throughout its entire coastdown period. Assuming these conditions exist with the maximum discharge rate established, the CO_2 should be adequate to smother any fire. By the end of the coastdown period the atmosphere inside the engine should be nearly 100 percent CO_2. If the planes of the CO_2 entrance and exit are above the engine and heat exchanger, the atmosphere should persist for some time even after the bottles have been exhausted, and this should prevent reignition after the engine has ceased to rotate.

Although the CO_2 system capacity should be sized for the worst condition, the injection rate can always be scheduled for shut down at engine part load speeds. Provision should also be made in the system for manual override to prevent damage in case of prolonged compressor surge.

There is some question as to whether or not the compressor would be damaged, due to thermal shock caused by the drop in inlet temperature, as a result of the CO_2 introduction. Since the effective source temperature for the air-CO_2 mixture is primarily dependent on the total, not the static temperature of the CO_2, means that the change in inlet temperature is not a step change at all. Quite often the rate of change of temperature is more important than the total temperature. No damage to either axial or radial turbomachinery has been experienced as a result of carbon dioxide injection at the compressor inlet during engine operation.

The foregoing CO_2 injection system is primarily suggested for new development engines only, where uncertainties as regards the engine and controls still exist. By the time the CO_2 system is actuated, the damage to the metallic core has usually taken place, and the smothering of the fire merely localizes the damage to the recuperator in an endeavor to protect the rotating components.