GER-3957B

GE Power Systems

Gas Turbine Repair Technology

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Abstract

Unit availability and effective utilization of maintenance funds are two of the most important concerns of a gas turbine owner/operator. Major gas turbine components have limited lives in comparison to the unit's useful life. Owners/operators are continually faced with decisions regarding component replacement and/or repair. A component repair program that minimizes maintenance costs and maximizes equipment availability can be instituted within the installed base to meet or improve financial objectives. This paper summarizes some of the state-of-the-art gas turbine component repair processes developed by GE to support the fleet of GE-designed heavy-duty gas turbines.

Operation and Maintenance Considerations

GE's recommended operating and maintenance practices are discussed in the publication, "Heavy-Duty Gas Turbine Operating and Maintenance Considerations" (GER-3620G). This paper discusses the factors that influence equipment life. These life-limiting factors must be understood and accounted for in the owner's maintenance plans (*Table 1*).

Each one of these factors has an effect on gas turbine maintenance intervals and component parts' lives and will vary depending on each unit's operation. Some of the potential and typical failure modes for hot gas path components in continuous and cyclic-duty machines are listed in *Table 2*.

Thermal mechanical fatigue is the predominant life limiting factor for peaking machines, while creep, oxidation and corrosion are the dominant limiters for continuous-duty machines. GER-3620G discusses these limiting factors in detail and provides criteria for establishing maintenance inspection intervals. The scope of typical maintenance inspections (combustion, hot gas path and major) are outlined there and estimated repair and replacement cycles are provided for some major components.

Repair vs. Replacement

Once a maintenance plan is established, the owner/operator implements it. The maintenance cycle starts with the pre-outage planning, continues through the outage, and ends with the post-outage assessment. As one would expect, most gas turbine components have a finite life or expected life in the turbine under the GE performance guidelines. (*See Table 3.*) During the maintenance or outage cycle, owners and operators decide to use the component "as is," repair the component, or replace the component. This post-outage assessment provides the basis for planning the next outage. Throughout this outage process, the owner/operator will be faced with many difficult decisions that will determine unit reliability, maintenance costs, and operating benefit.

- Fuel
- Firing Temperature
- Steam/Water Injection
- Cyclic Effects

Table 1. Major life limiting factors

Since GE is continually improving gas turbine technology and applying it to component designs that can be retrofitted in older units, the owner can evaluate the economics associated with upgrading or uprating the unit by replacing one or more components with state-of-the-art components. GE can consult in various manners by contacting a Customer Service or Product Service specialists. One can also perform some

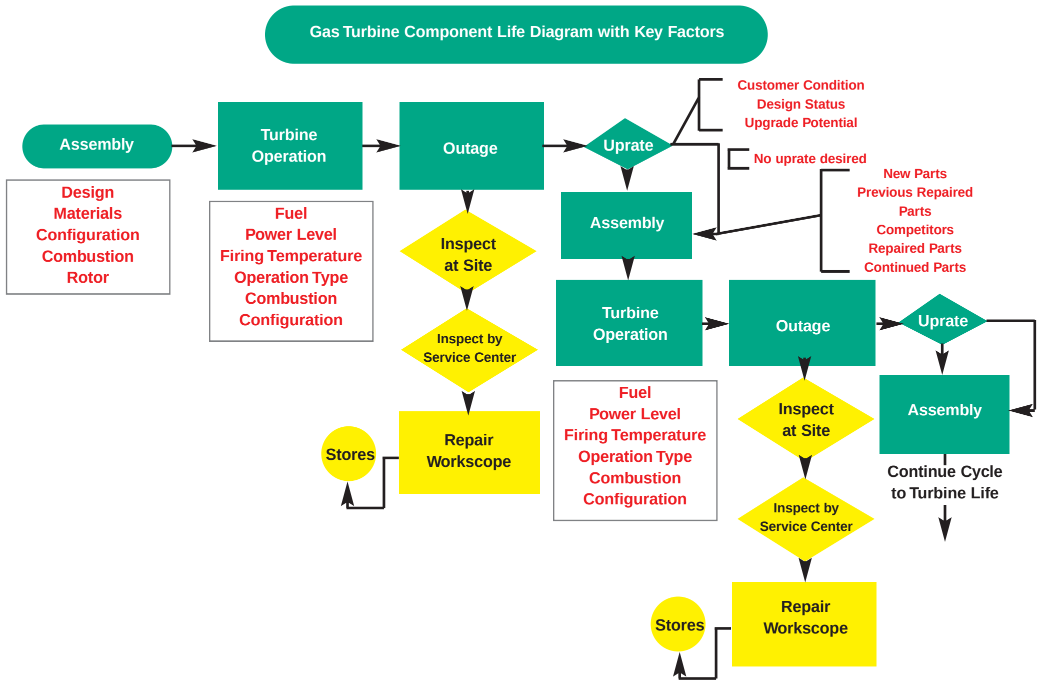

Table 3. Turbine component life flowchart

preliminary studies on which direction to take by looking on GE's web page, www.gepower.com, under the Turbine Optimizer.

- **Continuous Duty**
  - Rupture
  - Creep Deflection
  - High-Cycle Fatigue
  - Oxidation
  - Erosion
  - Corrosion
  - Rubs/Wear
  - Foreign Object Damage
- **Cyclic Duty**
  - Thermal Mechanical Fatigue
  - High-Cycle Fatigue
  - Rubs/ Wear
  - Foreign Object Damage

Table 2. Potential failure modes – hot gas path components

There exist several models that operators may incorporate to make the prime feasibility decision between the component replace, uprate or repair scenario. Typical gas turbine component damage that occurs during usage includes component cracking, foreign object damage (FOD), oxidation and corrosion. In many cases, the component's condition at any given inspection can be anticipated by the unit's performance. The damage may be obvious and the scope of repair may be relatively straightforward. Of course, a replace/repair decision must be based on situational specifics. For example, a set of coated buckets with high operational hours showing signs of wear may be mechanically repaired without recoating and allowed to run to the end of its remaining life. In this particular instance, recoating of the buckets was not a cost-effective option.

Some damage will not be detectable through visual observation. Accurate dimensional check and non-destructive examinations (NDE) techniques like flourescent penetrant inspection may reveal additional discontinuities, such as stress cracking, that require more extensive repairs (*Figure 1*). Additionally, on airfoils where

Figure 1. Stress cracked bucket

internal defects can hide, destructive sample analysis can provide valuable information about the set component condition and the repair workscope. For example, it enables the characterization of internal cooling passage microstructure, which may differ from the behavior of the external material. In addition, crack depths can be accurately determined. Furthermore, the information gathered during destructive analyses can be studied together with the gas turbine running conditions to help identify critical operating parameters. The customer is thereby able to optimize future operating conditions for enhanced performance, as well as improve the prediction of future repair process schedules on the hardware.

A complete repair scope is determined only after rigorous analysis of all inspection data. It is interesting to note that not all serviced or damaged components are candidates for repair. Some components are damaged beyond GE-prescribed repair limits. Since all gas turbine components have a finite life, the cost of repair or replacement and the component's future life expectancy are integrated into the engineering repair recommendations.

Component Repairs

With new technologies being implemented in the gas turbine world, component repair is an ever-changing challenge.

The effort toward increased operating efficiency and decreased heat rate requires that repaired components conform closely with original equipment manufacturer's (OEM) drawing requirements and specifications. With that in mind, the need for consistent repair practices throughout the service organization has become a top company priority. The sharing of piece-part qualifications, best practices, processes and procedures, fixtures and tooling has become more critical than ever.

Each repair is engineered to provide the customer with maximum benefit while balancing cost and cycle times. A multi-organizational engineering review and approval process is required by the GE Service Centers before a new repair is implemented. This ensures that critical design and life-enhancing features are checked and re-checked. Each service center documents a new repair in a Manufacturing Process Plan (MPP). This outlines the repair procedures and "freezes" the process so that the repairs are robust and reproducible. GE's internal audit team reviews each package and requires rigorous testing before approval and release is issued. These procedures are in keeping with the ISO 9000 standards embraced by GE and its repair organizations.

Nozzles

Stage One Nozzle

There are several nozzle failure modes associated with the high temperature environment of industrial gas turbines. These can be categorized under creep, thermal fatigue, oxidation, incipient melting and many forms of mechanical damage. Each failure mode presents different requirements for component repair.

Nozzles that are candidates for repair undergo an initial metallurgical evaluation. From these results, engineering recommendations are made on the nozzle's continued serviceability. The reparability and/or weldability of the nozzle and the required repair methods and operations are determined.

First, a triangle-shaped specimen is cut from the partition's trailing edge (*Figure 2*). It is mounted and polished for metallurgical evaluation (specimen "MetLab"). The metallurgical analysis includes microstructural evaluations of the "as-received" and "heat-treated" conditions, and observations of intergranular oxidation (IGO), chromium migration (CM), chromium depletion (CD), carbide precipitates (CP) and wall thickness. *Figure 3* shows a typical nozzle cooling hole with chrome depletion and oxidation, as indicated by the lighter contrast regions on the specimen's external surfaces.

Specimens may be taken from up to 10 partitions. The specimens are taken from the nozzle segment partition which is closest to the center of each adjacent transition piece. This center area experiences the highest temperatures

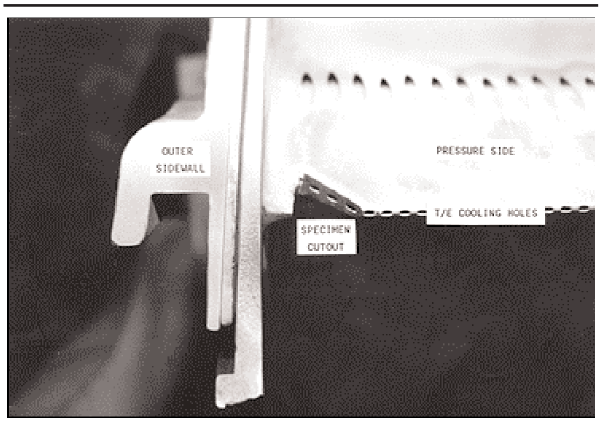

Figure 2. Trailing edge specimen

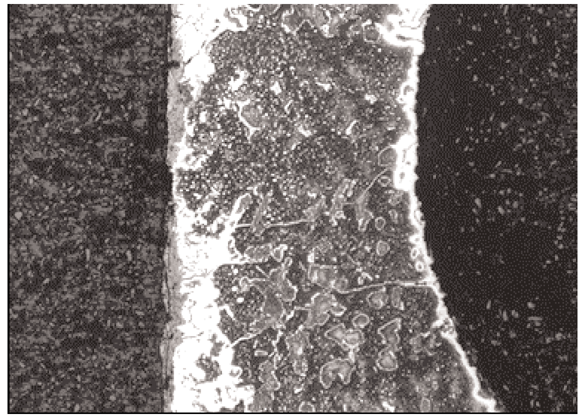

Figure 3. Metallurgical evalution showing chrome depletion/oxidation

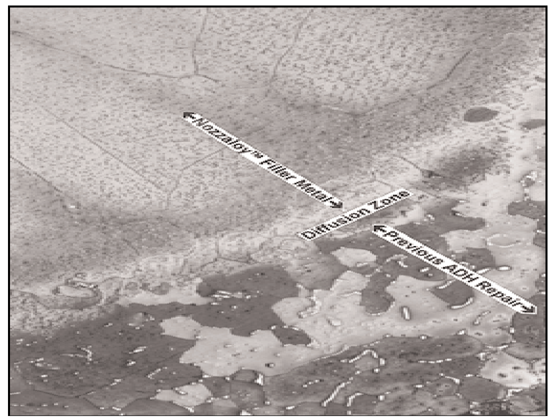

Figure 4. Nozzaloy™ repair over ADH

and reflects the nozzle's most severe operating conditions. Sidewall specimens may also be taken for evaluation if the nozzle has large areas of distress. If the MetLab inspected partition indicates a severe metallurgical problem, additional samples are taken on adjacent partitions to determine the extent of the distress.

The primary method of dimensional restoration to the nozzle is weld repair. To enhance and improve weld repair life, an advanced filler material was developed for repair of cobalt base (X-40, X-45 and FSX-414) investment cast nozzle segments. This material breakthrough was accomplished with the patented creation of Nozzaloy™. Nozzaloy™ repairs can also be applied over previously applied Activated Diffusion Healing (ADH) repairs.

A metallurgical evaluation of such a Nozzaloy™ repair (*Figure 4*) demonstrates its ability to form a sound bond and contamination-free interface. Nozzaloy™ extends repair intervals by inhibiting crack initiation by a factor greater than four when compared to those filler metal alloys more commonly used in the industry. Nozzaloy™ not only shows the highest resistance to crack initiation, but the crack propagation rate is also as low as the base metal. (*See Figure 5 and Figure 6.)*

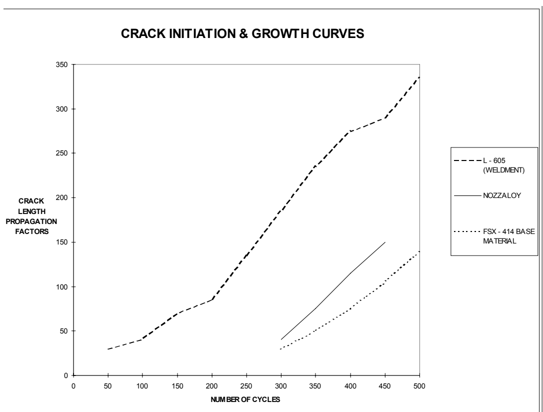

Figure 5. Nozzaloy™ crack initiation

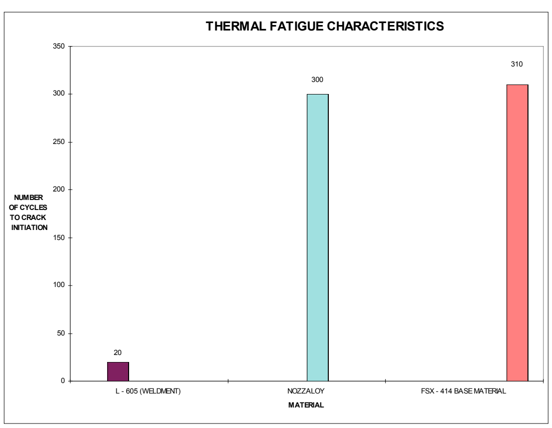

Figure 6. Nozzaloy™ thermal fatigue characteristics

Activated Diffusion Healing: Distortion-Free Nozzle Restoration

Activated Diffusion Healing (ADH) is a unique repair method used in nozzle restoration. The process deposits a metallurgically sound proprietary alloy combination to a nozzle substrate for minor and major repairs on hot gas path surfaces. A key attribute of ADH is that it causes no parts distortion during application and high-temperature processing. This technique was originally developed by GE's Aircraft Engine group for vane (nozzle) repair. GE Power Systems' Inspection and Repair Services (I&RS) has modified the process for use with heavy-duty industrial gas turbine alloys.

ADH lends itself to nozzle surface erosion restoration, craze crack repair and replacement of trailing edge metal loss. Typical erosion damage of a nozzle sidewall that is readily repaired with ADH is shown in *Figure 7.*

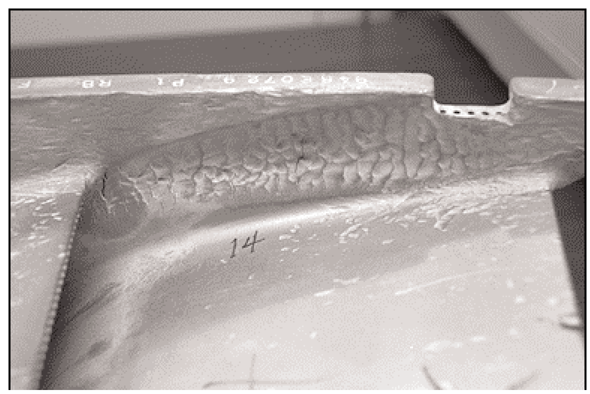

Figure 7. Nozzle requiring ADH repair

The ADH process uses a mixture of superalloy powders and an organic binder tailored to meet the part's specific design requirements. The mixture of ADH materials is designed to melt, solidify and diffuse when placed through a controlled thermal cycle in a vacuum furnace. ADH components produce a liquid which isothermally resolidifies, thus avoiding undesirable eutectic phases. With further thermal treatment, ADH repairs closely approach the composition, microstructure and properties of the parent metal. (*See Figure 8.*)

The ADH alloy system selected for nozzle repairs is compatible with previous repair weldments and is readily weldable. (*See Figure 4.*) Key mechanical test data acquired for comparison

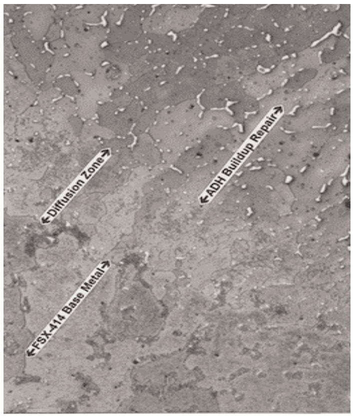

Figure 8. Metallurgical evalution of ADH repair on FSX-414

with base metal properties indicates that ADH-repaired nozzle trailing edges perform favorably. ADH is applied either in a preformed shape or as a slurry. In *Figure 9*, a GE I&RS repair technician uses a slurry-filled syringe to apply ADH to specific areas of a nozzle's sidewall.

Nozzle Modifications

An additional advanced repair offering includes a redesign and modification of nozzle cooling holes. Cooling hole upgrades directly improve the service life of investment cast nozzle segments by enhancing film cooling effectiveness and reducing thermal-mechanical fatigue. These changes are implemented on the nozzle's leading edge, pressure side, trailing edge and outer sidewall.

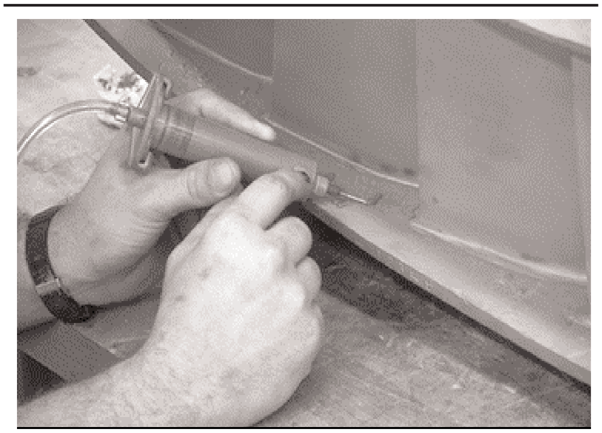

Figure 9. Applying ADH with syringe

Modification of cooling holes on pressure side airfoils and trailing edges is also accomplished with "wishbone coupon" replacements. Wishbone coupons provide improved cooling effectiveness and replace distressed airfoil material with new cast material. Foreign object damage of a nozzle's aft chord is also easily remedied with wishbone coupon replacements.

Another opportunity to improve a nozzle's efficiency during repair and refurbishment is to modify the inner support ring and outer retaining ring sealing surfaces. This is known as a chordal hinge modification and it results in a reduction in compressor discharge air leakage around the stage one nozzle. To accomplish this modification, a weld build-up is applied to the inner contact area on each segment and a new sealing surface rib is machined into the nozzle segments. A modification is also made to the flat seals which bear on the retaining ring against the stage one shroud blocks.

Stages Two and Three Nozzle Repair

Stage two and three nozzles are of a cantilevered design. They are supported from the outer wall by a series of hook fits to the shroud blocks to the turbine shell. Creep damage results in progressive distortion of the vane surfaces and the outer sidewalls. Excessive downstream deflection may result in rubs with the following rotor stage. Detection of excessive creep and resulting deflection is assessed utilizing three primary measurement techniques. Diameter measurements are taken on the inner and outer wall, diaphragm and labyrinth seals. Deviations indicate downstream deflection and/or ovality. Nozzles are inserted into a fixture that simulates the turbine casing to check their fit-up in a turbine shell. Critical dimensions are taken to determine the amount of distortion that nozzle has experienced and corrections are made. (*See Figure 10.*)

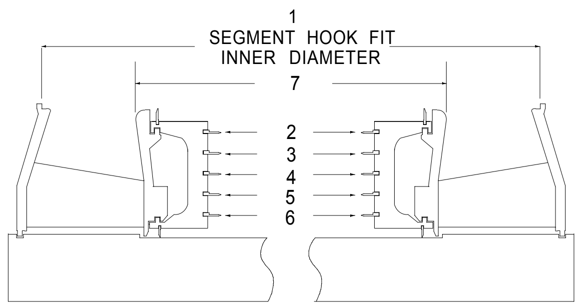

Figure 10. Nozzle diaphragm inspection

Empirical deflection calculations are also made based upon opening clearance data. Final verification, performed by GE Installation and Field Services (I&FS) field engineers, is simulated with deflection measurements carried out in the actual turbine cases of the hardware. These redundant checks define exactly how much upstream correction is required. Material build-up and remachining yields a nozzle that is correctly repositioned between adjacent stages of buckets. Specially-designed fixtures are used to verify all dimensions prior to returning nozzles to a customer.

The repair of newer technology stage two and three nozzles made from GE's patented GTD-222™ creep-resistant alloy includes refurbishing the airfoil with trailing edge coupons. These coupons are specifically designed to address physical and metallurgical damage. Recent advances have yielded an ADH repair for GTD-222™ nozzles. Additionally, select GE service centers now have Coordinate Measuring Machine (CMM) capability to accomplish inspection.

MS5001 second-stage nozzle refurbishment of both N-155 and FSX-414 metallurgy includes weld repair, restoration of diaphragm packing, heat pack modification and re-rounding the nozzle with machining or other techniques. MS3002 and MS5002 variable second-stage nozzle refurbishment includes partition weld repair, shaft grinding and metallizing and hardfacing bushing areas.

Advanced Bucket Repair

Gas turbine buckets must operate in extreme atmospheric and thermal environments while maintaining the structural integrity required of rotating components. GE has determined all of the critical failure modes and has developed repair technologies and processes specific to each. The failure modes most commonly encountered for rotating hardware are listed in *Table 4*.

The first five modes are related to the turbine's operating conditions and their subsequent effects on bucket metallurgy. A single bucket is typically sacrificed from each set of buckets to undergo a destructive metallurgical evaluation. (*See Appendix.*) From that work, engineering recommendations are made on the bucket's continued serviceability. The reparability and/or weldability of the bucket and the required repair methods and operations are also determined.

Typical repair processes include blending, welding, remachining and precision grinding. The advanced bucket metallurgy (vacuum cast nickel-based superalloys) to support the higher firing temperature gas turbines has required Global I&RS service centers to incorporate enhanced repair processes as well.

1. Creep to crack initiation
2. Low cycle fatigue to crack initiation
3. High cycle fatigue
4. Corrosion/oxidation
5. Incipient melting
6. Interference with adjacent components
7. Excessive strain/distortion
8. Foreign object damage
9. Wear and fretting

Table 4. Bucket failure modes

For repair of high strength bucket alloys like GTD-111™, weld wire of the same composition has been typically used in the past. This assures that the repair exhibits strength and oxidation resistance similar to the parent material. A weld repair process originally developed by GE's Aircraft Engine business has been adapted to industrial gas turbine components and produces crack-free high strength welds. The process, called WRAP™ (Weld Repair Advanced Process™), uses a controlled environment box to regulate heat input and cover gas. In *Figure 11*, a technician skillfully welds a bucket using the WRAP™ process.

For repair of high strength bucket alloys like GTD-111™, weld wire of compatible composition may be utilized based on the nature of the repair. GTD-111™ filler material may be used with an elevated temperature repair process or the newly developed "Bktaloy" (Bucketalloy™) may be utilized for an ambient temperature restoration. This assures that the repair exhibits the strength, oxidation resistance and service endurance similar to the parent material. (*See Figure 12.*)

Figure 11. WRAP™ weld operation

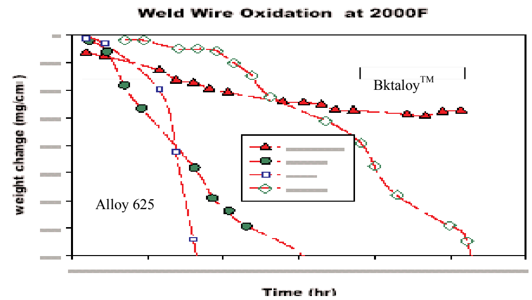

Figure 12. Oxidation characteristics of weld repair alloys

An alternative to the high temperature WRAP™ process effects the repair at ambient temperature with the use of an adaptive robot and specially designed welding fixtures. The system has the objective of welding the squeeler tips of turbine buckets of specific configuration automatically. The unique shape and positional variation of the bucket makes automation of repair processes difficult. The robot is a manipulative arm with six axes of motion. The automatic welding system is specially designed to adaptively change key parameters to weld each bucket tip to full height based on the edge thickness and position of the airfoil contour. (*See Figure 13.*) The basic parts of this system are the robot, the tooling, the welding system, the adaptive control system and the safety provisions. The robot is made up of very precise components including brakes, transmission systems, electric motors, and counterweight systems to deliver the process within the three-dimensional area known as the working area. Within this entire complex system are methods that will calibrate and visually monitor the process of welding the buckets.

The tooling is comprised primarily of a process fixture which places the bucket in a specific location within the operating range of the robot working zone and the vision system camera. The fixture must also provide a heat sink to the part being welded and be designed to function very close to the welding arc without damage

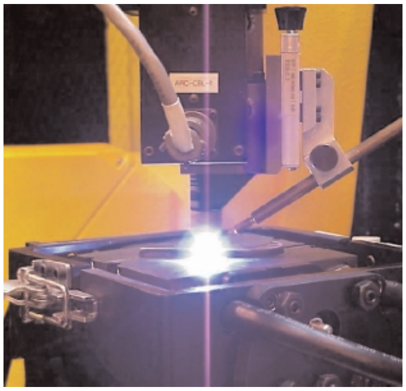

Figure 13. Automated weld repair system

during the welding process. The welding system generates heat into the part, the welding torch and the fixture which must be dissipated while in operation. A water chiller is part of this system to perform the function of cooling the components.

The process selected for welding the filler material to the bucket is the plasma arc welding process. A key to the process is the stable low currents which enables accurate weld placement and welding on thin knife edge surfaces. Key to the success of this welding process is the distance that the welding torch maintains from the weldment. An arc length controller utilizes the arc voltage and sensing devices to adaptively adjust the torch height and maintain a constant arc length for successful welding results. (*See Figure 14.*)

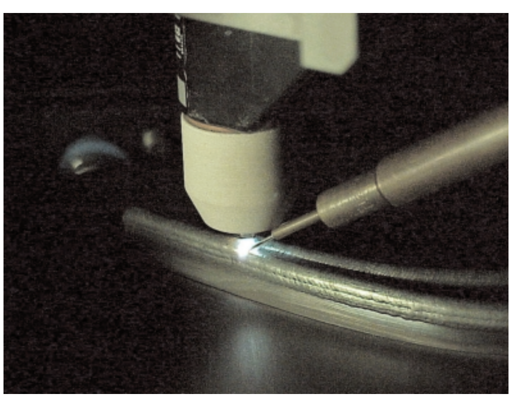

Figure 14. Close-up plasma torch

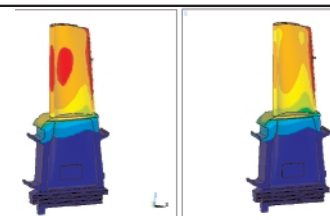

Figure 15. TBC effect on airfoil bulk metal surface temperatures

Post-weld heat treatment, Hot Isostatic Press (HIP), finish machining and grinding are easily accomplished while returning the bucket to its repair part dimensional requirements. The elevated temperature WRAP™ welding is also used for the restoration of rubbed tips and angel wing sealing surfaces.

Additionally, the elevated temperature WRAP™ process is used to generate cutter teeth on the integral labyrinth seal surface of shrouded buckets. This uprate is offered on new and serviced parts. The use of honeycomb material in stage two and three shrouds requires that the stage two and three buckets have “cutter teeth” on the bucket tip seals. Their purpose is to allow the buckets to cleanly cut into the honeycomb material when the rotor moves axially relative to the shrouds.

Restoration of integral shroud “Z” interlocks is accomplished via the fusion application of wear-resistant hard surfacing materials. In the case of GTD-111, the elevated temperature WRAP™ process is again employed. For “Z” interlocks originally employing plasma-sprayed chrome carbide, this original material can be reapplied or, at the customer’s option, upgraded to fusion-applied hard surfacing.

Bucket cooling effectiveness is a critical part of ensuring bucket life and integrity. Higher fired machines employ conduction and convection cooling as well as film cooling techniques to ensure that bucket temperatures do not exceed design limits. GE's I&RS Service Centers, during repair cycles, ensure that the cooling passages are not constricted or blocked. Applying an Advanced Thermal Barrier Coating to the external surfaces of the bucket airfoil can reduce the bulk metal temperature of the bucket. (*See Figure 15.*) Contact GE Energy Services for additional information about the correct coating for your particular application.

Rotors

During a common day, a base-loaded MS7001EA will ingest approximately 56 million pounds of air. The chemical composition of the air entering the compressor inlet in terms of humidity, trace gases and particulate determine the extent of corrosion, erosion and deposit which the air flow path surfaces exhibit. Deposits on the surface of the gas path components are carefully removed for initial inspections. The operating environment of the turbine rotor affects the maintenance needs and the inspection phase of the rotor overhaul cycle.

The full workscope of complete overhaul of a GE rotor can only be performed once the initial incoming inspection is accomplished. Once the compressor rotor is thoroughly cleaned, the assembly is visually inspected and characteristics such as wear, corrosion, macro-cracking, nicks and dents are fully documented. (*See Figure 16.*) GE has established criteria to which these inspection results are compared and decisions are made as to the workscope required to repair the assembly.

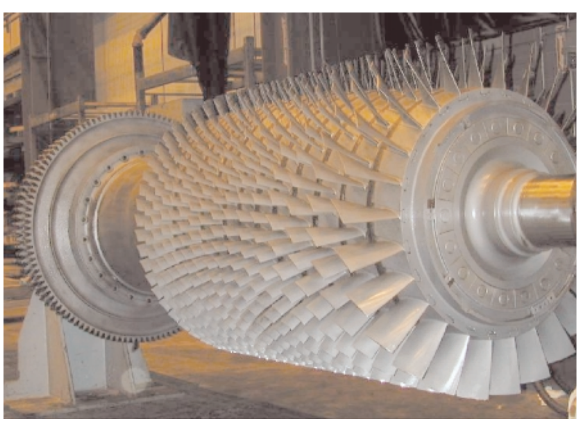

Figure 16. Compressor and turbine rotor assembled after cleaning

The functionality of the rotor is dependent upon the dynamic balance and vibration aspects that the rotor as an assembly exhibits. As part of GE's recommended rotor overhaul workscope during a rotor inspection, the total assembly is set up in a low-speed balance machine. A low-speed balance check of the rotor is made to determine any imbalance, its magnitude and location. Runout data is obtained on multiple diameters throughout the assembly to ensure the rotor concentricity and straightness. Each service center located throughout the globe has made the investments to provide similar capability in support of the growing fleet of gas turbines and the high standards that GE maintains.

In general, turbine rotors experience the same mechanisms of wear and degradation that compressor rotors face. Due to the extreme temperatures in the turbine, high temperature corrosion, creep and oxidation also contribute to component distress.

Some instances require that turbine and compressor wheels be given a rejuvenation of rabbet dimensions. These instances involve special processing such as High Velocity Oxy-Fuel (HVOF) sprayed deposits that have near-base material properties and can be precision machined. Specialized measurement tooling and procedures analyzed with Six Sigma methodologies have been implemented globally. They have demonstrated improvements to the assembly process and to the overall performance of the assembly long term.

At assembly, the GE gas turbine rotor construction practice is to individually balance rotor components, (e.g. stub shafts, blade and wheel assemblies, distance pieces, and turbine wheels and spacers). These components are assembled into major subassemblies using a computer stacking program to minimize any runouts of the assembly. GE has developed specialized tooling for FA class compressor rotor applications to improve the rotor straightness and minimize runout. (*See Figure 17.*)

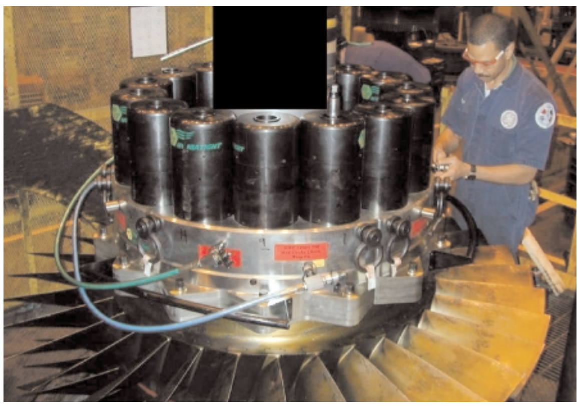

Figure 17. 7FA compressor with GE's multi-bolt tensioning device

GE recommends that each row of rotor blades and buckets be moment weighed and charted prior to installation to ensure the balance of the rotor. GE service centers are equipped to perform this type of work with highly accurate moment weighing and charting equipment. (*See Figure 18.*) The moment weight measurements are taken using a balance beam system to simulate the distance of the bucket from the rotational axis. The unit is computerized to record the measurements and run a program to select the bucket order (charting) that minimizes imbalance for that set of hardware. Records are kept so that in some cases if a bucket is damaged in service and needs to be exchanged, it can be done so with a bucket of similar weight without the need to re-weigh the entire set of buckets.

Figure 18. Bucket weighing and charting equipment

The major subassemblies, which consist of the compressor and turbine rotor assemblies, are then balanced in two balancing planes. With a single-shaft, two-bearing unit, such as MS5001, MS6001, MS7001F, or MS9001F, the mated compressor and turbine rotors are final-balanced by adding correction weights distributed in three or four planes according to axial rotor mass distribution.

GE global service centers have the factory-specified balance equipment and the skilled trained technicians to meet the design criteria outlined. Service center engineering personnel are linked to the GE Energy Services Product Service organization to support critical rotor issues as they arise during outages or on-site inspection processes. Further, in 1994, GE introduced transportable low-speed balance systems capable of performing the rotor inspection and balance operations at the customer's plant site. This has helped to reduce customer costs dramatically and determine rotor characteristics at the site very quickly.

Optimizing your rotor may involve upgrading with advanced components during the outage cycle. This effort has been shown to enhance the performance of your turbine dramatically. GE service centers are poised to help customers understand what it takes to get the most power from the turbines in place or to contact our web sites for existing information and programs. *Figure 19* shows a Frame 7B rotor that has been converted to a Frame 7E configuration using several new wheels and buckets.

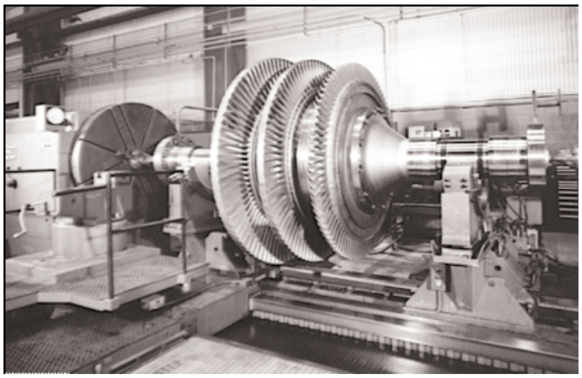

Figure 19. Upgraded turbine rotor

Figure 20. Non-destructive thickness survey for TBC on transition pieces

Combustion Hardware

In general, there are two primary failure modes associated with all combustion hardware. One is wear at the mating surfaces that connect the combustion components to each other and to the remainder of the turbine. The other is degradation of the Thermal Barrier Coating (TBC) system.

TBCs and their application will be thoroughly addressed in another section of this paper. However, in order to more closely monitor the degradation of the TBC system, global I&RS service centers have recently introduced non-destructive thickness surveys for combustion components as a part of their incoming inspections. This process allows the I&RS service center process engineers to better assess the ability of an existing coating to remain serviceable for another inspection interval without replacement. This process is shown in *Figure 20*.

A recent addition to GE's service offerings is refurbishment of 6FA combustion components. Tooling fixtures and methods for the repair of all 6FA combustion components have been developed. 6FA combustion liners are very similar to the 7 and 9FA DLN-2 designs. However, the transition pieces are quite different because the unit only has six combustion cans.

Combustor

A critical repair operation for louvered combustion liners is air-flow testing. Flow testing assures that each combustion liner in the set is flowing the same amount of air, thus minimizing temperature variances. (*See Figure 21.*)

When a liner is tested, it is placed on the flow check machine and a vacuum is drawn through the liner. The test machine calculates the effective air flow area. A determination is then made as to whether corrections are necessary.

Repair procedures for all types of Dry Low NO_X (DLN) components have been developed. On DLN-1, procedures have been established for the restoration of the liner body, venturi, and the cap. They may include repair or replacement of fuel nozzle collars and other minor piece parts.

DLN-2 liners require a repair operation that removes all body distortion by straightening and rounding the liner wall, returning the component to right cylinders. The process involves mechanical adjustment of the liner bodies with appropriate heat treatment procedures. Circumferential cracking around the aft end of the DLN-2 liner is also a common distress. These liners can be made more robust by the replacement of the aft section with a design that provides better cooling. TIL 1240 covers this modification in some detail.

DLN-2 cap assemblies are restored by both piece part replacement and/or repair, depending on the severity and type of wear. Impingement plates on the cap often crack and require weld repairs. The many tiny cooling holes in the cap are restored by Electrode Discharge Machining (EDM) after the weld repairs.

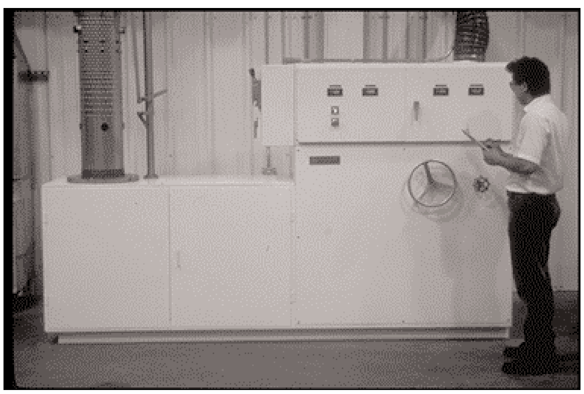

Figure 21. Combustion liner air flow test machine

Transition Pieces

Most turbine-run transition pieces (TPs) experience distortion around the picture frame due to time and temperature causing excessive gaps between the end seal slots between adjoining transition pieces. Uniquely designed inspection fixtures are employed to ensure the dimensional fits of the transition pieces against the mating surfaces of the turbine. A single-piece fixture is used for individual adjustments and a 360° fixture is used to fit-up a complete set, to simulate installation in a unit. Coordinate Measuring Machine (CMM) technology is being implemented in select service centers in order to minimize inspection times and improve accuracy.

Where needed, oversized end seals are used to assure proper seal engagement. The custom fit seals are sized during the final inspection in the 360° fixture which simulates installation in the machine. (*See Figure 22.*) This saves time and machining costs during installation in the turbine. However, turbine shell and first-stage nozzle "out-of-roundness" may alter the simulation fixture data obtained by the service center.

Figure 22. 360° transition piece fixture

When it is more expedient to replace the picture frame, another fixture is employed. Replacement picture frames are aligned in the fixture and welded in place. The replacement frames can be manufactured from original material, or in some instances a more creep- or wear-resistant material may be employed, depending on the nature of the distress encountered.

In FA model TPs, cracking is also common along the body sidewall. This cracking can be very severe, and requires repair using coupon inserts to replace damaged areas of the TP body with new material. GE has also developed a modification to the TP outer impingement sleeve that can be retrofitted to existing transition pieces. This modification will direct more cooling air to the body sidewall area, to minimize the cracking. The modification is shown below in *Figure 23*.

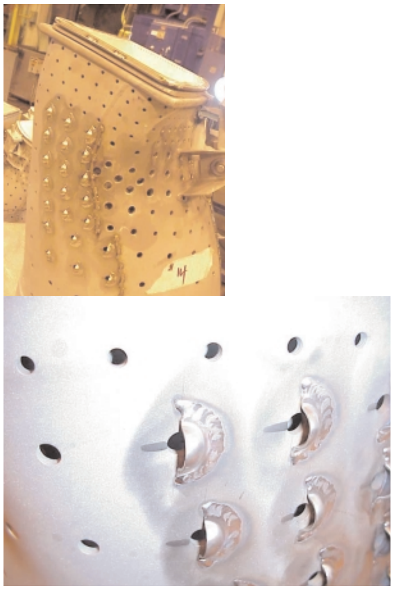

Figure 23. TP impingement sleeve "scoop"

Fuel Nozzles

The global service center network repairs all types of GE fuel nozzles, from single tip "gas only" to multi-port dual fuel DLN-2 units. The evolution of combustion systems from single-tip to multi-tip fuel nozzle systems has necessitated new repair processes to be implemented at the service centers. These repairs result in restored fuel nozzles meeting new part dimensions and flow differentials that meet or exceed new part specifications. GE's service centers maintain a broad inventory of consumable parts, such as c-seals, gaskets and lock plates, for all fuel nozzle types. This ensures the fastest turnaround time possible.

Flow testing of fuel nozzle tips and passageways is of critical importance, especially for multi-nozzle systems. It is vital that the same amount of fuel flows through each nozzle in a set. Equalized fuel flow minimizes temperature spreads as measured by the exhaust thermocouples and can-to-can pressure differences between the combustors. Computerized flow-test equipment is used to meter and measure flows. Air-flow testing (*Figure 24*) is used for gas and air passages and water-flow testing is used for liquid passages.

Figure 24. Fuel nozzle air flow test machine

The flow-test units use a computer-controlled system that calculates the percent variation of each to that of the set tips. Bodies or covers are tested and then matched to fuel tips to completely optimize the system. The final assembly is typically limited to a variance of less than 2% between assemblies. All accumulated fuel-flow data is saved for permanent records.

Often, GE can help the customer trouble-shoot any problems by doing an incoming flow test. Chemical analysis, performed by taking residue samples as the fuel nozzles are disassembled, further identifies any additional fuel related problems. After disassembly, the parts are cleaned using ultrasonic equipment or glass bead blast. Parts then go through a non-destructive testing (NDT) process where bodies and covers are pressure checked for leaks. Detailed reports of fuel nozzle performance are then generated for the customer's review.

Component Enhancement

Extendor™

GE has established a protective package, the Extendor Wear Kit, that addresses the most common areas of wear on liners, transition pieces and fuel nozzles (*See GEA 12276*). Kits are available for Frame 6B, 7E/EA and 9E combustion systems, whose units typically run in baseload applications. Wear points throughout the combustion system are modified, including transition piece "H" blocks and bullhorn brackets, floating and end seal slots, and liner interface. The liner modifications include the fuel nozzle and crossfire collars, liner stops and spring seal. Flow sleeves, fuel nozzles and some crossfire tubes are also modified. The major GE service centers have been qualified to make all of the wear enhancing modifications to the combustion components. Special fixtures are used to position the modification and replacement parts for optimal fit in the turbine.

Coatings

Compressor Corrosion Protection

Protective coatings used on heavy-duty gas turbine compressors are divided into two classes: barrier coatings and sacrificial coatings. Barrier coatings isolate the corrosive environment from the steel substrate, while the sacrificial coatings provide a reservoir of reactive metal in a galvanic couple. To avoid potential failure scenarios from single layer coatings, GE's preferred repair for corrosion protection utilizes both a non-conductive barrier coating over a sacrificial coating. The barrier coating prevents the sacrificial coating from continually reacting with the environment, while the sacrificial coating protects the base metal from attack in the event of barrier coating breach. If a breach occurs, the barrier coating limits the corrosion cell to the breach area.

The dual layer coating consists of a sprayed-on aluminum-based layer that is burnished to make it conductive, followed by a ceramic-based top layer that forms the barrier. (*See Figure 25.*) These coatings have been applied to individual blades and wheels or to fully bladed and stacked rotors.

Figure 25. Compressor airfoil coated with GECC-1

Turbine Corrosion/Oxidation

If a turbine bucket's external coating is breached or compromised, the bucket requires a repair coating to protect the nickel-base alloy from oxidation and corrosion attack. The metallurgical evaluation discussed previously determines the extent of distress and whether the bucket is repairable. A chemical stripping process is employed to remove all of the serviced coatings on repairable buckets.

Any welding, dimensional restoration and subsequent processing is performed on buckets in this stripped condition. GE reapplies its patented Extendcoat GT-29™ or Extendcoat GT-33™ chemistries using a proprietary thermal spray process. These coatings provide a surface reservoir of elements that form protective and adherent oxide layers, thus protecting the underlying base metal from oxidation and corrosion attack and degradation. The primary coating applications are listed in *Table 5*. By virtue of its higher aluminum and nickel contents relative to GT-29™, GT-33™ offers a significant improvement in high temperature oxidation resistance and improved ductility and crack propagation resistance. On the other hand, a reduction in chromium content results in some loss of hot corrosion resistance relative to GT-29™. Type II low temperature corrosion and Type I high temperature corrosion may occur when alkali metal salts condense on a part surface and destroy the normally protective oxide scale. Low temperature corrosion is only a concern where temperatures are below 1350°–1400°F, but it has a high rate of attack. Type 1 corrosion would only be a concern in the temperature range 1400°–1700°F where contaminants are present. Chromide pack coatings are effective barriers to Type II corrosion.

Coating Type	Composition	Oxidation Resistance	Type I Corrosion Resistance	Type II Corrosion Resistance
GT-29	CoCrAlY	Poor	Excellent	Poor
GT-33	CoNiCrAlY	Good	Good	Poor
GT-29IN-PLUS	CoCrAlY + internal and external aluminide	Very good	Execellent	Poor
Chromide Coating	Cr	Poor	Good	Very good

Table 5. Coating applications

Either of these repair coating systems can be applied with the addition of an over-aluminide. The combination of Extendcoat with over-aluminide is identified with a PLUS™ designation. Buckets with internal air cooling may require the over-aluminide be reapplied to the internal passages as well. The designation for buckets with internal and external aluminide coatings is IN-PLUS™. The aluminide is provided to enhance oxidation resistance.

Thermal Barrier Coatings

Thermal barrier coatings (TBCs) are reapplied to combustion components to provide an insulating layer that reduces the underlying base material temperature and mitigates the effects of hot streaking or uneven gas temperature distributions. TBC characteristics and advantages of TBCs are listed in *Table 6*.

Characteristics
- 15-25 mil Thickness
- Insulating-porous
- Plasma sprayed in air
- Two layers
  - bond coat - NiCrAlY
  - top coat - Yttria-stabilized Zirconia

Advantages
- Reduces metal temperature of cooled components
- 8-16°F Reduction per mil of coating

Table 6. TBC coating

GE emphasizes the importance of applying TBC robotically to ensure quality and repeatability not available with manually applied coatings. An operator, encumbered with the required protective gear, cannot come close to the accuracy and repeatability in terms of plasma gun distance and traverse speed to that of robotically applied coatings. *Figures 26 through 28* display robotic coating operations performed at one of GE's service centers.

GE's service center network has standardized its coating equipment and robotic capability with

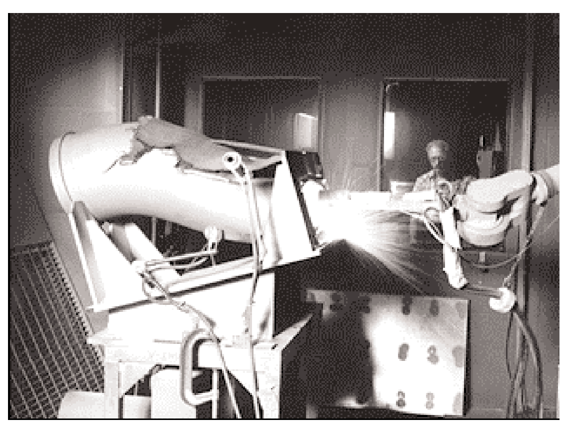

Figure 26. Robotic application of TBC on MS7001E transition piece

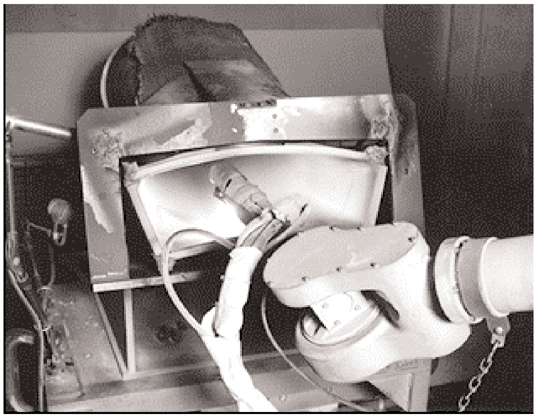

Figure 27. Robotic application of TBC on MS7001E transition piece

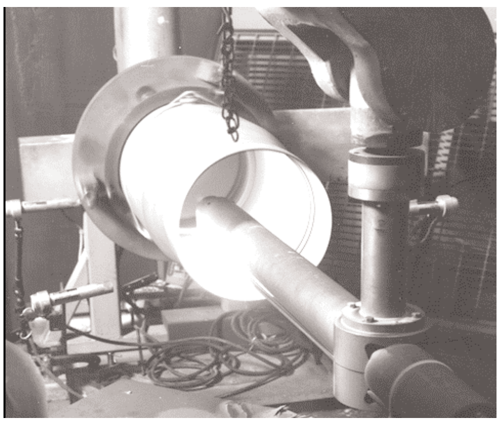

Figure 28. Robotic application of TBC on MS6001B combustion liner

that of GE's gas turbine manufacturing operation (GE Gas Turbine, LLC), which applies TBC to new OEM components. This standardization allows the use of the same qualified programs throughout the service center network, ensuring quality product every time. The significance in using OEM generated programs is that all hardware must be restored to OEM di-mensions or else the robotic arm would crash into the out-of-tolerance component. It also minimizes the global inventory of spare parts needed for the thermal spray equipment.

TBCs are divided into classes depending on the bond coat and top coat thickness. Class B TBCs (0.014"/0.3556 mm to +/-0.004"/0.1016 mm top coat) are the standard for pre-DLN series combustion liners. (*See Figure 29.*) Class C coatings (0.020"/0.508 mm to +/- 0.002"/0.0508 mm top coat) significantly improve the cooling effect on selected DLN liners.

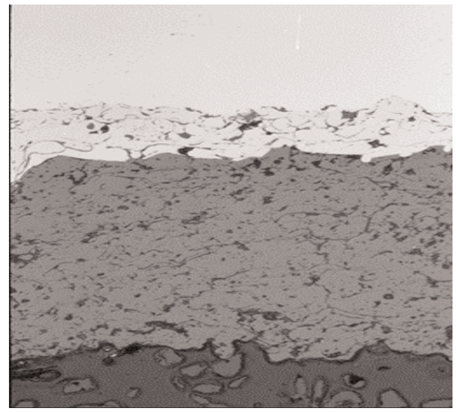

Figure 29. Photomicrograph of Class B TBC

Transition pieces may receive either coating (Class B or Class C). However, the differences between robotically-applied and manually-applied coatings are more pronounced on these components. The nature of the hot gas impingement on the transition piece wall cause greater thermal distortion than what typically occurs in combustion liners (e.g. axial flow).

Thickness uniformity is critical to transition piece coatings reaching their expected life. If thickness variations occur during manual spray applications, then chances are high that the coating will spall during thermal cycling. This is shown in *Figure 30 and Figure 31* by two transition pieces run in a rainbow test. *Figure 30* displays a transition piece with robotically-applied coating. The TBC coating is still intact after 8,000 hours. *Figure 31* illustrates a transition piece from the same unit, with a manually-applied coating. This transition piece has spalled coat-ing under the hanger bracket.

TBCs on nozzles have been proven to extend the life of nozzle segments, and are also offered as a repair or upgrade modification to stage 1 nozzles. *Figure 32* shows TBC applied to nozzle

Figure 30. Turbine run transition piece with robotically-applied TBC (8,000 hours)

Figure 31. Turbine run transition piece with manually-applied TBC (8,000 hours)

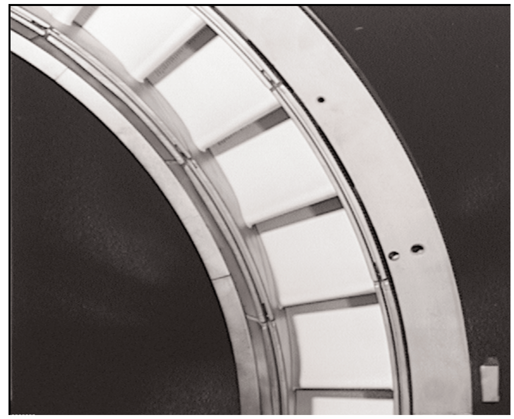

Figure 32. TBC applied to nozzle partition

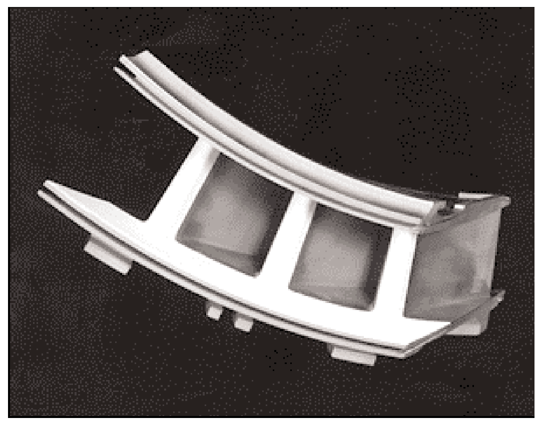

Figure 33. TBC applied to nozzle sidewall and leading edge

partitions, while *Figure 33* shows TBC applied to a nozzle sidewall and leading edge.

Recent advances in nozzle coating technology include a Class A TBC (MCrAlY bondcoat with an yttria-stabilized topcoat). Maintaining the critical dimensions of the throat area during the coating application is accomplished by controlled robotic application. This assures that the nozzle's airflow and harmonics are not compromised, as can happen with manually applied coatings. Special finishing operations also assure proper gas flow dynamics. When these material enhancements are combined with GE's robotic control process, a superior life extension product results.

Service Background

GE has developed an entire technology area for its gas turbine repair businesses. By coordinating the repair business (Global Inspection and Repair Services) with GE Gas Turbine, LLC, GE Power Systems has reduced repair technology development and implementation cycle times to the marketplace.

GE's gas turbine repair business is a global network of wholly-owned and joint venture facilities. *Figure 34* shows the facilities' global locations. Including service centers that work only on steam turbines and generators, there are more than 50 repair facilities around the world

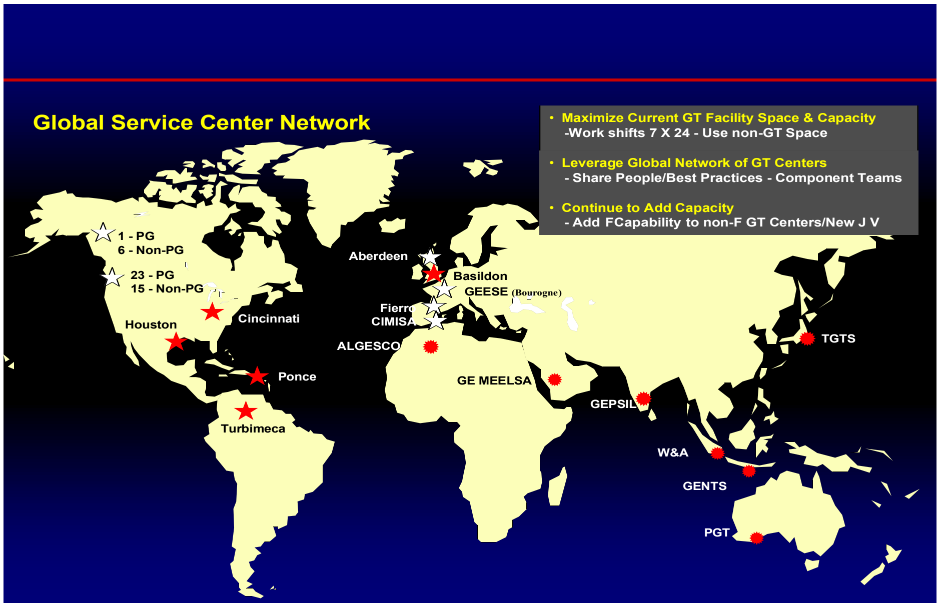

Figure 34. Global gas turbine service centers (www.gepower.com)

for the repair of GE-designed power generation equipment. To enhance the sharing of best practices among repair facilities, component teams have been formed for buckets, nozzles, rotors, combustion hardware, fuel nozzles, and coatings. These teams have members from each repair facility, as well as representatives from Energy Services and Power Generation Technology and commercial support organizations. The teams communicate on a regular basis to share information and work together on improvements in global repair procedures.

The global network of service centers is supported by Gas Turbine Design Engineering, Manufacturing Engineering, Reliability Engineering, Materials and Processes Engineering, New Products and Processes, as well as GE's Corporate Research and Development Center. In addition to the support given by the abovementioned organizations, the repair facilities are partnering with The Repair Development Center at the GE Aircraft Engines facility in Cincinnati, Ohio. The repair philosophy is simple: "restore all components to OEM specifications."

In order to better serve the customer and understand metallurgically intense processes, GE's Inspection and Repair Services business is investing to have fully operational metallurgical labs in the U.S., Europe, and Asia. These facilities will be used to support repair processes from a materials and serviceability viewpoint, as well as to provide the customers with information about the condition of their components prior to commencement of repair. (*See Appendix*).

The technology and processes generated in meeting this objective are shared with and transferred to GE repair facilities worldwide. Periodic audits and component team meetings ensure the sharing of best practices throughout the Global Service Center Network.

GE's Global I&RS also maintains a training center in Schenectady, NY for repair engineers, craftsmen and technicians. Employees from all gas turbine service centers gather to learn the latest repair techniques, as well as to share and exchange information. Students spend approximately 30% in the classroom and 70% on the shop floor perfecting the proper techniques. Courses cover the turbomachinery as well as fuel nozzle repair of the entire GE product line currently in service. Courses are added as new repairs are developed and new product lines are released into service. The ultimate goal of the training center is for GE gas turbines to be re-paired utilizing the best techniques and proce-dures, regardless of geographic location.

Summary

This paper describes some of the repair processes and technologies currently used by GE's Global Inspection and Repair Services operation. It also serves to verify GE's commitment to customer service and continued leadership in the development and implementation of "state-of-the-art" gas turbine repairs. The activities described in this paper are by no means complete. Major initiatives are continuously being initiated to assure that GE maintains its market leadership.

Appendix

Destructive Analysis: A Tool for Understanding Component Life

GE Meeting Industry's Demands

The GE network of metallurgy laboratories have a wide range of capabilities to deal with the many material issues faced during the repair of Hot Gas Path components. (*See Figure 35 and Figure 36.*)

The services that these laboratories provide have been developed to meet the exacting needs of the Power Generation and Oil & Gas industries. Each analysis is conducted to a consistently high standard by a dedicated team of experienced technicians and is supported by GE Materials Engineers.

Figure 35. Houston Service Center

Figure 36. Basildon Service Center

Material Issues

Gas turbine buckets are exposed to severe loading conditions, both in terms of temperature gradients and stress concentration. Any mechanism that influences the material microstructure likely varies bucket behavior and may adversely affect component life. It is therefore essential that the bucket coating/ base material system is characterized to assess the component set integrity.

Limitations of Non-Destructive Evaluation

Non-Destructive Evaluation (NDE) can provide information on the effect of service on component integrity. However, many life-limiting material characteristics cannot be assessed by such techniques. (*See Figure 37.*)

Destructive analysis is often the only reliable and accurate means to obtain details from critical features beneath the surface that restrict component performance. Destructive investigations therefore play a central role in assessing the component set integrity. (*See Figure 38.*)

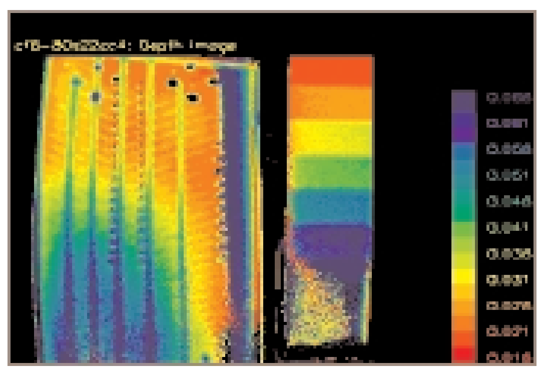

Figure 37. Infrared thickness measurement

The Need for Destructive Analysis

Destructive analyses obtain fundamental information to help determine the necessary repair workscope. Selecting the appropriate rejuvenation program optimizes component life extension and gas turbine efficiency. Furthermore, the information gathered during a destructive analysis can be studied together with the gas turbine running conditions to help identify the critical operating parameters. The customer is thereby able to understand component behavior so that future operating conditions can be optimized for enhanced machine performance. (*See Figures 39–42.*)

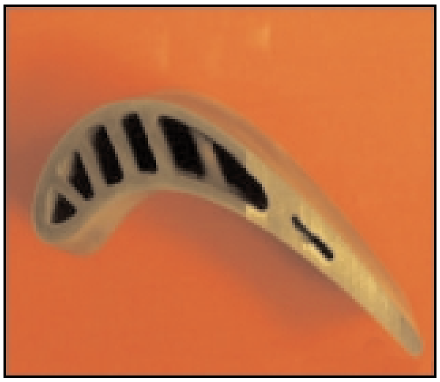

Figure 38. 9FA bucket section by EDM

Benefits of Destructive Analysis

- Establishes possible sources of contamination from chemical characterization of corrosion products.
- Determines the most effective repair workscope by characterizing the internal cooling hole microstructure, which often differs from the behavior of the external material.
- Correlates component service temperature from both gamma prime coarsening and diffusion zone growth.
- Prevents blending of sound base material by establishing crack location, frequency and penetration.
- Minimizes cost associated with non-value added work by identifying irreparable components early in the rejuvenation program.
- Helps determine the risk of component fallout prior to blending. Ordering the appropriate components early maximizes availability of replacement OEM parts for re-installation into the gas turbine.

Figure 39. Serviced 9E bucket

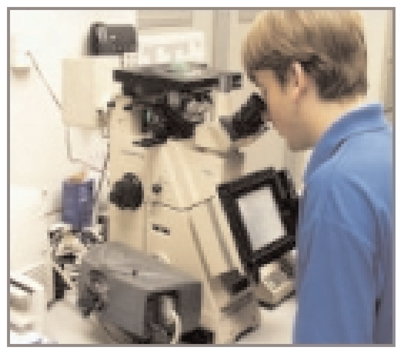

Figure 40. Microscopic examination

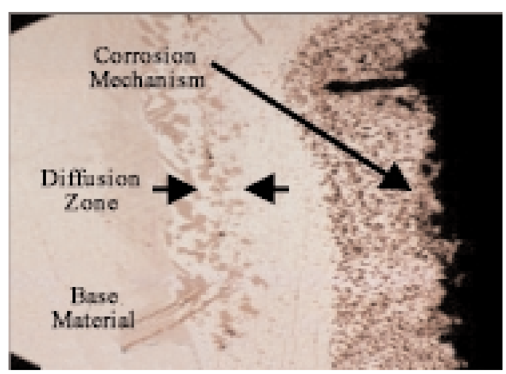

Figure 41. Characterizing bucket features

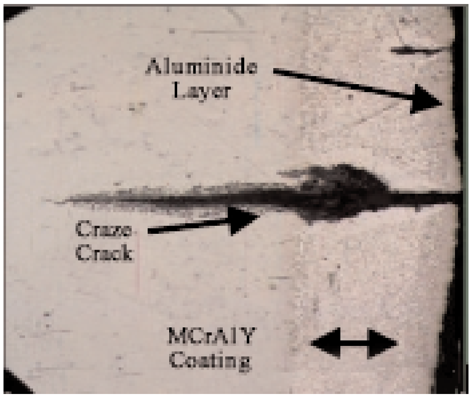

Figure 42. Determining crack penetration

Customer Satisfaction

Considering the value of destructive analysis, it is not surprising to learn the high level of satisfaction from customers who have requested this type of investigation.

Destructive analysis will play a critical role in future repair schemes and the facilities at the GE Service Centers will seamlessly evolve so that destructive analysis continues to satisfy customer expectations.

Find out more

To discuss your specific requirements in more detail or to receive additional information, please contact your nearest GE Service Center. You can find us online at www.gepower.com.

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