

SUPERALLOYS: THEIR USE AND REQUIREMENTS IN ADVANCED ENERGY SYSTEMS

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ABSTRACT

The potential role of Superalloys in large advanced energy systems is examined. The characteristics of seven basic systems in which superalloys are expected to see service are discussed as background. The problems in the system are outlined, and an estimate is made of the properties expected from superalloys serving in these systems.

Introduction

In the weeks, months, and years immediately passed the need for vastly improved systems to provide more energy at reasonable cost has become apparent to all but the most unread on our old Earth. That need is now being attacked through implementation of massive energy conversion programs. Among those, heat systems for energy conversion no matter what their intended use or generic type, depend upon Carnot cycle philosophy. This means that to achieve maximum efficiency the top temperature in the system should be as high as possible, while the heat rejection temperature should be kept as low as possible. Accordingly, inventions and developments will drive hard toward energy systems and subsystems operating at high temperatures. This means that superalloys will have an increasingly vital share of the action where metallic structures up to 1400C (2550F) are needed.

Where will superalloys be needed in these systems, and what properties will be required of this remarkable family of materials? In an attempt to answer this broad question and stay within reasonable limits of space, this author has chosen to focus on large prominent energy conversion systems, particularly (but not entirely) those involved with generation of electrical power. Thus, this paper discusses advanced methods of conversion of fossil and nuclear resources to electric power.

The approach taken to cover the subject is somewhat as follows:

First, those major power systems in which superalloys appear to have a significant future are described in generalized terms. Then the problems which suggest or require the use of superalloys are discussed. This leads to a statement of requirements and needs, for each system, - at least as best estimated by this author at this time. An overall summary attempts to identify the most significant broad areas of superalloy future need and also to identify possible problem areas where more than just new invention is needed.

The systems chosen for discussion in this article are those, which, in the writer's opinion, hold a significant need for superalloys. Many power systems may not need superalloys, also. At this time, water-cooled reactors, closed-cycle MHD, fusion reactors, supercritical CO₂ cycles, solar and geothermal energy, and also steam turbines (when considered alone) are probably in this latter group.

A final introductory note to get a sound foundation in place. In these massive energy systems there appear two essentials. Not only are there big "things" that run, but there is the "stuff" that runs them! The latter, of course is a vital and common thread, the combustible fuels and working fluids. To give a brief feeling for this "stuff", Table I summarizes the fuels and fluids of prime importance which superalloys will face. It's a tough scene!

I. Combined Cycles

The Systems. Combined cycle systems are well-known electric power sources. A combined cycle is simply a steam turbine and a gas turbine combined. The significant feature is that the gas turbine acts as a "topping cycle" to the steam turbine system, raising that upper combined cycle temperature significantly. Very importantly, steam/gas turbines operating in combined cycles will be integrated as the major rotating electrical-generating equipment operating from both moderately advanced and distant future sources of heat such as coal gasification, fluid bed combustion and certain types of reactors as well as with conventional boilers and fuels. Thus, while discussed alone as a separate system here, combined ST/GT cycles will be found integrated with many other systems. For simplicity here, use of superalloys for gas turbines designed for significantly increased operating temperatures will be discussed.

As the recent rise in fuel cost occurred, combined cycles have become of increasing interest to utilities for operation at 2000-5000 hours per year ("mid-range"). In these cycles, a contemporary industrial gas turbine combined with an exhaust heat recovery steam system with modest non-reheat steam conditions of, let's say, 850PSIG/900F, about 42% overall plant efficiencies are attainable; the incremental capacity from the bottoming steam system is approximately half of the gas turbine, and is attained with no additional fuel. This high efficiency compares with about 38% for the best modern reheat steam plants. This efficiency advantage, plus relatively low cost for the combined cycle plant (about \$225/Kw) make combined cycles attractive for base load service. Further, the exhaust heat from the gas turbine, instead of being rejected into the air, is used to raise steam to help drive the steam turbines. In effect, this use of a gas turbine improves its share of the efficiency load markedly. In fact, fuel economy is so good that combined cycle owning costs (28 mils/kwh) compare favorable with modern steam plants (39 mils/kwh) and thus have become attractive for base load application as well. (1) At 1600C (2900F) fuel cost savings of 25% might be possible.

Combined cycle plants can, of course, be developed into a number of differing arrangements. For instance, the gas turbine and steam turbine can be arranged to drive a single electric generator in line, or the plant can be complexed with several gas turbine units driving generators and the steam turbine driving a separate electric generator.

Figure 1 illustrates simplistically the typical combined cycle with the two major turbine components, a steam turbine and a gas turbine. Combined cycle steam plants are not new; in fact, the 234-MW Oklahoma Gas & Electric plant was installed in 1959, and dozens of combined cycle plants are working throughout the world today. Net plant efficiencies of 44% are being forecasted for about 1980, with advances in the gas turbine the critical contributing factor. Plant sizes up to 600 MW are possible.

The Problem. However, combined cycle plants are not yet "advanced" systems in the sense intended for this article. The challenge comes when designers and manufacturers will attempt to build combined-cycle plants that show net plant efficiencies in the range of 50-55%. To do this the gas stream must reach or exceed about 1600C (2900F). Without question, no contemporary gas turbine remotely can survive under these conditions, - and lives of 100k hours or more are needed. Further, while generalized predictions often assume that the fuel to be burned is a natural gas or clean oil, it is now clear that fuels combusted for the gas turbine stream will often be heavy, contaminant-laden crudes or combustion or conversion products from coal. While the effects on materials or contaminated gases from combusted coal are covered specifically under Fluid Bed Combustion for temperatures of 900-1200C (1650-2000F), here we will attempt to face needs for very high temperatures.

To meet the challenges of higher temperature for gas turbines, technology appears to divide into three categories: (1) air cooling; (2) water cooling; (3) very-high-temperature materials, - such as ceramics or refractory metals. These will be discussed in order from the standpoint of superalloy requirements.

Air cooling is well-known and technology is well advanced, of course. Superalloys can live in gas streams that are much hotter than the superalloys could normally survive by cooling the metal, through use of compressed air bypassed from the compressor into the turbine section. This technology is becoming complex and for industrial gas stream temperatures the approach has some practical limits. For instance, as temperatures increase, increasing amounts of cooling air will be required; eventually, so much is required that efficiency of the whole gas turbine system drops, even though temperature and output continues climbing. Practically, this appears around 1400C (2550F).

Superalloys in these advanced cooling systems will be similar to those we

know now, but more strength and improved oxidation and corrosion resistance are needed, even though alloys already operate at 80-90% of their melting points. Improved compositions will yield some advance, and directional solidification and eutectics may get in the game. However, the size of industrial gas turbine parts is so great that use of the latter will be severely limited. Single crystals will not be used at all. Thus, in a sense, we might say the picture is clear; superalloys, - improved a little, - will be used for this service; 1400C (2550F) or so will be the limit.

Water cooling is probably the next step.(5) Water cooling really opens such a large new door that design considerations immediately reach towards temperatures of about 1600C (2900F); further, the "hot" gas turbine nozzle and diaphragms economically can be cooled to operate at very moderate temperatures indeed, such as about 600C (1100F). If so, it might appear superalloys might not even be necessary, except for the following considerations:

- a. Surface Stability. The fuels generating these high-temperature gas streams may very well be highly corrosive. Therefore, the materials servicing at 600C could require unusual corrosion resistance, and stainless steels and certain superalloys with high chromium content have such resistance. Where strength is needed, superalloys will still dominate.
- b. Support Structures. While the very hottest parts will be water cooled, components such as diaphragms, supports, exhaust structures and combustion systems might best be operated with superalloys just as now, and they will have to demonstrate considerable strength and surface stability.

Very-high-temperature materials are under intensive study also. The current effort to apply ceramics in gas turbine hot stages is well known and certain of these would appear to have the strength and durability to operate up to about 1600C, - although successful design and acceptable materials are a long way from being proven.

Here, the approach is quite different from water cooling. The materials will just sit there and take it. As the designer backs away from the searing 1600C gas stream, the materials which support the ceramics must be defined.

While the first echelon of support may be ceramics also, secondary support should be at sufficiently low temperature to be metal. Once again, the characteristic strength and surface stability of superalloys will be needed here, - even though they don't have the front-rank honor of facing the gas stream itself. In this application, the superalloys must demonstrate chemical stability in contact with ceramics, should be relatively low in cost, and should be fabricable and weldable.

SUPERALLOY REQUIREMENTS FOR COMBINED CYCLE PLANTS

Principal Equipment Types and Superalloy Component Form/Type

Gas turbine components: buckets, nozzles, combustion liners, transition sections, support members.
Forgings, plate & sheet, castings.

Estimated Top or Critical Application Temperature

1600C (2900F) gas stream; 1300C (2375F) metal temperature.

Surface Stability Requirements

Oxidation and corrosion resistance at both intermediate and upper temperatures.
Non-reactivity with ceramics.

Major Mechanical Property Requirements

Rupture strength and ductility; 0.5% creep to design life.
Low cycle fatigue resistance.

Special Requirements or Considerations

Resistance to thermal fatigue and low-cycle fatigue problems generated by sharp thermal gradients.

II. Coal Conversion Processes

At least for the purposes of this paper, a major group of processes related to the use of coal as an energy source are classified into "Coal Conversion Processes" and "Coal Combustion Processes". The former case refers only to the conversion of coal into fuel used in other physical forms, - gas or oil obviously. In the latter case, reference is to processes in which the coal is combusted (essentially completely); the "flue gas" from the coal combustion process is directly utilized in a power generation process. Of course, there is a little cross-ruffing; for instance, the Consol and the BMI/UC coal con-version processes use a portion of the gas made for "power recovery" in expansion turbines.

For conversion processes, two technologies are readily evident, that of coal gasification and that of coal liquefaction. World-wide activity generating for years in these areas is now being sharply accelerated by far-seeing governments with coal resources.

Table II identifies many of these processes (5) essentially in the present state of technology. Many changes can be expected as new processes develop and existing processes don't make the grade. Of the two types of conversion, coal gasification appears to have considerably more support than liquefaction, but there is no single technology leader.

Coal Gasification

The System. One way or another the coal is heated to drive off and/or be converted to useable synthetic gases, which go into pipelines or directly to nearby process plants as a substitute for natural gas or oil. Gasifier systems generate low-BTU or high-BTU gas. A low-BTU gasifier (such as the well-developed Lurgi) for a producer gas (110-150 BTU/ft³) system is shown in highly simplified version with a combined cycle in Figure 2. It uses counter-current flow of coal and gases, lock hoppers to control coal feeding and ash removal, - and dust, sulfur, and alkali are removed at low temperatures. Other gasifiers also exist. For instance, a developing General Electric/Babcock and Wilcox system uses co-current flow and a coal extrusion process which can handle fines, - important in eastern US bituminous coal use, - and claims better stirring.(6) However, a major feature of most low-BTU systems is that the gas is cooled and cleaned following gasification, so that the effluent gas will be relatively non-corrosive.

High-BTU gas systems (200 BTU/ft³ or more) are more fashionable. Currently, ERDA and AGA have in place a large joint program to produce pipeline quality gas. The processes supported are IGT Hygas, Consol CO₂ Acceptor, BCR Bigas, and the Bureau of Mines Synthane process. High-BTU systems generate gas which is more readily combustible to high temperatures and thus leads directly to more efficient gas turbines, although the gas may be more corrosive.

Other major differences also exist between coal gasification schemes. For instance, the type of bed is very significant. The Lurgi and GE Gas systems use a fixed bed, Westinghouse and IGT use a fluid bed, the Koppers-Totzek and Pittsburg-Midway systems feature suspension bed, and Fischer-Tropsch a molten

bed. For openers, don't forget that simple fixed bed gasifiers have been industrial equipment for 150 years!

The Problems. Coal gasification is a technology involving many developing systems so it is difficult to nail down neatly the materials problems involved.(8) However, using McNab(7) for help, Figure 3 is an attempt to collate the various coal gasification systems into a series of major process steps to use as a roadmap for consideration of materials applications and needs.

The map divides into about three major segments. From the top, "Coal Preparation and Handling" involves processes conducted at moderate ambients; major problems expected are erosion, wear and abrasion. Skipping to the bottom, it turns out that the steps below "Heat Recovery" are well-known to contemporary chemical processes industries. The non-superalloy materials needed should be available from current practice, although the great component size may be a problem. It is in the "Coal Pretreatment", Coal Gasification", and "Gas Quench" steps and their appendage processes where the voracious process stream will rival Chengis Khan in the fury of its attack, and where the properties of superalloys may be needed.

In "Coal Pretreatment" the problems encountered relate principally to heating the coal and the reactants to near-reaction temperature through exchanging heat with the reaction products from gasification. The problems are hot erosion and abrasion from the feed coal and corrosion from the after-products of gasification, supplying heat. For the sake of brevity, these problems are not detailed here, but will be, at least in the corrosion sense, similar to those discussed below in "Gas Quench".

Depending on the specific process, "Coal Gasification" will operate at temperatures up to over 1200C (2000F) and at 100 atmospheres. Typically, a gasifier will be an extremely large vessel or vessel group into which the coal flows and in one method or another is reacted to produce a gas.

First, there will be significant erosion effects from the abrasive solid coal being injected and erosion from the solid ash ultimately produced; components must withstand this. However, it is from the coal gas product that the greatest problems generate. In addition to vital hydrogen and carbon-containing gases with high intrinsic energy of combustion produced, the coal gas will contain many undesirable species including sulfides, sulfites, sulfates, CO₂, ammonias, cyanides, H₂S/H₂ combinations, volatilized oils, phenols, and our old trace-element enemies potassium, sodium, vanadium and lead. The incredible corrosion potential is obvious! Further, from this gaseous melange, liquids with high corrosion potential condense down on cooler parts of the system. The departing ash, in addition to being erosive, will be composed of oxides, sulfates, other inorganics and organics, and alkali metal concentrates. It is not overly reactionary to note the systems may be reducing or oxidizing, - or both in different places. High pressures complex these problems.

Figure 3 gives more specific examples of some constituents expected but still fails to identify fully the potential for corrosion. For instance, sodium, potassium or lead are not noted, but they are there. Based on experience in gas turbine firing of crude oils, these are the most crucial elements in generation of hot corrosion on high-temperature materials.

Another problem is expected to be the huge size. Vessels or shells for the gasifier will be over 200 feet high. They must meet Section VII of the ASME pressure vessel code. Obviously, such systems are so large that costly superalloys cannot be used. Instead one solution is to use ceramic linings somewhat as used in blast furnaces, although gaseous corrodents will still penetrate and raise hob with the metallic support structures. One technique to control corrosion is to water-jacket the vessels creating a "cold wall" system. However, while the latter approach will avoid high-temperature gaseous

corrosion, it will lead to low-temperature corrosion from condensation on the wall.

By extrapolating from the extensive background in these problems from the petroleum industry, and noting that the coal-derived process streams will be heavier in contaminants, Cuiffreda and Krystowe in an Ohio State Symposium⁽⁸⁾ have categorized the types of corrosion and attack that can be expected, as follows:

- Oxidation and corrosion
- Hydrogen attack
- Sulfite stress cracking
- Temper embrittlement
- Carburization/metal dusting
- Hydrogen blistering
- Chloride stress-corrosion cracking

To this we would further identify acidic condensate corrosion, organic attack (by phenols, polythionic acids, etc.) Na- and K-catalyzed hot corrosion, and Pb- or V-induced attack.

It is very important to understand that only a few ppm of elements such as Na, K, V or Pb can initiate a severe reaction. Current specifications for heavy oil (which has many similarities) burned in gas turbines identify a limit of about 1.0 ppm for Na + K.

Even though these huge reactor vessels may be constructed of strong fabricable low-alloy materials utilizing ceramic linings or water cooling for protection, it is inevitable that other components within the system must withstand the full force of the corrosive media without protection. Solids separation cyclones, dip legs, solids transfer piping, valves, instrument probes, refractory wall anchors and stirring mechanisms all require high strength and fabricability and face extremes of temperature and corrosion attack. It is in these applications that superalloys will find applications. Their high-temperature strength, structural stability, and oxidation resistance will be requisite. However, some weaknesses are also evident (hot corrosion), and gasification systems certainly include the potential for exploiting these; such weaknesses must be corrected.

Following the coal gasification operation itself, further corrosion problems are expected in "Gas Quench and Heat Power Recovery" components. In the Battelle and the Consol processes, gas turbine power will be generated from gas streams at 750C (1500F) and 1500 psi. In addition to carryover of corrosive species from gasification, SO₂ will be present in quantity. With sodium or potassium present classic, aggressive alkali sulfates will form. Thus, again we are brought back to the continuing problem of identifying materials with corrosion resistance. Also, one cannot ignore the high potential for erosion and for fouling on ducting separators, valves, gas turbines parts, and the like. (For more technical coverage of the corrosion, erosion and fouling phenomena, see the discussion of the Pressurized Fluid Bed Process below.)

Wherever a hot gas stream is directed to heat recovery, the "gasification gas side" of the heat exchanger will be subject to all of these problems also. Temperatures can range up to 1000C (1800F) and pressure to perhaps 70 atmospheres. The heat exchangers will be large, and the piping must be strong, corrosion-resistant alloys; fabricability and weldability are obviously essential. The "leaner" superalloys may find application here as HX piping.

In many gasification systems, the coal gas will be water quenched to allow removal of sulfur and other corrosion contaminants. During cooling, of course, a variety of liquids will condense; again, the potential for severe corrosive attack is generated; again, whenever a combination of high temperature and high stress exists, superalloys will be needed.

SUPERALLOY REQUIREMENTS FOR COAL GASIFICATION

Principal Equipment Types and Superalloy Component Form/Type

Heat exchangers	Valves
Gas ducting	Cyclones
Gas turbine hot stages (in power recovery)	Instrumentation
Tubing	Small forged parts
Fabricable sheet	Investment castings

Top Critical Application Temperature

1200C (2000F)

Surface Stability Requirements

Resistance to all types of enhanced oxidation (hot corrosion)
Resistance to carburization

Major Mechanical Property Requirements

Less than 0.2% creep in 100,000 hours for sheet and tubing
Typical gas turbine hot-stage properties for investment castings

Coal Liquefaction

The System. Coal consists of high-molecular-weight carbonaceous compounds with a hydrogen/carbon ratio of about 0.8. If that ratio can be increased to about 1.5, the resultant products range from low-sulfur ash-free materials with a melting point of 300-400C (550-750F) up to liquids comparable to fuel oil, petroleum distillates and gasolines. As early as the 1950's processes to make this conversion were being developed in oil-poor Europe. Perhaps the most well-known process was Fischer-Tropsch, but many others exist. (Table II). OCR and the USBM began serious US activity in the 1950's, which now of course, is increasing.⁹ In fact, coal liquefaction now appears favored in economics and time for commercial applications in coal conversion.

Coal liquefaction can be classified into about five groups. These are: pyrolysis, which is the heating of coal (such as in a fluid bed) under reducing conditions and often high pressure to convert the solid; solvent extraction which entails use of a solvent to transfer hydrogen atoms into the carbon compounds in the coal; non-catalytic hydrogenation where coal also is treated in a liquid, but gaseous hydrogen is introduced to react with the coal; direct catalytic hydrogenation, again using a slurry or solvent type of matrix with a catalyst and gaseous hydrogen, to cause hydrogenation; direct liquefaction, where coal is reacted with super-heated steam at high temperature and pressure with the reactions producing a variety of liquids, such as gasoline or methanol, depending upon how the reaction is conducted. The H-Coal Liquid Coal Fuel Process, driving a combined cycle, is diagrammed in Figure 4. It is even much more complex than shown here, - related to the variety of products created.

The Problem. Of the categories of coal liquefaction described above, some of the pyrolysis processes and direct liquefaction appears to be conducted at temperatures and pressures where the corrosion and strength requirements identify that superalloys may be called upon for plant construction needs. The other processes occur at less than 600C (1100F).

As in coal gasification, coal liquefaction must be conducted in huge vessels and reactors to be commercially viable. So, in all cases the size of the component is significant metallurgically; where superalloys may be applied, large components may often be needed. Further, as coal is moved into the processing vessels erosion, abrasion and the myriad of corrosion effects are similar to those in coal gasification, with erosion by pulverized coal-laden

liquids identified as perhaps the most severe problem.

In the direct liquefaction process the coal must be reacted with superheated steam at temperatures above 900C (1475F) and at moderate pressures, - producing carbon monoxide and hydrogen. The CO shift reaction uses more water to create CO₂ from CO. These are all at reducing conditions, and depending upon the specific product desired, reaction pressures can reach 2000 psi. Thus, construction alloy strength and corrosion requirements are essentially the same or similar to those identified under coal gasification, with the obvious exception that the prime product is not a gas but a liquid. (Even then, much of the liquefaction by-products are gaseous and gasification products liquid.) As with gasification, other products from liquefaction will be heavy tars, liquids, char, and corrosive slagging ashes.

Thus, it seems overly repetitive here to recant the essential horror of the corrosion problems in the high-pressure high-temperature steps of liquefaction, since almost all of the coal gasification discussion applies. Materials with acceptable durability will be difficult to find, and superalloy requirements will be as described above. Ceramics and water cooling may be needed.

III. Coal Combustion Processes; Fluid Bed Combustion

The System. The US Office of Coal Research (now part of ERDA) has stated "the most efficient way to utilize coal is by its direct combustion. Processes to permit combustion in fluidized bed boilers have a high potential payoff and will be pursued." (10) The fluid bed combustor (FBC) represents one such major potential method for energy conversion. In the FBC coal is burned in a fluid bed, usually under pressure (PFBC) to produce a hot gas stream which drives gas turbines directly; boiler tubes criss-cross within and immediately above the fluid bed for steam generation. The result is a steam/gas combined cycle plant for electric power generation. Fluid bed combustion has the advantage (compared to coal gasification) that the hot high-pressure gases are never cooled and drive the gas turbine directly. Thus, no loss of sensible heat occurs; however, this also means the gas is not cleaned before use. A simplified flow diagram for a PFBC system is given in Figure 5.

It is presently believed that PFBC's under study and development will operate with bed temperatures up to about 950C (1700F), and that the beds will be fed by coal mixed with dolomite to control sulfur content. Combustion in the fluid bed will take place at about 10-15 atmospheres. The systems will be designed for about 200,000 hours life. However, to avoid cooling for gas clean-up or to avoid use of intermediate heat exchangers the hot gases must pass from the combustion zone through several stages of hot filtration, and then into the gas turbine.

The fluid bed has high vertical thermal conductivity so combustion of the fluidized coal buttons occurs relatively uniformly and quietly compared to a conventional boiler. Efficient combustion of the gases released by the coal also occurs, and these bubbles of "flue" gas help mixing in the bed. Second, the dolomite (or limestone) in the bed reacts with the sulfur in the coal to form SO₂ and a rejected ash. NO_x emission is claimed relatively low. Design must minimize carryover of particulate fines by the escaping flue gas, and the steam boiler-tube geometry throughout the bed effects this significantly.

Additionally it has been experienced that in the bed steam tube construction alloys become coated with a thin enamel-like layer of oxide which appears to protect from serious corrosion attack. Importantly, the temperature of combustion occurs below the ash fusion point (see below), a benefit to the type of ash formed.

However, despite the energetic promises of PFBC systems, it is this author's opinion that the FBC gas stream as we know it now has more potential to destroy

construction materials that in any other energy system operating below 1200C (2000F) under oxidizing condition. Some of the details are described following.

The Problems. The potential of the atmosphere generated from the fluid bed to erode, corrode and foul boiler tubes, ducting, filtration systems, and the gas turbine is considered the most significant problem in PFBC systems; the hot-stage components of the gas turbine will be particularly susceptible. The gases will carry particles of ash/dust as well as a variety of vaporized aggressive chemical species. These can impact or condense on the alloys and materials of the hot gas path and critical gas turbine hot parts to cause hot corrosion, erosion and fouling. All of these problems have been seen previously to varying degrees of severity in studies of gas streams from directly combusted powdered coal and from burning of residual fuels.(10, 11)

Experience in the industrial gas turbine business has shown that hot corrosion can be controlled to reasonable levels if Na and K (the most aggressive commonly found contaminants) do not exceed about 1.0 ppm in an oil fuel (which is about 0.2 ppm in the gas stream) depending upon the air-to-fuel ratio. However, analysis of the Leatherhead PFB gas stream showed Na + K contents over 100 times these levels.(12) Thus, there is far more Na + K in this type of system than the minimum needed to initiate hot corrosion; further, it is now suspect that K attacks cobalt alloys more than equivalent Na. The considerable experience with heavy liquid fuels with similar contaminant level confirms that very severe hot corrosion problems will exist in gases from fluid bed combustors unless-

- Na + K (at least) contaminants in the combustion products are reduced more than 2 orders of magnitude and/or,
- much more hot-corrosion-resistant materials than presently available can be brought into service.

It is probable the control of hot corrosion is the critical materials problem in any fluid bed combustor system.

Erosion effects are also feared. In coal FBC the gas stream will entrain initially a considerable volume of particulate matter(both ash and inorganics) from the combusted coal. This could cause surface wastage on ducting, cyclones, other separators and hot-stage gas turbine parts downstream.

For instance, the Locomotive Development Committee of BCR, Inc., studied a directly coal-fired gas turbine between 1949-59. Catastrophic erosion of the trailing edges and bases of rotor blades at 1400-1700C (2500-3000F) occurred.(11) Shape and arrangement of airfoils were then changed to direct the ash towards the casing instead of the root of the rotor blades. Titanium carbide wear-strips were installed at key locations. These changes resulted in a significant reduction of erosion, but the results were still far from satisfactory for the long-time service essential for power generation use.

In order to minimize such erosion problems from direct combustion of coal a comprehensive approach involving parts design, materials tolerance, and filtration must be considered. This involves, from a design standpoint, -

- control of gas velocity
- design which avoids particulate flow concentrations
- use of highly effective filtration systems.

Material studies must consider -

- control of the fluid bed to minimize emission
- testing and evaluation of materials to resist the attack
- application of materials protection techniques, such as cladding,

coating and hard surfacing.

However, experience from fluid bed combustion is more promising.(12) Only slight erosion-related attack was observed on the superalloy components following 200 hours in the gas stream from the Leatherhead FBC boiler test. Evaluation of the airfoil vane cross-sections indicated no significant metal loss by erosive particles although most of the aluminide coating was gone. In addition, 1/8" nickel alloy pins located downstream of the vanes showed no significant change from their original round shape.

Therefore, the flue dust particles were studied by use of the electron scanning microscope and compared to fly-ash particles from locomotive experience with direct coal combustion. The contrast is striking, as shown clearly in Figure 6. The "conventional" combustion of coal in the range of 1400-1700C (2500-3000F) yields flue dust particles which are melted and sintered to round, hard, apparently glassy particles; obviously, these can cause severe erosion damage when impacting metallic compounds.

However, in FBC the temperature in the fluid bed is maintained below 900C (1700F). The fly ash does not form hard spheres. Instead, the particles appear to be low-density agglomerates of a very friable nature. When impacting, the particles themselves may break up, sharply reducing damage to the impacted component. The possibilities of erosion damage on turbine hardware and other components appear reduced greatly and may be insignificant! However, very effective particulate filtration will still be needed to prevent fouling and hot corrosion, so even further improvement in the erosion situation can be expected.

Fouling is another problem. Unwanted effluent from combustion of heavy ash-bearing liquid fuels form deposits on downstream components, particularly when treated to reduce lead. Gas turbine nozzle passages become plugged, airfoil shapes are altered, and turbine output and efficiency drop, possibly leading to compressor pulsation. These deposits can be very tough to remove. Coal is a particularly prolific source of such ash, and uncontrolled fouling can be expected in a relatively short time.

In the Leatherhead program (12) considerable fouling occurred in less than 50 hours on the nozzle cascade, and other fluid bed activities have found similar effects. Turbine output and efficiency are reduced, and cleaning techniques become mandatory, in addition to potential effects on other gas-stream contaminant and treatment components.

The critical effects and results to date can be summarized as follows:

- As in hot corrosion, Na and K content appear to be an essential requirement for deposit formation, and Al and Ca in coal ash can increase the rate of deposit buildup.
- The deposits usually promulgate corrosion of the host material.
- Cleaning of deposits from hot-stage parts is often effectively done by water-washing, thermal shock, and injection of nutshells.
- To date no information exists which identifies that the type of alloy present effects the fouling process itself significantly.

Thus, coal burned in FBC will certainly generate gas-stream particulate matter which will cause serious turbine fouling, even below 900C (1700F). Cleaning techniques to remove the deposits must be developed.

SUPERALLOY REQUIREMENTS FOR FLUID BED COMBUSTION

Principal Equipment Types and Superalloy Components Form/Type

Gas turbines	Valves	
Separators/cyclones	Ducting, elbows	
Tubing	Investment castings	Large forgings
Sheet and plate	Coatings and claddings	

Estimated Top or Critical Application Temperature

1000C (1800F)

Surface Stability Requirements

Resistance to hot corrosion \geq IN-617 or HS-188
Resistance to erosion \geq TIC

Major Mechanical Property Requirements

2.0% creep (Max.) for 100,000 hours in fabricated components
0.5% creep (Max.) for 50,000 hours in castings for gas turbines

IV. High-Temperature Gas Reactors

The Systems. The high-temperature gas-cooled reactor (HTGR, or HTR, - as in Europe) is a concept which embraces a nuclear core of graphitic materials activated by uranium and thorium compounds held within it, designed to heat a transfer fluid, invariably He. Application of the HTGR may be to supply heat for electric power generation or for an industrial process (Figs. 7,8). These reactors fall into two general types, a "prismatic" type and the "pebble-bed" type.

Several prototype or demonstration plants exist, usually designed to raise steam for electric power generation, the obvious first step in plans for application of this concept. These include the 40-MW Peach Bottom reactor of Philadelphia Electric Company, and the 300-MW Ft. St. Vrain plant of Public Service of Colorado. Both are characterized by a "prismatic" reactor core of graphite right hexagons favored by General Atomic Corporation; the blocks of graphite contain fissionable UO_2 in pellet form, and channels in which high-pressure He is heated, and then flows to generate steam through heat exchangers.

Alternately, an experimental "pebble-bed" HTR plant of about 8-MW is operated at Jülich, Germany by KFA (kernforschungsanlage Jülich); a commercial version, the 300-MW THTR is being built at Oberhausen. A pebble-bed consists essentially of a large graphite hopper filled with 6-cm graphite balls containing particulate UO_2 fuel. The He coolant passes through the interstices of the bed. The pebble-bed is particularly well-fitted for process heat applications. The Jülich AVR has operated up to almost 1000C (1800F).

Present HTGR steam plants operate at about 700C (1300F). While interesting materials problems exist in these reactors, application of superalloys is modest if at all. The turbine-like circulators for the He use stainless steels or intermediate-temperature iron-nickel alloys. However, the potential of HTGR's to generate helium temperatures to the 1000-1200C range is important. It leads to the concept of direct cycle, - wherein He (at 70 atmospheres) drives gas turbines integrated directly into the system as electric generators. Other versions of HTGR's use hot helium temperatures to conduct chemical reactions such as the reforming gas reaction or the reduction of iron ore, to provide heat for steelmaking, to gasify lignite (coal) to methane or synthetic gas, or (ultimately) to crack water for hydrogen generation, vital to German national energy plans. Bear in mind these reactors are virtual "concrete mountains" in the sizes to 1100 MW_e envisioned, and component lives of about 250,000 hours are desired.

Thus the generic technology of HTGR's are under development and in plant-building stages for essentially three types of systems.

- to raise steam for steam turbine electrical plants,
- to drive gas turbines (directly) for power generating systems, and
- to operate high-temperature chemical or metallurgical processes, usually through intermediate heat exchange systems.

Of these, the latter two must operate to 900C or higher to yield economical systems, and it is in these two that the properties of superalloys are needed. Obviously, successful application of superalloy materials in hot gas ducting, heat exchangers and major gas turbine components is of prime desire to ensure ultimate success of these types of systems.

In contrast to normal oxidizing gas streams, the opportunity to design components for He (an inert gas) should appear a delight, - but that is not the case! It was found early on that impurities in the He can cause surface interaction problems with construction materials, and with time this has been demonstrated to be a significant problem. A need for engineers, metallurgists, and scientists to develop resistant materials exists. The road to travel is clear, however, and the opportunities great.

The Problem. While He itself is obviously entirely non-reactive, the He atmosphere (often called HTR-He) contains contaminants. Typical levels of these contaminants (in atmospheres) are:

Reactor	H ₂	H ₂ O	CO	CO ₂	CH ₄	N ₂
Dragon ^a	10	1	8	0.5	1	12
Peach Bottom	200	1	11	1	22	15
Direct Cycle GT ^b	200	0.5	20	1	20	5-10
Process Heat ^{b,c}	100	0.5	20	1	15	5-10

- Experimental 8-MW reactor of the O.E.C.D. Project Dragon.
- Estimated levels at maturity.
- With intermediate heat exchanger.

Under high pressure and temperature these contaminants may cause at least two deleterious effects in steels, stainless steels, and austenitic superalloys which must be considered in materials selection, development and protection. These effects are:

- Localized surface reaction with selected elements from the alloy, leading to thin or patchy surface oxidation, internal oxidation, and ultimately to surface cracking.
- Internal carburization of reactive components from the alloy, usually as a general front moving into the alloy.

In normal high-temperature oxidation service these effects, or something like them, are legion. However, the significant factor in He is that P_{O₂} is so low that insufficient (if any) protective oxide film forms on the metal, - allowing internal oxidation and carburization reactions to proceed into the alloy as fast as diffusion will allow, - so it can be faster than in normal oxidative service.

The effect of these gas/metal reaction on mechanical properties can be quite serious. For example, Figure 9 shows effects on rupture properties (14, 15). Creep is effected similarly. Some alloys show a 25% reduction in stress capability, - depending on severity of the atmosphere studied; strength reductions have been found in N-80A, N-115, IN-102, Hastelloy X, IN-625 and

Incoloy 800. Temperatures of about 700-900C (1300-1650F) are worst. It is of less concern at low-to-intermediate temperatures where 12Cr steels, Cr-Mo-V steels, and carbon steels are used. However, regardless of alloy, it is probable that little deleterious effect will be encountered below 800F (430C).

Recently, Graham(13) has reported that over about 1000C (1800F) oxidation reaction essentially ceased on AISI 321SS, which is expected from oxide stability thermodynamics. Therefore an upper temperature limit appears to exist. However, carburization can still occur as observed by Hozoi and Abe(16) who found a related creep effect at 1000C.

Incoloy 800 illustrates classic effects from HTR-He with relatively high oxidation potential (Figure 10a). Exposure at 750C (1380F) at 42 N/mm² (about 8 ksi) for 5000 hours to 2% strain generated uniform oxide scale and grain-boundary oxide intrusions. Carburization and an intragranular plate-like precipitate to a depth of several grains develops simultaneously. Hastelloy X (Figure 10b) was exposed at 750C (1300F) and 33 N/mm² (about 5 ksi) for 5000 hours to 0.2% strain. A thin surface scale developed, with minimal oxide intrusions. Precipitate decoration of M₂₃C₆ along grain boundaries shows tentative estimate of the load/temperature limit for a significant life (~10,000 hours) by this author suggesting something like 10 ksi at 700C (~1300F) in Dragon-type HTR helium test atmospheres might be expected. Nimonic 115 exposed by Dragon Project at about 800C (1470F) in a very "wet" atmosphere is shown in Figure 10c. The oxide patch underlaid with oxide-filled metal and alloy-depleted areas is typical. The interior shows a continuous network of plate-like M₂₃C₆. Even in this relatively "wet" high-oxygen atmosphere, extensive carburization occurred.

Superalloys are expected to be work-horses in gas turbines, helium circulators, ducting, and heat exchangers. The effects of alloy composition have been studied for 15 years; O.E.C.D. Project Dragon has operated test loops in HTR-He with varying contaminant levels including highly oxidative, ("wet"), moderately reducing conditions ("dry"), and in the Dragon Reactor, - a very clean, dry atmosphere. From this work, empirical observations of the effects of composition have been published by Huddle and co-workers.(17) To clarify the problem and guide alloy development, they are summarized very briefly as follows:

- Ni, Co and Fe are essentially inert to HTR-He.
- Cr, Ti, and Al (obvious reactive elements) are major sources of gas/alloy reactions. Carbon is also deleterious.

The implications of these observations are obvious. The major austenite-formers, Ni, Co and Fe, are viable superalloy bases, although they readily allow diffusion of contaminants. For solution strengthening, Mo and W might be helpful. Cr will not protect superalloys, since it does not generate sufficient protective Cr₂O₃ in HTR-He. The classic γ' strengtheners Al and Ti are undesirable since they can react readily to precipitate internal oxides and carbides. Co and Ta are undesirable for nuclear reasons.

Obviously, effects of varying contaminant are critical. As shown above, if HTR-He is reducing or very "dry", then carburization and related reducing effects occur; if it is oxidizing or "wet", then internal oxidation can be severe. Neither type of attack is exclusive of the other. Graham(13) has noted that oxidation potentials, P_{H_2}/P_{H_2O} and P_{CO}/P_{CO_2} , are not pressure-dependent, while carburization potentials, P_{CH_4}/P_{H_2} and P_{CO_2}/P_{CO} , are.

A correlation of these effects has been developed by Bates(18) (Figure 11) who compares severity of attack against the oxidation/reduction tendencies of the atmosphere, using H₂O concentration as the independent variable. Present materials testing is done near the minimum. As HTGR technology develops (19), it seems clear HTR-He will become more "dry", moving to the left. Carburization

potential will increase, oxidation potential lessen.

SUPERALLOY REQUIREMENTS FOR HTGR SYSTEMS

Principal Equipment Types and Superalloy Component Form/Type

Gas turbines	Heat exchangers
Circulators	Large diameter ducting
Investment castings	Sheet, plate and turbine
Large forgings	

Estimated Top or Critical Application Temperature

1100C (2000F)

Surface Stability Requirements

Resistance to oxidizing and reducing internal contamination-type attack at low reactant partial pressures.

Major Mechanical Property Requirements

Investment castings; 30-40,000 psi for 250,000 hours
Ducting; 10,000 psi for 250,000 hours.

Special Requirements or Considerations

May need to meet nuclear criteria.
Wrought products to be weldable.

V. Liquid Metal Fast Breeder Reactor (LMFBR)

The System. While the specifics of predictions concerning the systems from which we will obtain energy vary from year to year, one consensus appears to vary little. This is that nuclear energy will shoulder a greater portion of the electric power load as time goes on, perhaps rising to as much as 100% by the year 2010. LMFBR's will be the principal energy-generating nuclear plants and will probably be about 75% of all nuclear plants under construction at that time.(20)

An LMFBR system is shown in Figure 12. A fast breeder reactor is "kind of a catalytic nuclear burner" which consumes U_{238} or Th_{232} so that the Pu_{239} or U_{233} catalysts are more than self-regenerating. The LMFBR's will be the most economical systems, because of their capability to produce ("breed") more fissile material than consumed. Further, in addition to production of direct electric energy, the additional plutonium and uranium will be available for thermal reactors (LWR's and HTGR's) to use. Even more, they will be fueled with depleted uranium from the tailings built up from enrichment needed for LWR's running at present. Plutonium being held from LWR's will also be used. LMFBR's will be more thermally efficient than LWR's.

Major technical features of LMFBR's, of course, are that liquid sodium is used as the primary coolant. The fuel elements will be some form of uranium or plutonium oxides clad with stainless steels or higher alloys. Most systems visualized show an intermediate heat exchanger between the reactor and the steam generator. Currently conceived systems then identify typical steam turbine-generator sets to make power. Reactor temperatures are not high enough to make gas turbine introduction into combined cycles possible. However, gas cooled breeders, not discussed here, also are being studied; steam or gas turbines might take off power directly; temperatures will probably hold below about 550C.

The promise of these reactor systems appears to have been regarded as far more viable to Europeans than to Americans. Despite operation of the first liquid metal cooled reactor (by 8 years), the US will have only about 8% of the Worlds demonstration or commercial LMFBR's by 1984. The major US effort will be in the Clinch River Breeder Reactor (CRBRP), a prototype plant of 975 MW_{Th} (380 MW_e) power.

The Problem. The action center of an LMFBR is the plutonium and/or uranium fuel material contained in a metal cladding or sheeting. These fuel elements and their interrelated structure are all supported in a large moving bath (15-25 feet/second) of liquid sodium, (the heat exchange medium) and operated in a neutron flux of $\sim 10^{15}$ n/cm²-sec. In the general sense, the major problems can be summarized as follows:

- The core materials must have corrosion resistance to the liquid sodium heat exchange medium.
- The core materials must resist damage from fission-generated fast neutrons.
- There must be mechanical strength and corrosion resistance in the structural members in order to provide support in the fuel and assure a compact ductile core.

Thus a strong, fabricable, and corrosion-resistant alloy is needed, - with high thermal conductivity, alloy structural stability and strength up to 800C (1300F) - and obviously resistance to neutron damage. Nuclear engineers originally chose cold-worked stainless steels. However, as technology for the LMFBR has developed, a number of more specific materials problems have become evident.

First it was found that the fast neutrons generate significant radiation damage in most of the materials considered for fuel cladding use. This includes classical radiation hardening, probably due to small defect clusters, void formation with associated dislocation networks from high doses of fast neutrons, and helium bubble formation due to (n- α) transmutations.(21) Attacking from within, perhaps swelling from void formation is the most concerning and serious phenomena (Figure 13) since it results in metal distortion and possibly an unworkable core. To combat this, early plans were to utilize heavily cold-worked stainless steel for the claddings. This provides strength of course, but it also was claimed expected neutron damage would keep the cold work "locked in" to the metal structure. However, results of radiation experiments finished several years ago showed that while this technique would be useful for modest periods of time, in the long run fast neutron flux results in severe void generation and reduction in strength properties.

It is now generally believed that all commercial austenitic alloys are subject to some degree of void swelling in a fast neutron flux. Since swelling is directly proportional to dose, any neutron flux gradient in the core will cause differential swelling. The problem is acute in fuel assemblies in which the radial flux gradient produces differential swelling across a single assembly, causing outward bow from the core center. This has prompted modification in design of the reactor core.(22).

Two such modifications are currently being considered: a "constricted" core and an "unrestricted" core. In the latter, assemblies are supported only from the bottom and are free to bow. It is estimated that such a design can accommodate no more than 0.35% swelling for good service. In a "constricted" core assemblies are firmly supported at both top and bottom. Thus restrained from bowing, the assemblies are designed to withstand as much as 5% swelling. Use of 316SS was considered acceptable for the US demonstration LMFBR (CRBR) which utilizes a "constricted" core. However, the amount of swelling encountered at high fluences precludes use of 316SS for long time commercial plants.

In development of the "unrestricted" core concept, the UKAEA is exploiting the greater strength and swelling resistance of superalloys like Nimonic PE-16, - which is a significant improvement over the 316 (Figure 13b); moreover, the English believe that cold-worked PE16 will retain its strength throughout irradiation and that the strengthening γ' will be merely redistributed.

Obviously, then current LMFBR designs generate materials requirements which approach the performance limits of presently used 300-series austenitic stainless steels. For longer reactor lifetimes and higher operating temperatures the requirements are higher. Further, gains in reactor efficiency can be achieved through use of materials which offer both higher strength and greater dimensional stability than the stainless; this also would permit reductions in the structural metal alloy content in the reactor core. Recent advances in the study of radiation damage attest to the attractive swelling behavior of high nickel superalloys. Reduced swelling in austenitic systems has been clearly shown to be a function of nickel content, (23, 24) and the basic relation to austenitic systems is obvious (Figure 14). Even though neutron absorption of nickel-rich alloys is greater than for stainlesses, the reduced volume of core structurals needed more than compensates for the reduced breeding ratio.(25) Thus, for the longer range and for improved performance, superalloys appear to offer considerable potential for use as LMFBR construction materials. Coating of present and future alloys for nuclear service, long ignored, should be given much more attention;(26) it is a workhorse in jet engines where safety is of prime consideration.

SUPERALLOY REQUIREMENTS FOR LMFBR'S

Principal Equipment Types and Superalloy Component Form/Type

- Plate or rod-type reactor fuel element.
- Sheet, plate, tubing.
- Cast structural members.

Estimated Top or Critical Application Temperature

700C (1400F)

Surface Stability Requirements

Resistance to sodium corrosion for fuel element life.

Major Mechanical Property Requirements

Steady stage creep about 0.2% in 8-10,000 hours, plus added transient of about 0.1%.

Special Requirements or Considerations

- Reaction compatibility with contained fuel.
- Low neutron absorption cross section.
- Less than 0.35% swelling response to neutron flux.

VI. Summary

A significant portion of major energy generation systems, both those now in developing stages and those of longer-range interest, will need superalloys, both as we know them now and in further-improved versions. Superalloys will be used in (at least) advanced gas turbines, coal combustion and conversion systems, liquid-metal fast-breeder reactors, and HTGR electric power and energy generating systems. These will be critical applications. It is also certain that superalloys will find many applications in lesser applications, and in applications not yet known.

In the overall sense, this author feels the most provocative developmental challenges now facing the superalloy business are as follows:

- Gas/Gas Heat Exchange Service. Heat transfer from "dirty" to clean gaseous systems at highest possible temperatures is essential. Present alloys do not nearly "get us there". A deep need exists for superalloy sheet, plate, and tubing with better oxidation and corrosion resistance, weldable if possible, and at lowest possible cost for 1000C+--- service.
- Corrosion Resistance to Coal Products. A second major need is for the development of much more corrosion-resistant superalloy materials (investment castings and forgings) - for use in gas streams of high corrosion potential generated from coal combustion.
- The Size, the Size (!). Advanced power systems equipment will be gigantic. Many potential uses of superalloys will be limited by ability to make very large components.
- Technology Transfer. Unusually inventive alloy and process development technology has arisen from the challenge of the gas turbine businesses. A significant effort is needed to assure transfer of this technology into advanced nuclear systems.

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TABLE I COMBUSTIBLE FUELS AND WORKING FLUIDS FOR CERTAIN HIGH-TEMPERATURE ENERGY SYSTEMS

<u>FUEL OR FLUID</u>	<u>MAJOR UTILIZING DEVICE</u>	<u>PHYSICAL FORM</u>	<u>"GOOD" INGREDIENTS</u>	<u>"BAD" INGREDIENTS</u>	<u>OTHER</u>
Hydrogen	Chemical Systems	Gas	Everything	Water	21st Century
Helium	HTGR's Gas Turbines Heat Exchangers	Gas	The Helium	CO, CO ₂ , H ₂ H ₂ O, H ₂	Mainly process heat applications at first
Natural Gas	Gas Turbines	Gas	H ₂ , CO	Na, S	Problems are infrequent
Distillate Oil	Boilers Gas Turbines	Liquid	Hydrocarbons	Na, S	Not usually a severe problem
Residual and Crude Oil	Boilers Gas Turbines	Liquid	Hydrocarbons	Na, S, V, Pb	Always different and usually difficult
Coal	Direct-fired Boilers Fluid Bed Boilers Gasifiers MHD	Solid	Carbon	Na, K, S, V, Pb	Fluid bed combustion foremost
Coal Oil	Boilers Gas Turbines	Liquid	Hydrocarbons	Na, K, S, V, Pb	Not well known
Coal Gas	Gas Turbines	Gas	Hydrocarbons	Na, K, S	Not well known can be cleaned
K Vapor	Gas Turbines	Gas	Potassium	Little	Closed cycle
Tritium	Laser Fusion	Liquid to Gas			

a. Includes both equipments which utilize fuel and utilize products of combustion.

TABLE II
SELECTED COAL CONVERSION PROCESSES

<u>PROCESS NAME</u>	<u>SPONSOR/OWNER</u>	<u>GASIFICATION</u>	<u>LIQUIFICATION</u>	<u>STATUS/REMARKS</u>
Bi-gas	Bituminous Coal Res. Inc.	•		120 T/day plant in construction
CO ₂ acceptor	Consolidated Coal Co.	•		40 T/day pilot plant operating
Gegas	General Electric and Babcock and Wilson	•		Pilot plant oper- ating.
Koppers-Totzek	Heinrich Koppers	•		15 plants operating
Lurgi	Lurgi Minreal Technik	•		14 world wide plants
Synthane	US Bur of Mines	•		Pilot plant operating
Coalcon	Union Carbide/ Chem. Constr. Co.	•	•	Pilot plant operating
Cogas	Consortium	•	•	Synthetic crude oil
Fischer-Tropsch	M. W. Kellogg & others	•	•	Gas, gasoline and other products
Garrett	Garrett R&D Co.	•	•	Gas and liquids
Hygas	Inst. of Gas Tech.	•	•	75 T/day pilot plant operating
Toscoal	Oil Shale Co	•	•	25 T/day pilot plant operating
Coed	FMC Co		•	Synthetic crude
H-coal	Hydrocarbon Research Inc.		•	Synthetic crude
SRC	Pittsburg-Midway Coal Co.		•	Synthetic fuel oil

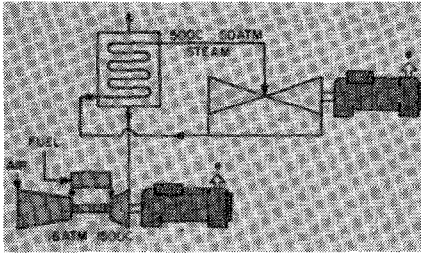


Fig. 1 Gas turbine-steam turbine combined cycle plant.

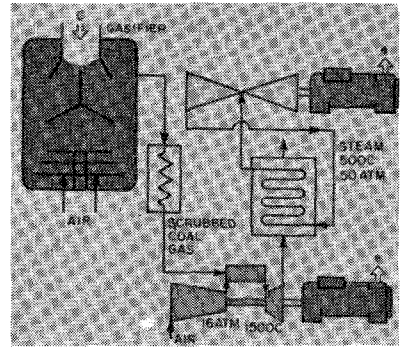


Fig. 2 Coal gasification with combined cycle.

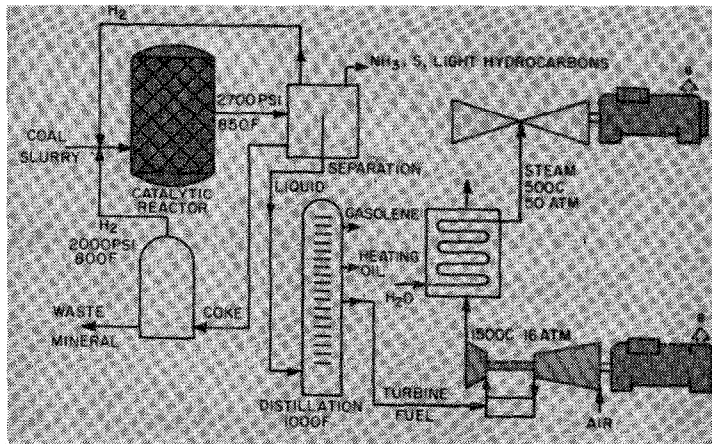


Fig. 4 Coal liquification with steam and gas turbine cycle

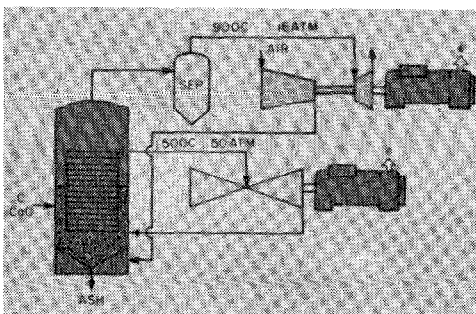


Fig. 5 Pressurized fluid bed combustion power plant with gas and steam turbine combined cycle.

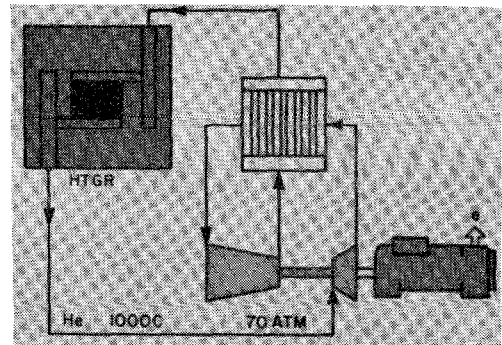


Fig. 7 HTGR Direct-cycle gas turbine power plant.

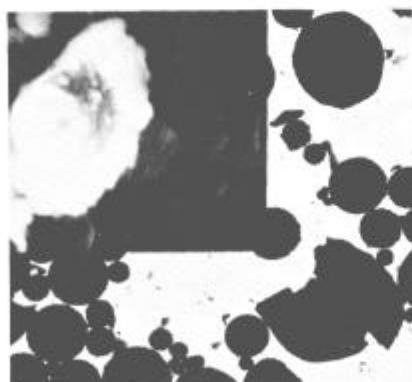
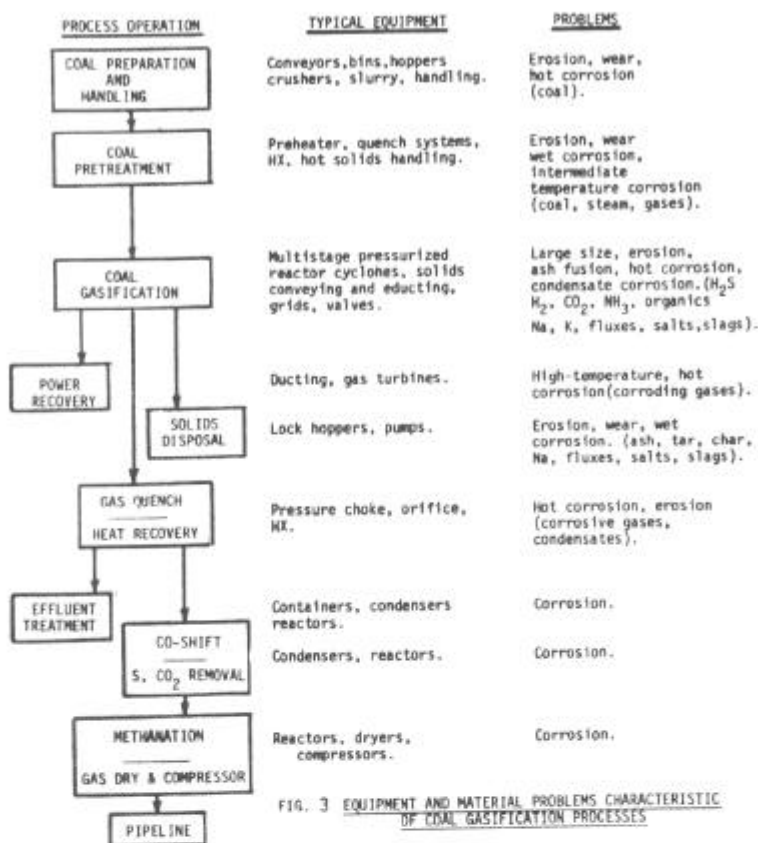


Fig. 6 Scanning electron micrograph of fly-ash, 10,000X
Background: From direct combustion of coal.
Upper Left: From FBC gas stream.

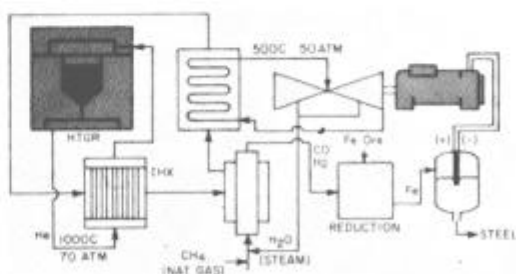


Fig. 8 Process Heat HTGR applied to steel making.

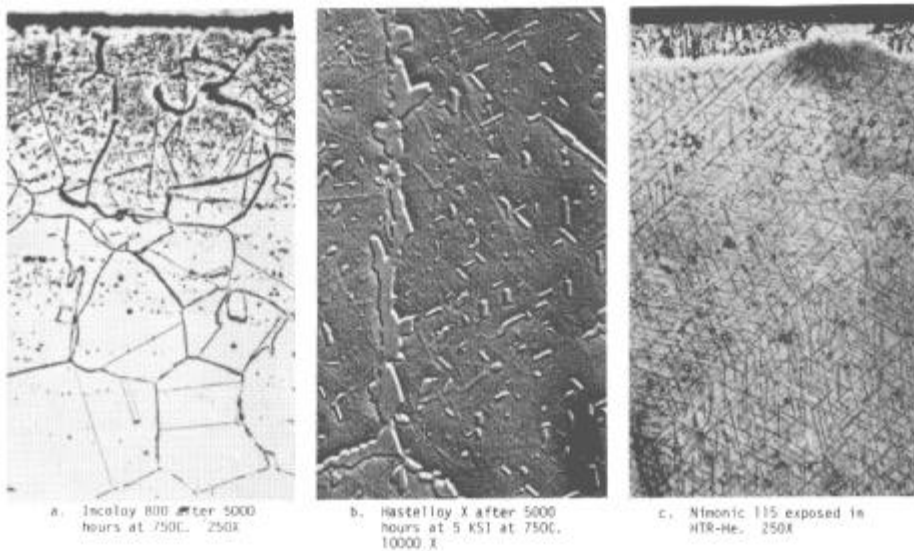


Fig. 10. Various structural metallurgical effects in superalloys from exposure in HTR helium.

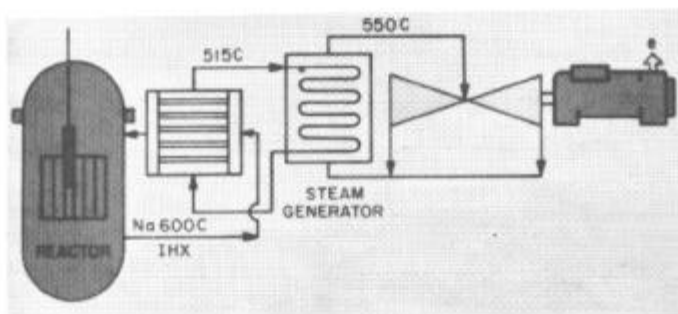


Fig. 12. Liquid metal fast breeder reactor.

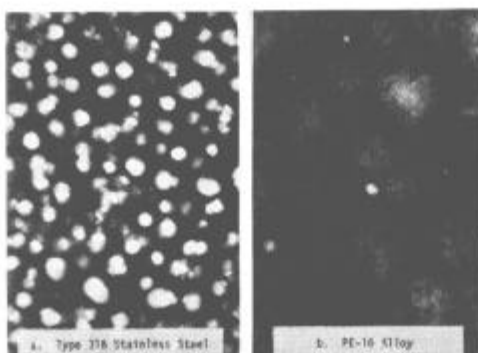


Fig. 13. Cladding alloys showing LMFBR-type void formation generated by bombardment with 5 MEV nickel ions at 625C. Damage level, ~ 140 displacements per atom. 75,000X. Courtesy Johnston and Turkalo.

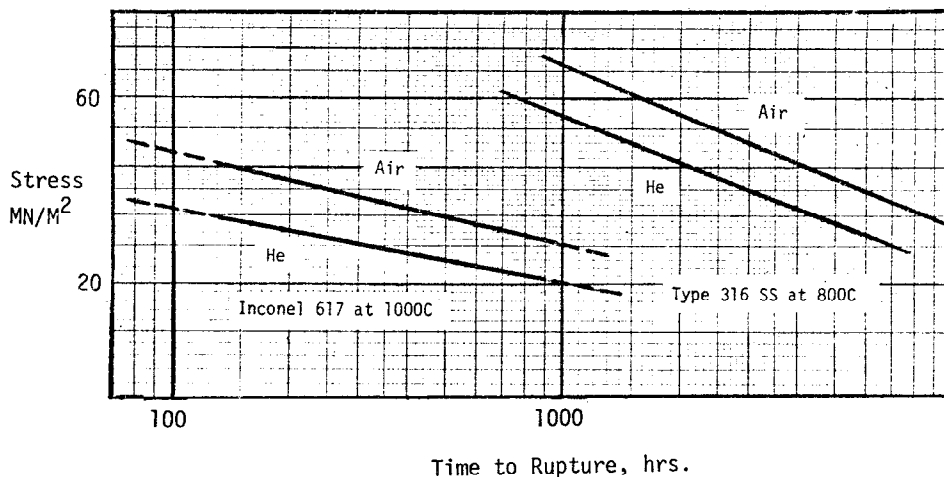


Fig. 9 Effect of impure HE on rupture properties. After Wood (316SS) and Tanino (IN-617).

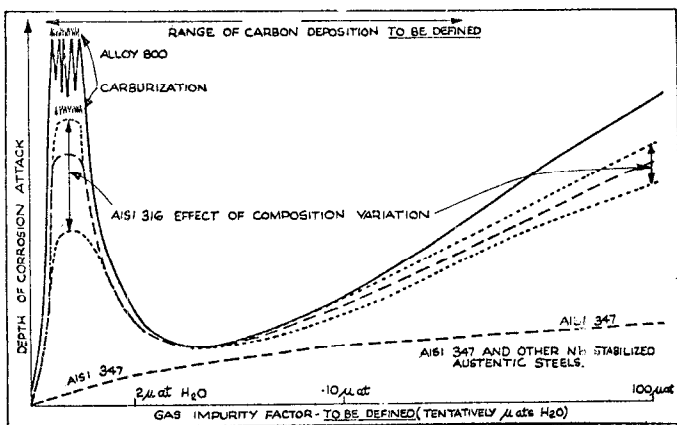


Fig. 11

Proposed relation between gas impurity levels and rate of corrosion attack on AISI 316, AISI 347, and Alloy 800. After Bates

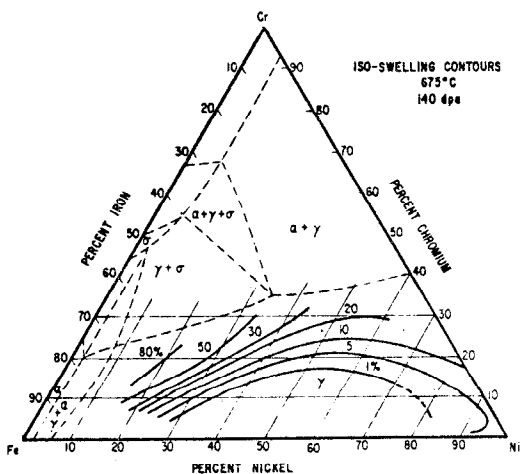


Fig. 14

Iso-swelling contours in the Fe-Ni-Cr Austenitic system created by bombarding with 5 MEV nickel ions. After W. G. Johnston