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GE Power Generation

Steam Turbine Sustained Efficiency

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ABSTRACT

GE steam turbines have traditionally been recognized for their superior sustained performance. This paper discusses the causes of steam path deterioration, and describes the features incorporated in GE steam turbine designs that minimize the effect of steam path deterioration on efficiency. These features include GE's "impulse" or "lower reaction" design philosophy, advanced design lower solidity nozzle partitions, advanced clearance controls, solid particle erosion and moisture erosion protection. Actual test data demonstrates the ability of these turbine features to sustain the efficiency of a steam turbine.

INTRODUCTION

Designing steam turbines that have the lowest life-cycle cost to their owners requires that the manufacturer considers reliability, availability, maintainability, efficiency and cost. This paper focuses on efficiency and how the efficiency changes over the life of the steam turbine.

There are three important considerations that determine the impact of steam turbine efficiency on the owner's operating costs. These are illustrated in Figure 1, which represents the performance of the unit over its life. The first point represents the initial level of performance. This point is important since it is usually the only one guaranteed by the manufacturer. However, more important to the total operating cost of the steam turbine are the second and third portions of the curve. The second describes the rate of performance deterioration that the steam turbine experiences between major overhauls. The third represents the ability of the steam turbine to economically recover from any deterioration in performance during a regularly scheduled maintenance overhaul.

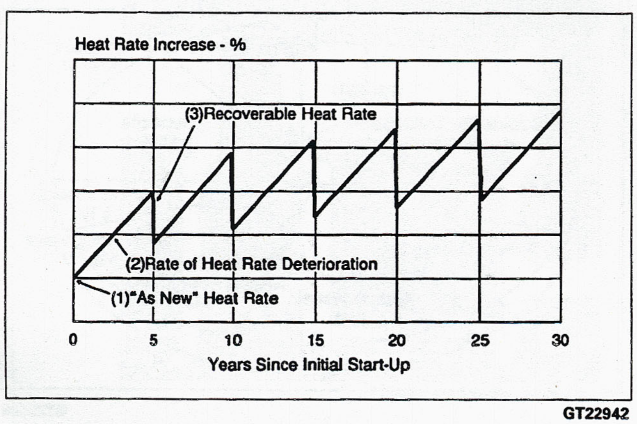

Figure 1. Steam turbine-generator heat rate change versus time

GE recognizes the importance of sustained efficiency to the turbine owner and incorporates features that result in superior sustained efficiency. These features range from the fundamental impulse wheel-and-diaphragm design to small details, such as centerline support of the diaphragms to achieve uniform thermal growth and, hence, tighter clearance control. The technical basis for these and other design features is discussed in this paper.

DESIGN PHILOSOPHY

The criteria that have to be considered to achieve the lowest life cycle costs interact in many complex ways and must be optimized to achieve an acceptable design. Historically, optimization of these parameters has resulted in two basic design philosophies: "impulse" wheel-and-diaphragm construction and "reaction" drum rotor construction.

The fundamental difference between these two design philosophies is the distribution of the pressure drop within a turbine stage.

The turbine stage consists of a set of stationary nozzle partitions and a set of rotating buckets or blades. The stationary nozzle partitions turn and accelerate the steam, converting its potential energy (pressure) into kinetic energy (velocity). The buckets convert the kinetic energy of the steam leaving the nozzles into both an impulse force (due to the change in direction of the steam) and a reaction force (due to the pressure drop across the rotating blades), causing the shaft to rotate and generate power. In the impulse design, the stage pressure drop is primarily taken across the stationary nozzle partitions, whereas in the reaction design the pressure drop is about equally divided between the stationary and rotating blades. When turbines of each of the two design philosophies are optimized for efficiency, the impulse design requires only about half the number of stages of the reaction design.

These basic differences lead to major differences in design and construction. The fewer stages in the impulse design allow for more space per stage and a more rugged construction. Universally, manufacturers of impulse steam turbines have adopted a wheel-and-diaphragm type construction (Figure 2). With the reaction design, the larger number of stages and the larger pressure drop across the rotating blades design prompts manufacturers universally to adopt a drum rotor type construction (Figure 3). The large pressure drop across the buckets causes a large thrust loading on the rotor. If the rotating blades of a reaction turbine were mounted on a separate wheel with a packing between the wheels, as with the impulse design, additional thrust would be developed proportional to the area of the wheel, making it impractical to control the magnitude of the thrust produced. A possible solution would be to design double-flowed units to balance the high thrust loads produced by the reaction design. Unfortunately, this solution has one major disadvantage: the volume flow to each stage would be cut in half, forcing unacceptable efficiency compromises resulting from increased leakage losses and aspect ratio losses. In general, turbine stages should only be double-flowed when other designs will not work.

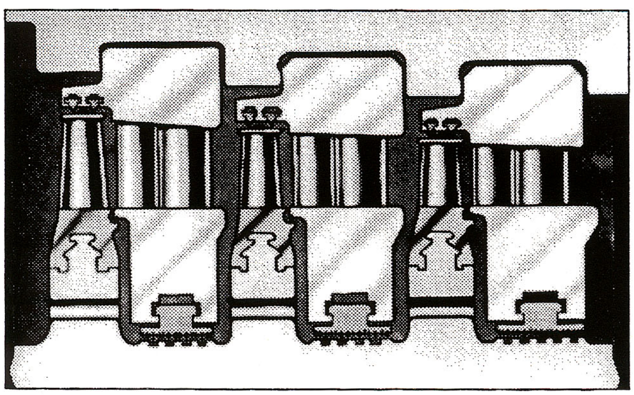

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Figure 2. Wheel-and-diaphragm construction used in impulse steam turbines

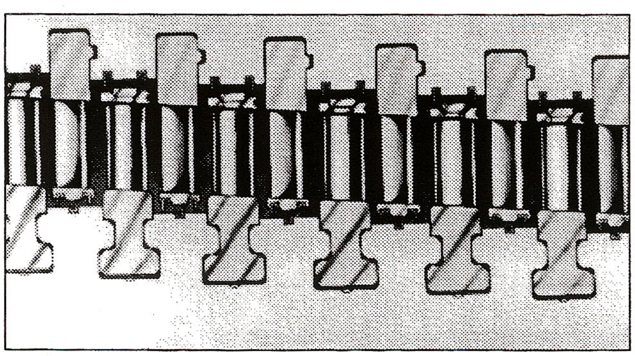

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Figure 3. Drum rotor construction used in reaction steam turbines

With the impulse design, the majority of the pressure drop is taken across the nozzle and very little across the bucket, so that thrust is not as much of a problem as with the reaction design. Theoretically, either type of construction could be selected. However, manufacturers of impulse turbines have universally adopted the wheel-and-diaphragm construction because of its more rugged nature and better leakage flow characteristics.

CAUSES OF PERFORMANCE DETERIORATION

As shown in Figure 1, turbine performance deteriorates with time. The rate of deterioration is a function of the design of the turbine, the quality of the steam environment that the turbine experiences, the way the unit is operated, and the ease at which the efficiency can be restored during regular maintenance outages.

There are five main causes steam turbine performance deterioration: (1) leakage control damage; (2) solid particle erosion (SPE); (3) moisture erosion; (4) steam path deposits; and (5) foreign object damage.

Steam path efficiency audits conducted by trained personnel during maintenance outages can identify the sources of efficiency loss within a turbine. Figure 4 shows the breakdown of these losses for a typical large fossil steam turbine. 40% of the total identified efficiency loss is due to clearance control damage, 15% due to solid particle erosion damage, 15% due to steam path deposits, and the remaining 30% resulting from the general aging of the steam path caused by increase surface roughness and geometry changes of the nozzles and buckets.

This paper describes the design features incorporated in GE's advanced steam turbine designs

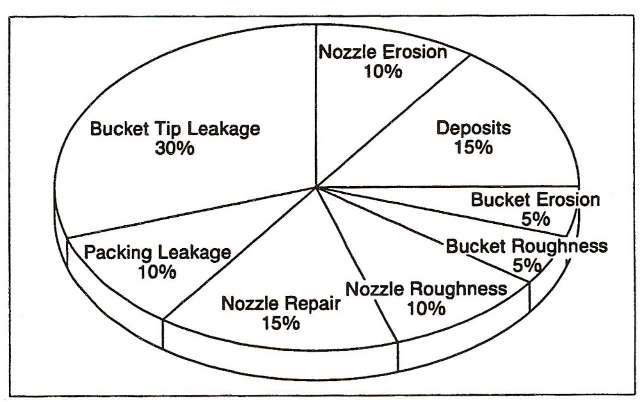

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Figure 4. Typical breakdown of causes of steam turbine efficiency deterioration

to minimize impact to the turbine steam path of these sources of efficiency deterioration,. The application of many of the features described in this paper has resulted in the rate of efficiency deterioration being reduced by approximately half of what it has traditionaaly been.

DESIGN FEATURES TO MINIMIZE LEAKAGE LOSSES

An important factor that influences steam turbine efficiency deterioration is increased leakage losses within and around the turbine stage. For steam to generate power in a turbine stage it has to pass through both the nozzles and the buckets. Any flow that bypasses either nozzles or buckets produces an efficiency loss. The leakage paths that result in an efficiency loss are shown in Figure 5. Rubbing of rotating and stationary parts will result in increased clearance and, hence, increased steam leakage. Rubbing the diaphragm packings and the radial tip spill strips can be caused by high vibration of the rotor, thermal distortion of the stationary parts, bearing failure, water induction, etc.

Design Philosophy

The sensitivity of a particular design to the impact of increased clearances will significantly impact the rate at which the steam turbine performance deteriorates. A comparison of the two design philosophies, the impulse wheel-and-diaphragm and the reaction drum rotor construction, is useful in considering diaphragm packing or stationary blade leakage and bucket or rotating blade tip leakage losses.

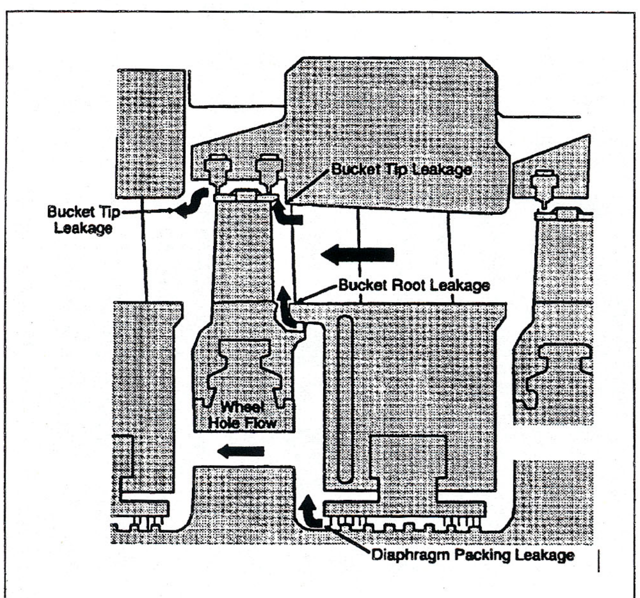

Figure 5. Impulse wheel-and-diaphragm construction

In addition to the type of construction, another important physical difference between impulse and reaction designs is the number of stages and the pitch diameter of those stages. One of the fundamental design parameters of a turbine stage is the isentropic velocity ratio, normally expressed as W/Vo, where W is the tangential velocity of the moving bucket (often known as wheel speed) and Vo is the isentropic velocity equivalent to the pressure drop across the stage (proportional to the square root of the stage available enthalpy drop). It can be shown, on a theoretical basis (Reference 1), that for a pure impulse design, the optimum nozzle-bucket efficiency occurs at a velocity ratio (W/Vo) of 0.5, while for a 50% reaction design it occurs at a velocity ratio (W/Vo) of 0.707. Therefore, for stages operating at the same diameter and stage pressure drop, the peak efficiency for a reaction stage would occur at a wheel speed considerably higher than for an impulse stage. Since steam turbine-generators operate at constant speed, the W/Vo for the optimum efficiency can only be obtained by: increasing the stage diameter to increase wheel speed, while maintaining the same number of stages; increasing the number of stages to decrease the pressure drop per stage and hence the Vo, while maintaining stage diameters; or some combination of these two.

Detailed calculations given in an earlier revision of this paper (GER 3750B) show that GE's impulse wheel and diaphragm design is less sensitive than a reaction drum rotor design to the increase radial clearance at both the bucket tip spill strips and the shaft packing.

Figure 6 details the results of these calculations, showing the impact on stage efficiency of both GE's impulse design and a reaction design to increased radial clearance over the bucket tip. The impact on stage efficiency due to the increased pressure drop across the bucket tip of a reaction stage, can clearly be seen from its greater level of stage efficiency loss for a given clearance. This makes it more sensitive to increased radial clearance than GE's impulse design.

Figure 7 shows the impact on stage efficiency of GE's impulse design and a reaction design to increase radial clearance at the shaft packing. The advantage of the smaller shaft packing diameter and the large number of sealing teeth of the impulse wheel and diaphragm construction, outweighs the impact of the greater pressure across the stationary nozzles of the impulse design, resulting in the impulse wheel and diaphragm design being less sensitive to increased radial shaft packing clearance than an equivalent reaction design.

GE's impulse stage design philosophy, with it's

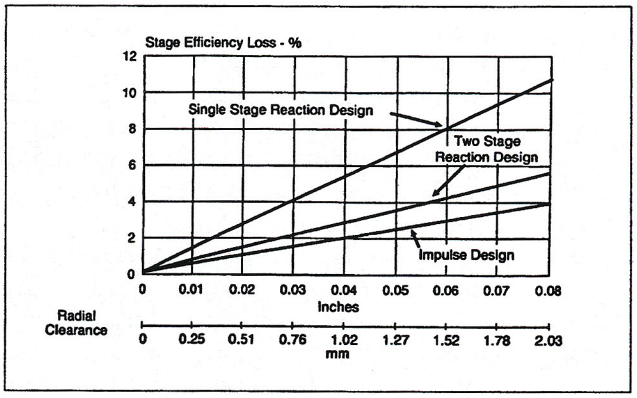

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Figure 6. Stage efficiency loss due to increased bucket tip clearance

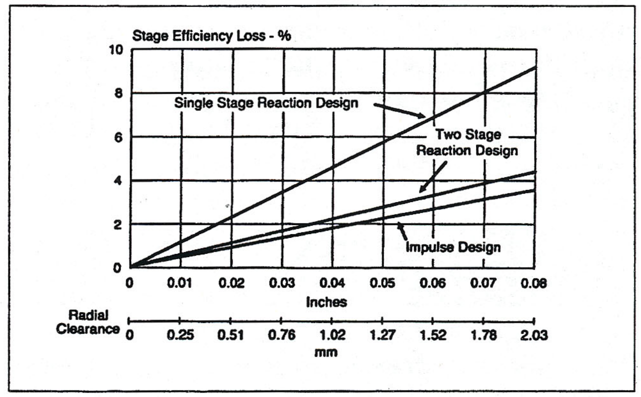

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Figure 7. Stage efficiency loss due to increased diaphragm packing clearance

wheel and diaphragm construction, is less sensitive to increased radial clearance at both the bucket tip clearance controls and the shaft packings, than an equivalent reaction stage. Therefore, for the same increase in radial clearance, a stage designed with the impulse wheel and diaphragm design philosophy will deteriorate in performance at a slower rate than an equivalent stage designed with reaction design philosophy.

Wheel-and-Diaphragm Construction

High-pressure sections on large steam turbines utilize an inner shell to contain the high pressure regions of the turbine (Figure 8). This HP inner shell is subject to high steam conditions and is likely to distort unevenly, especially when a heavy bolted horizontal joint is used to join the two halves. This distortion is not a major problem for impulse turbines with their wheel-and-diaphragm construction. The clearance controls are located in the diaphragms, which remain relatively undistorted (Figure 2). However, this inner shell distortion has been a historic problem for reaction turbines where tip seals and seals between the rotor and the blade carrier are supported by the inner casing (Figure 3). Any distortion of the inner casing causes a loss of alignment between the rotating and the stationary parts, resulting in clearance control damage and excess leakage loss.

To overcome this inherent disadvantage of the reaction design, intricate and inconvenient means of joining the inner casing halves have been used. One manufacturer uses an un-split outer shell, or barrel construction, that is exposed to almost full steam pressure to minimize the inner shell distortion. Another manufacturer shrinks a series of rings over the inner casing, imposing a net inward radial force, obviating the need for a heavy horizontal joint flange. Both of these solutions seriously reduce the maintainability of reaction turbines compared to impulse turbines.

Centerline Support

As the turbine is started and loaded, the temperatures of various turbine components change considerably, causing radial differential expansion. If no special provisions are made, the rotor will move relative to the stationary components so that it is positioned eccentrically. This eccentricity would lead to a significant loss in efficiency, since extremely large sealing tooth clearance would have to be established to allow for the misalignment between nozzles and buckets.

GE utilizes various designs to ensure that all stationary and rotating components remain concentric as temperatures vary. Typical support details for diaphragms and inner shells are shown in Figure 8. The weight of the high-pressure (HP) intermediate-pressure (IP) shells is carried on arms that extend from the flange at the horizontal joint.

For high-temperature shells, the shell arm is carried from the upper half shell for true centerline support. For intermediate-temperature shells,

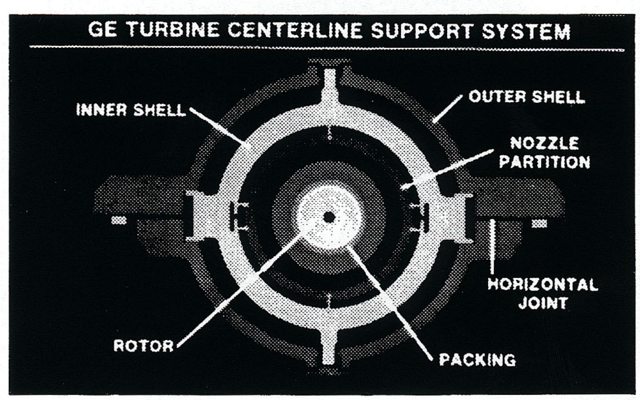

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Figure 8. Method of support of stationary components for precision alignment

the shell arm is carried from the lower half shell, providing approximate centerline support. This simplifies maintenance for cases where true centerline support is not required, since temporary blockage of the lower half shell is not required when the upper half shell is unbolted and lifted. Very low-temperature components, for example, exhaust hoods, need not be centerline supported because their low temperatures minimize the potential for differential expansion.

Spring-backed Shaft Packings

GE's wheel-and-diaphragm construction allows sufficient room in the inner web of the diaphragm to mount spring-backed packings that have room for radial movement. During a rub, the packings are free to move away from the rotor, minimizing the effects of the rub. These moveable, spring-backed packings can be easily replaced when they become worn.

Positive-pressure, Variable-clearance Packing

Labyrinth seal packings, close to the mid-span of a high-temperature steam turbine rotor, are susceptible to rubbing. Operation below the first critical, acceleration through criticals, and boiler temperature variations all occur at startup, making the packing most vulnerable during this period. Excess clearance caused by rubbing during the startup of the unit results in increased fuel costs and a reduction in unit capacity. In addition, vibration problems associated with packing rubs can prevent the turbine from getting through its critical speeds, prolonging the startup of the unit. Positive-pressure, variable-clearance packing provides a large clearance during startup and reduces clearance after the unit has synchronized. This arrangement minimizes rubs associated with turbine startups while providing optimum sealing when the unit is loaded.

Positive-pressure, variable-clearance packing utilizes a combination of the pressure drop across the packing and an additional pressure force, when required, to close the packing rings after synchronization. A more detailed description of the positive-pressure, variable-clearance packing is given in Reference 2.

Even if a diaphragm becomes elliptical with time due to high-temperature creep, the movements of the positive pressure packing can be adjusted so that the segments close concentrically with the shaft to produce uniform radial clearance and minimum leakage losses.

Wheel Holes

The impulse wheel-and-diaphragm construction allows for the use of bucket root radial clearance controls and wheel holes (Figure 4). The wheel holes minimize any flow into and out of the wheelspace. Any reentry flow disturbs the main steam path flow, causing an additional efficiency loss. This additional root intrusion loss is almost equivalent to the loss associated with the diaphragm packing leakage itself.

On impulse turbines having wheel holes, or bucket dovetail holes, the majority of any increased shaft packing leakage flow caused by a rub passes through the wheel holes, minimizing root intrusion losses. Reaction turbines do not have any means of diverting the shaft packing leakage flow, so any increase in shaft packing leakage will result in a proportional increase in root intrusion loss, increasing the sensitivity of the reaction design to increase clearance.

Improved Tip Leakage Controls

Traditional bucket tip leakage controls have either a single radial tip spill strip or two spill strips, one on either side of the bucket cover tenon. To investigate improved tip leakage controls, GE conducted a series of tests with different sealing configurations. The results of these tests (Figure 9) show a significant benefit when a stepped or high-low spill strip is used to minimize bucket tip leakage. Stepped-tooth radial tip spill strips are now used on the HP stages of all large utility units that have adequate axial space.

The application of improved radial tip leakage controls, such as stepped-tooth and high-low radial tip spill strips, will also result in improved sustained efficiency. Any damage to an improved radial tip due to a rub will result in less leakage than an equivalent rub on a single radial tip spill strip.

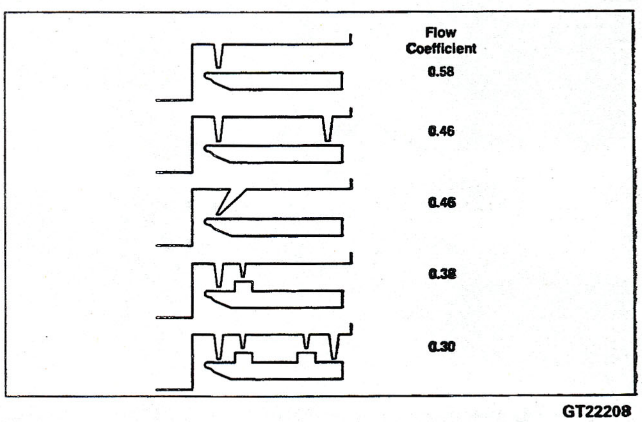

Figure 9. Results of tip sealing geometry tests

SOLID PARTICLE EROSION DAMAGE

The inlet stages of most steam turbines operating with fired boilers and steam temperatures of 1000F/538C or greater experience SPE damage to some degree. The traditional way of restoring the damage caused by the SPE to nozzle partitions has been to cut back, weld up and re-contour the partitions. This repair is time consuming and typically on the critical path of a turbine outage. Because of the economic impact that SPE has on the utility industry, GE started a development effort in the 1980s to identify design changes to their steam turbines that would minimize SPE damage and, hence, the efficiency loss associated with it. GE has succeeded in designing turbine stages that are significantly more erosion–resistant than the earlier designs through a four-pronged development effort: the inspection of eroded steam path components; the analysis of particle trajectories; the development of erosion resistant coatings and the implementation of design changes.

Control Stages

Trajectory analysis, confirmed by field experience, demonstrated that control stage nozzle erosion resulted from the solid particles coming from the boiler impacting the pressure or concave surface at a high velocity and a shallow angle near the trailing edge. Laboratory test erosion data had already demonstrated this condition to be very erosive. Since the trailing edge region of the nozzle partition is relatively thin, it can erode away rapidly.

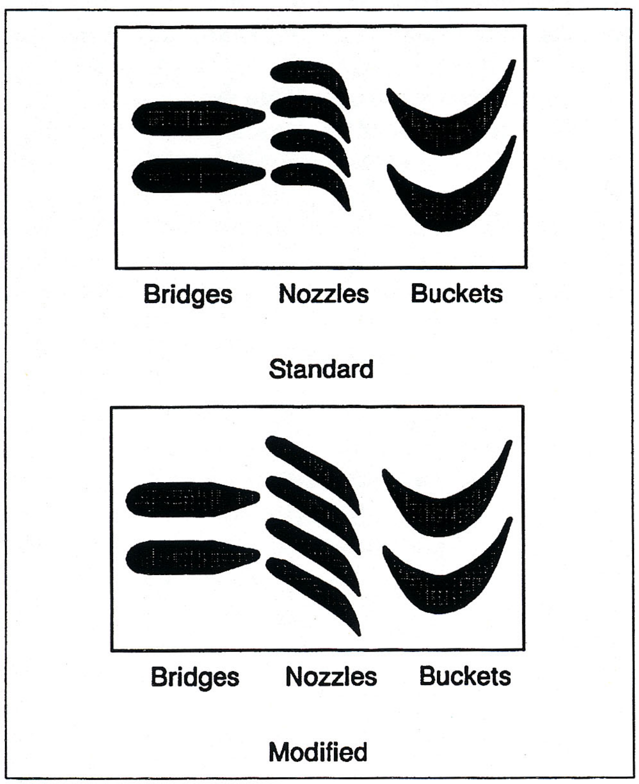

Figure 10. First stage – high-pressure turbine

Understanding the SPE mechanism at the control stage nozzle partition was essential in redesigning the nozzle partitions to achieve the goal of changing the velocity and impact location of the particles. Figure 10 shows a comparison of the present nozzle partition with the modified nozzle partition that was developed to minimize SPE damage. With the modified design, the majority of the particles now impact the nozzle partitions before the trailing edge and at a lower velocity. Fewer particles impact the trailing edge region, and those that do, impact it at a shallower angle. The nozzle partition is further protected by an erosion-resistant diffusion coating of iron boride. The combination of the modified profile and the diffusion coating is expected to nearly triple the life of the nozzle partitions.

Reaction steam turbines that are designed for partial-arc admission utilize an impulse first stage, and experience SPE damage similar to the control stage of impulse turbines.

In 1987, modified diffusion-coated nozzle partition were retrofited on the control stages of two 650 MW supercritical, double-reheat units. Prior to the modification, the HP section efficiencies deteriorated at an average rate of about 0.2% per month. This deterioration caused the utility to open the unit every two years to repair severe SPE damage to the control stage. Since the application of the modified, diffusion-coated control stage, the rate of HP section efficiency loss has been reduced to 0.08% per month. Since no other changes were made in the HP steam path to minimize SPE damage, the change in the rate of deterioration was directly attributed to the new SPE-resistant control stage. After two years operation, the utility has demonstrated a 0.4% heat rate improvement directly attributed to the installation of the modified SPE-resistant control stage. Because of the excellent performance of these new control stages, the utility has extended the time between scheduled maintenance outages.

Figure 11 shows the heat rate loss associated with severe damage to the control stage, together with the expected benefit for the modified, diffusion-coated control stage. A significant improvement in sustained efficiency is evident.

First Reheat Stages

Trajectory analysis, confirmed by field experience, demonstrated that first reheat stage nozzle

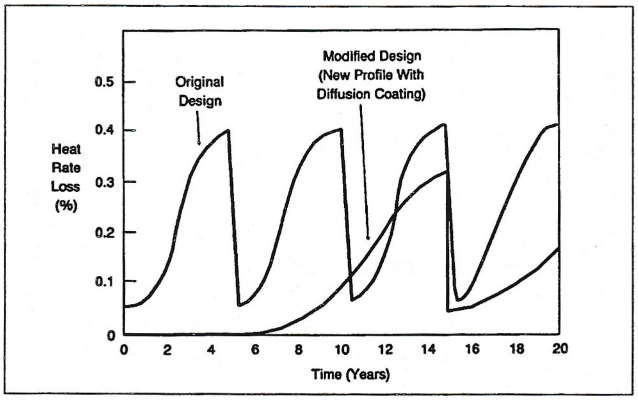

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Figure 11. Control stage heat rate loss due to severe SPE damage

partition erosion resulted from the rebounding of the solid particles back toward the nozzle partitions. The particles then impact the suction, or convex surface, of the nozzle partitions at a high velocity and a shallow angle. This creates a very erosive condition.

Trajectory analysis indicated that by increasing the spacing between the nozzles and the buckets, the drag on the rebounding particles is great enough to turn most of the small particles back toward the bucket, greatly reducing the number of particles that cause damage to the suction side surface of the nozzle partition. The results of the trajectory analyses and the influence of increasing the axial spacing between the nozzle and the bucket are shown in Figure 12. To further protect the suction side surface of the nozzle partition, an erosion-resistant chromium carbide coating is applied. A more detailed description of the first reheat stage design to minimize SPE damage is given in Reference 3.

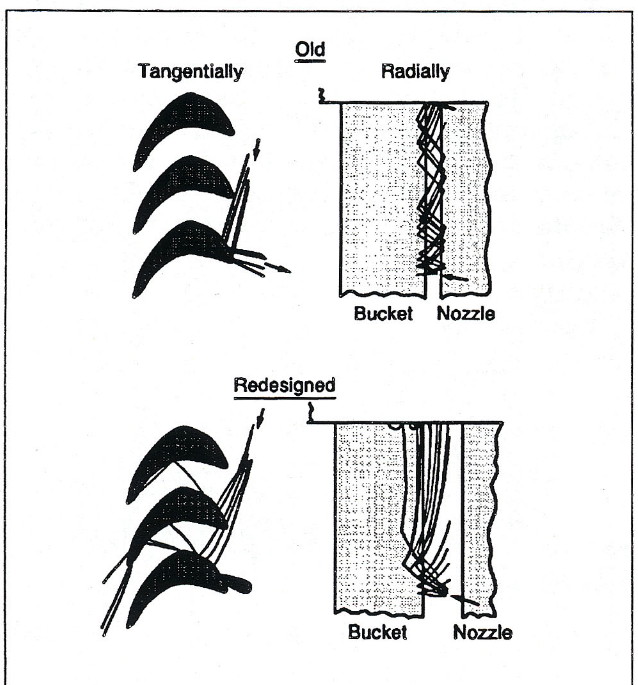

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Figure 12. Reheat particle trajectories

Increasing the axial spacing between the nozzles and the buckets to minimize SPE damage can be applied to other stages in the IP section, if required.

Trajectory analysis of a reaction turbine stage indicates that the first reheat stage would suffer the same rebounding erosion phenomenon as an impulse design stage. This is confirmed by Figure 13, which shows severe first reheat stage erosion on a reaction turbine. The magnitude of the erosion can be judged by comparing the first reheat stationary blades with the second row of stationary blades. With the wheel-and-diaphragm construction, the diaphragm nozzle partitions can be repaired relatively easily by welding and recontouring. With the reaction design, the stationary blades, located in a multi-stage blade ring, are inaccessible and cannot be weld-repaired. To restore the performance of a reaction turbine, the stationary blades have to be replaced.

In 1987, a new plasma spray-coated first reheat stage double flow diaphragm with nozzle partition setback was installed on a 500 MW supercritical single reheat unit. This unit had a history of severe SPE damage. This unit was inspected in the spring of 1990. The customer commented that, "It looks just like new."

A number of other modified first reheat stage diaphragms have been inspected after several years of operation, and have demonstrated significantly improved SPE resistance. One such inspection was reported in Reference 4. An initial inspection of the erosion-resistant diaphragms revealed minor erosion on the nozzle trailing edge at the outer sidewall. This condition has been attributed to the inability of the particles that collected on the outer sidewall to escape. To prevent this, a modification was made that relieved the outer sidewall and allowed the parti-

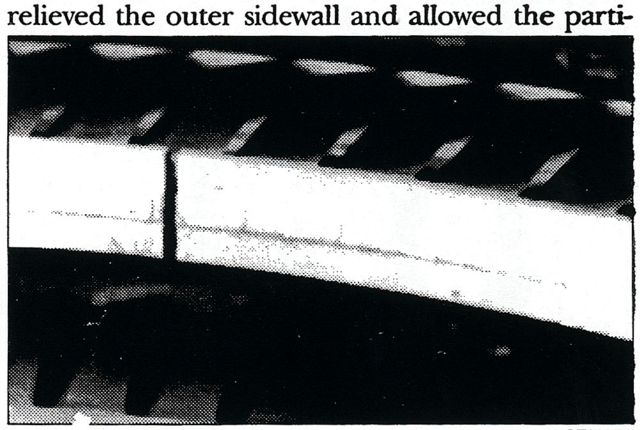

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Figure 13. Erosion in first reheat stage of a reaction turbine

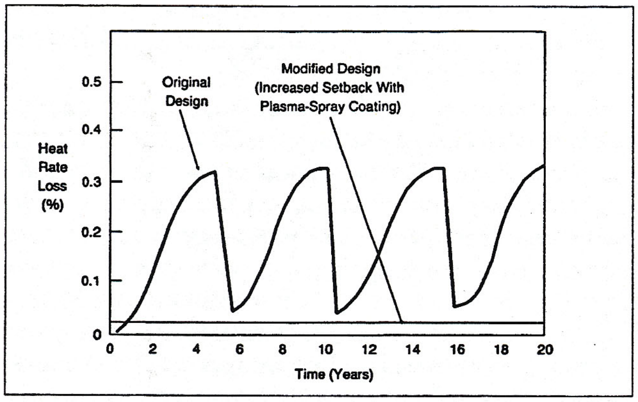

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Figure 14. First reheat stage heat rate loss due to severe SPE damage

cles to collect but not impact the trailing edge of the partitions.

Figure 14 shows the heat rate loss associated with severe SPE damage to the first reheat stage. Also shown on Figure 14 is the expected performance of the modified design with increased setback and erosion resistant coating. A significant improvement in sustained efficiency is evident.

High-pressure Section Diaphragms

Field observation of HP diaphragms on units with severe SPE indicates that diaphragms having high-low nozzle partition construction and a large number of nozzle partitions (Figure 15) are most susceptible. The high partition acts as a dam to the solid particles from the previous stage, channeling them through the nozzle passage adjacent to the high partition and eroding them at a greater rate than the other partitions. Also, diaphragms with a large number of small nozzle partitions erode at a greater rate than those with fewer large nozzle partitions.

Using these field observations, HP diaphragms that experienced solid particle erosion damage can be designed to eliminate the high-low nozzle partition construction and incorporate fewer larger nozzle partitions to improve sustained efficiency.

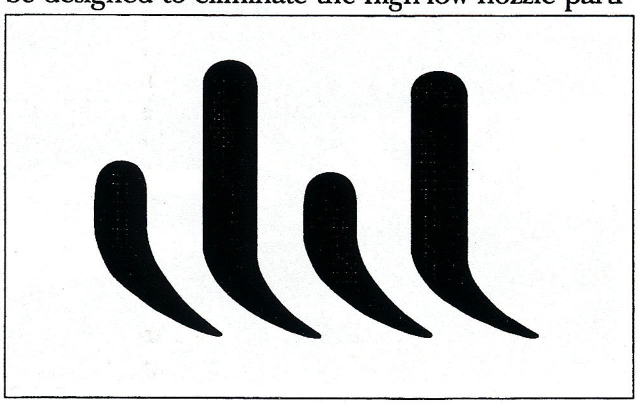

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Figure 15. High-low nozzle partition construction

Bucket Tip Leakage Controls

Erosion of bucket tip clearance controls can significantly impact the sustained efficiency of a turbine. Where possible, GE designs the turbine steam path with replaceable radial tip spill strips to allow for easy replacement during regular maintenance outages.

For many years, radial spill strips applied at steam temperatures below 750F/399C have been made of a bronze material having excellent rubbing characteristics. Unfortunately, this bronze material is relatively soft and can be eroded away rapidly by the solid particles coming over from the boiler.

A more erosion-resistant radial tip spill strip material is now used throughout the HP and IP sections where SPE may potentially be a problem.

On reaction turbines, the tip clearance controls are often caulked into the blade ring. Replacement requires significant machining and installation effort, resulting in an extended outage or, in many cases, the reaction units are returned to service with damaged clearance controls.

MOISTURE EROSION

Moisture erosion in steam turbines is caused by droplets that form in steam as it crosses the saturation line. On fossil reheat steam turbines, moisture erosion is generally limited to the tip section of the long last-stage buckets. However, on nonreheat fossil units, all the LP section is in the wet region. On nuclear units, moisture can be present throughout the turbine steam path. There are two main sources of efficiency loss due to moisture erosion: the erosion of the bucket leading edges and the erosion/corrosion of the stationary components.

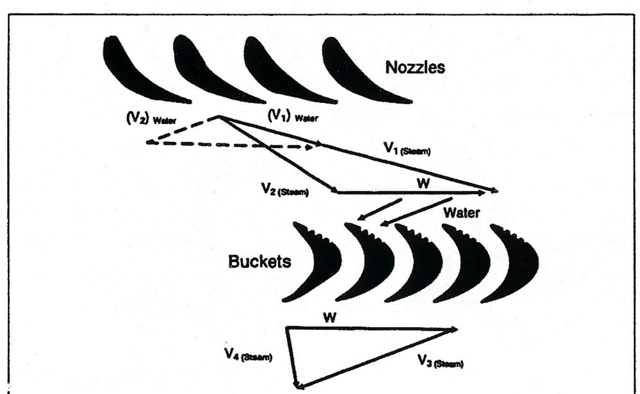

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Figure 16. Typical velocity diagram for steam-water mixture

Moisture erosion of the tip region of last stage buckets is caused by the high tangential velocity of the buckets as they run into the large, slow-moving droplets formed and blown off the stationary blading and the nozzle side walls. The roughening of the bucket leading edge results in increased friction and aerodynamic losses. To minimize this effect, GE provides a method of erosion protection. On older last-stage bucket designs, either satellite shields were used, or the buckets' leading edges were flame hardened. For newer last stage buckets, GE has developed a self-shielded design that utilizes a strong hard steel with an erosion resistance comparable to satellite.

On nonreheat fossil and nuclear turbine designs, GE utilizes internal moisture removal stages to minimize the amount of water that reaches the last stage. Special grooved "moisture removal" buckets are used. This feature operates on the basis that a substantial portion of the water passing through the turbine collects on the nozzle partitions and, because of adhesion, tends to leave the nozzles' trailing edges in the form of large drops at relatively low velocity. Thus, the water droplets impact the convex side of the buckets and are caught in the moisture removal grooves, (see velocity triangle, Figure 16). The rotating buckets act as a centrifugal pump and throw the water into the moisture removal pockets in the adjacent stationary parts (Figure 17). From there, it is drained to a feedwater heater or the condenser.

The second source of efficiency deterioration caused by the presence of moisture is an erosion/corrosion phenomenon that occurs on the stationary parts that are made of carbon steel. These include the latter LP diaphragm sidewalls and LP inner casings. This phenomenon roughens up the surface, increasing friction losses and leakage around steam path components. This phenomenon is a function of the alloy content of the material. Steam path components that were previously susceptible to this erosion/corrosion attack are now manufactured with higher alloy content steels to significantly reduce the damage and improve the sustained efficiency.

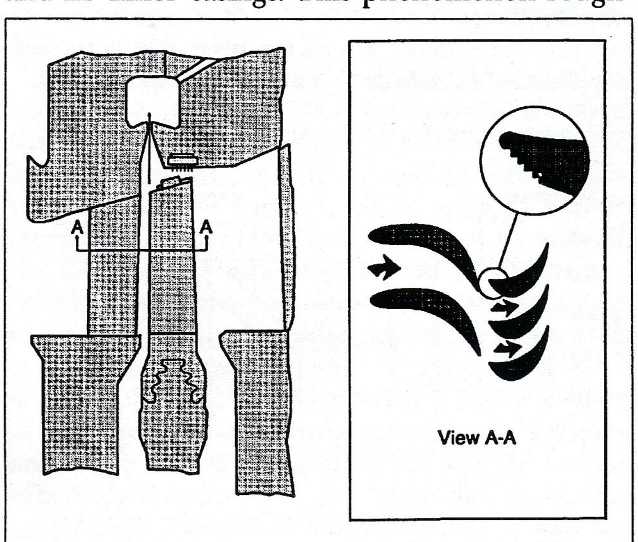

Figure 17. Internal moisture removal provisions

STEAM PATH DEPOSITS

A major source of efficiency and capacity loss in large reheat fossil and reheat steam turbines is chemical deposition in the turbine steam path, caused by boiler carryover or excessive use of main stream and reheat attemperation. Poor feedwater chemistry control is the major source of the deposits found in the steam turbine.

The impact of steam path deposits on turbine efficiency depends upon their thickness, their location on the nozzles and buckets, their location within the turbine, and the resulting surface condition. Major steam path deposits can change the basic profile shape of the nozzles and the buckets resulting in efficiency loss associated with changing the energy distribution within the turbine, poorer aerodynamic profiles, and increased friction losses due to rougher surface condition.

Another major effect of steam path deposits, when they occur in the HP section of a steam turbine, is to reduce the maximum output of the turbine. This results from the steam path deposits reducing the nozzle and bucket throat areas. A 0.01" deposit thickness in the nozzle throats of the HP stages of a typical large steam turbine would reduce the maximum capacity of the turbine by about 2 to 3%.

As a result of GE's development programs to improve the overall efficiency of GE steam turbines, the trend has been to apply lower solidity high efficiency nozzle partitions. This has not only improved the initial performance of GE's steam turbines, but it has also resulted in them being less sensitive the steam path deposits. It is estimated that a 0.01" deposit thickness in the nozzle throats of the HP stages of GE's modern high efficiency steam turbine would reduce the maximum capacity of the turbine by about 1 to 1.5%, rather than the 2 to 3% of a more traditional design.

FOREIGN OBJECT DAMAGE

Foreign object damage to the turbine steam path is caused by the admission of foreign material into the turbine. Typical foreign materials include weld rod, weld bead, weld spatter, loose debris such as small nuts and bolts, and other material, or parts, that may have come loose from upstream components in the steam system or the turbine itself. The damage due to foreign objects is usually found on the trailing edge of the nozzles and the leading edge of the buckets. The reason for the observed damage is that the foreign object can easily pass through the nozzle, however, it cannot accelerate enough to be able to pass through the rotating bucket passage way, resulting in the foreign object ricocheting back and forth between the nozzle and the buckets. This will continue until it breaks up, passes up over the top of the bucket damaging the bucket tip spill strips, or gets enough energy to be able to pass through the bucket passage way. The amount of damage is very much a function of the ruggedness of the nozzle and the bucket.

GE's trend to fewer more rugged nozzle partitions, will result in reduced nozzle surface and profile damage, hence improving sustained efficiency and resulting in a smaller impact on flow capacity of the damage cause by a similar sized foreign object.

MEASURED PERFORMANCE DATA

The sensitivity of the reaction design to damaged clearance controls should tend to make the turbine deteriorate more rapidly than the equivalent impulse turbine. Also, experience has shown that it is more difficult and time-consuming to replace the caulked-in clearance controls of a typical reaction unit compared to the replaceable clearance controls of a GE impulse unit. If these technical arguments are correct, operating performance data should support them and demonstrate a sustained efficiency advantage for the GE impulse design compared to the reaction design. Two sources of sustained performance data have been examined, the Federal Power Commission heat rate data, and enthalpy drop test data supplied by utilities.

Federal Power Commission Heat Rate Data

Up until 1983, the Federal Power Commission (FPC), later known as the Federal Energy Regulatory Commission (FERC), requested, for its annual report, that utilities supply unit heat rate information for their top-10 units having capacity factors greater than 50%. In 1983, as a result of the Paper Work Reduction Act, the FERC stopped requesting the top-10 unit heat rate information from the utilities, and this valuable information was no longer available. The data for the 10-year period from 1973 until 1983 has been used to examine the sustained efficiency of the impulse and reaction units that entered service after 1970.

The unit heat rate data reported to the Federal Power Commission (FPC) was a measure of overall unit heat rate and was influenced by factors other than the steam turbine, such as boiler performance, condenser pressure, capacity factor, etc. Care has to be taken so that these other effects do not distort any comparison of steam turbine performance. To minimize the influence of the other-than-turbine effects, impulse and reaction units in the same plant that are duplicate in size and steam conditions have been compared.

Figure 18 shows the reported FPC heat rate information for a power plant operated by a southern utility. Unit #1 is a 710 MW reaction turbine that started up in 1970, while units #2 and #3 are 700 MW GE impulse-designed turbines that started up in 1972 and 1974, respectively. Both of the GE impulse-turbines had a consistently better heat rate than unit #1 over the 10-year period during which the unit heat rates were reported. Figure 18 clearly shows the superior sustained efficiency of the impulse design. Unit #2 has a 210 Btu/kWh/222 kj/kWh heat rate advantage over unit #1 after they started out with the same heat rate in 1973. Unit #3 shows even better sustained performance, deteriorating less than 100 Btu/kWh/106 kj/kWh over a seven-year period. The rate of heat rate deterioration of unit #1 is greater than for both unit #2 and unit #3.

Figure 19 shows the reported FPC heat rate information for a power plant operated by a mideastern utility. Unit #1 is a 760 MW double reheat reaction turbine that started up in 1970, while unit #2 is a 737 MW double reheat GE impulse-designed turbine that started up in 1971. Even though unit #1 started out at a better heat rate than unit #2, unit #1 has continued to deteriorate with time, while unit #2 has been able to recover any heat rate deterioration during scheduled outages.

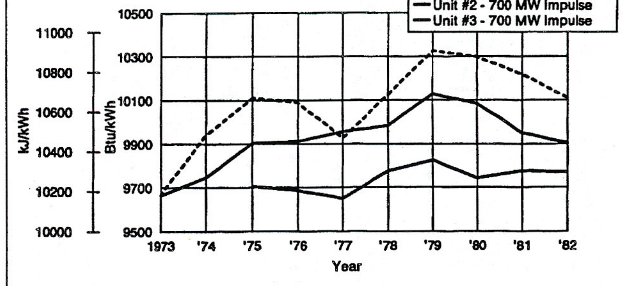

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Figure 18. Federal Power Commission heat rate data – southern utility

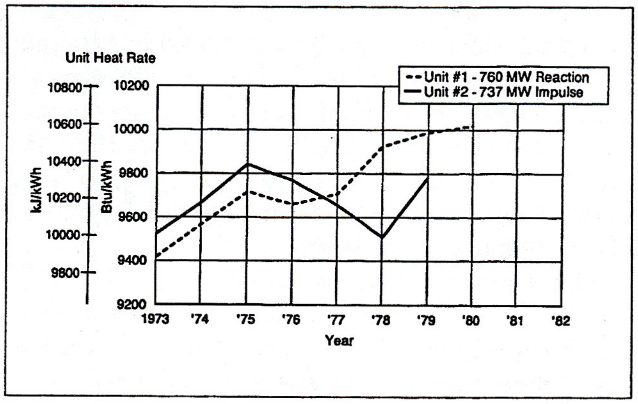

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Figure 19. Federal Power Commission heat rate data – mideastern utility

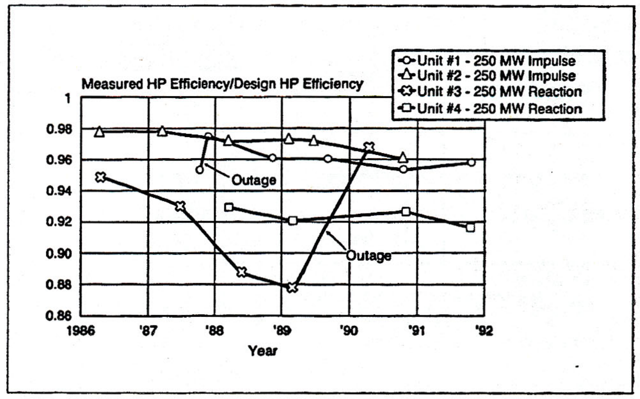

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Figure 20. HP section efficiency – Plant A

Enthalpy Drop Performance Test Data

During a recent proposal request for a new steam turbine, a large utility indicated that GE's impulse design had better sustained efficiency compared to the reaction design. The utility stated that regular performance test data recorded on units in the system demonstrated the better sustained efficiency of the impulse design, and invited GE to review the data.

The goal of the utilities performance test program was to annually perform accurate enthalpy drop efficiency tests on the HP and IP sections of each of its units. Although the utilities have not yet tested each unit, they are well on their way. A major cause of steam turbine efficiency deterioration is the increased leakages caused by damaged clearance controls. This effect is greatest in the HP section where the pressures are the highest and the stages are the smallest. Therefore, an examination of the change in HP section efficiency versus time indicates the influence of the turbine design on the sustained efficiency of the unit.

Figure 20 is a plot of the ratio of measured valves wide open (VWO) HP section efficiency to the design VWO HP efficiency for each of four 250 MW units in Plant A. Units #1 and #2 are 250 MW GE impulse turbines while units #3 and #4 are reaction designed turbines. Units #1 and #2, the GE impulse turbines, showed a gradual and relatively uniform deterioration in performance, while the reaction turbines showed both a greater rate of deterioration between outages and a much lower level of HP section efficiency. At the request of the utility, the author inspected unit #4 during an outage in 1988. About 4% of the HP section efficiency deterioration was identified to be due to damaged clearance controls which could not be fixed during the scheduled outage. This information and experience was factored into the planning of the unit #3 outage in 1989, and the outage extended to allow time for all the clearance controls to be restored; hence, the large increase in HP efficiency.

Figure 21 is a plot of the ratio of the measured VWO HP section efficiency to the design VWO HP efficiency for each of four units in Plant B. Units #1 and #2 are 125 MW GE impulse-designed turbines. Unit #3 is a 220 MW reaction-designed turbine. Unit #4 is a 350 MW GE impulse-designed turbine. After outages in 1987, units #1 and #2 have held their level of HP section efficiency, with less than a 1% deterioration over the last five years. Unit #3, the reaction design, was the poorest performer during 1987 and 1988. However, an outage in 1988, restored a significant amount of performance, but not up to the level of units #1 and #2. On unit #4, the HP section efficiency had deteriorated gradually since 1987. However, during an outage in 1991, the performance was restored to the efficiency levels of units #1 and #2, and better than the efficiency level of unit #3, the reaction turbine.

Figure 22 is a plot of the ratio of the measured VWO HP section efficiency to the design HP efficiency for unit #7 at Plant C and unit #5 at Plant

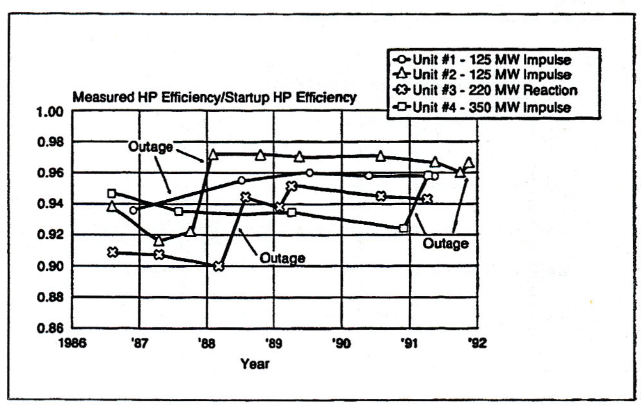

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Figure 21. HP section efficiency – Plant B

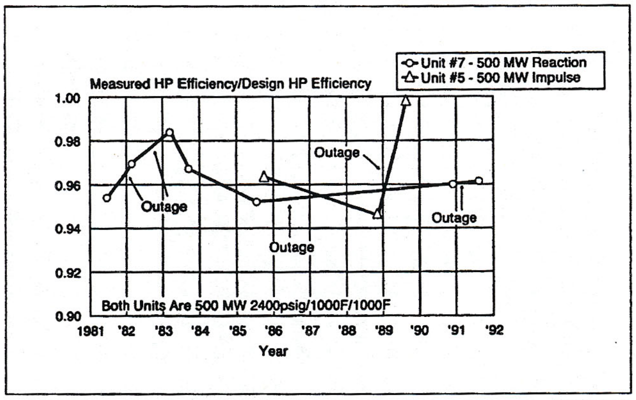

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Figure 22. HP section efficiency – Plant C unit #7 – Plant D unit #5

D. Unit #7 is a 500 MW reaction turbine. Unit #5 is a 500 MW GE impulse turbine. Although there is very little data for unit #5, it is important to notice the ability of the unit to be restored back to its design performance during a 1989 outage. During an outage in 1991 on the #7 unit, the reaction turbine, very little HP efficiency was recovered, even though the level of efficiency prior to the outage was the same as the #5 unit.

The utility's experience with the units at Plant E also demonstrates the inherent sustained efficiency advantage of GE's impulse design. Units #1 through #3 at Plant E are 660 MW GE impulse turbines. Figure 23 shows a plot of the ratio of the measured VWO HP section efficiency to the start-up VWO HP efficiency for units #1, #2, and #3. All three units have shown less than 2% deterioration in HP efficiency compared to their original "as new" start-up efficiencies. Considering that unit #1 went into service in 1978, this is an outstanding testimony not only to the ability of the impulse turbine design to sustain its efficiency, but also to how well the units have been operated.

The recent introduction by GE of features to minimize efficiency deterioration, such as SPE resistant turbine stages and positive pressure variable clearance packings has given GE the opportunity to measure the impact of these features on sustained efficiency.

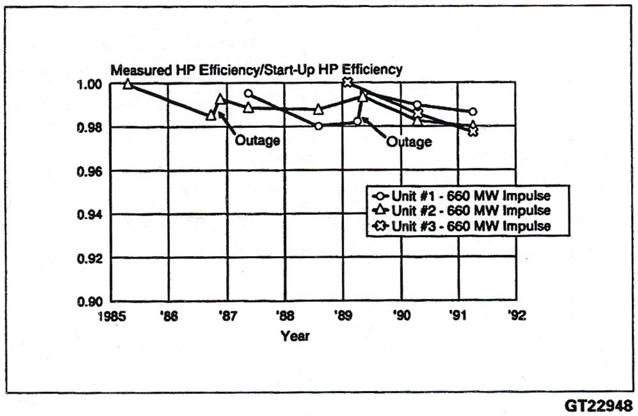

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Figure 23. HP section efficiency – Plant E

Figure 24 shows the measured HP section efficiency deterioration of a 650MW super-critical double reheat unit. Prior to the installation of an SPE resistant nozzle box in 1987, the HP section efficiency deterioration averaged about 2% per year. Since 1987 the rate of HP section efficiency deterioration has been dramatically reduced demonstrating the effectiveness of GE's SPE nozzle box design.

The utility inspected the nozzle box in 1990, after three years of operation, and found it in excellent condition. The nozzle box was re-installed with the expectation of many years additional operation.

Figure 25 shows the HP section efficiency of an 800 MW super-critical single reheat unit. Prior to the upgrade of the HP section in 1992, the HP section would deteriorate about 1.5% per year, resulting in a three year inspection cycle. In 1992, an SPE resistant nozzle box and positive pressure variable clearance packings were installed in the unit.

Since 1992, the HP efficiency has deteriorated only about 1% during almost four years of operation, about a three fold reduction in the rate of efficiency deterioration.

The sister unit was upgraded with similar components in 1993. Figure 26 again shows the dramatic improvement in sustained efficiency for that unit also.

CONCLUSION

The combination of GE's basic impulse design philosophy, with its wheel and diaphragm construction, together with recent design features such as SPE resistant stages, lower solidity nozzles, enhanced bucket tip leakage controls and positive pressure variable clearance packings, results in GE's modern turbine steam paths having a sustained efficiency second to none in the industry.

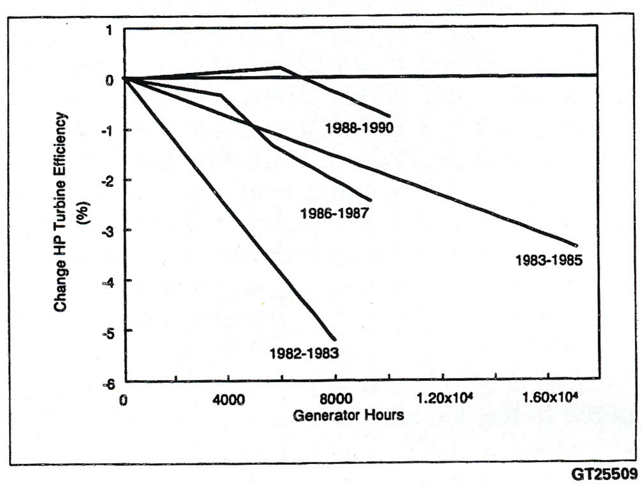

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Figure 24. HP section efficiency deterioration of a 650 MW supercritical double reheat unit

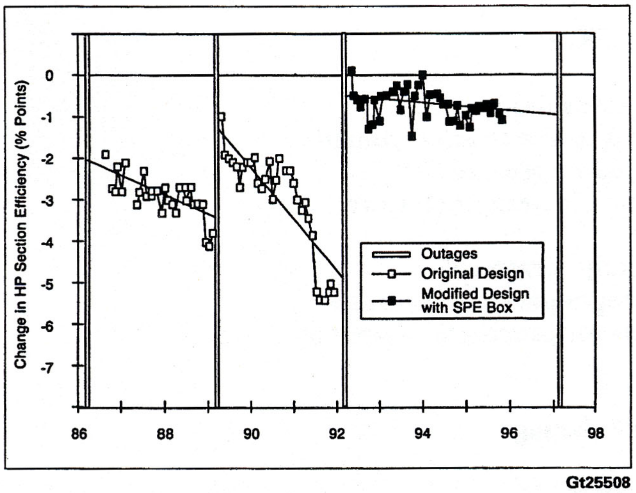

Figure 25. HP section efficiency deterioration of a 800 MW supercritical single reheat unit

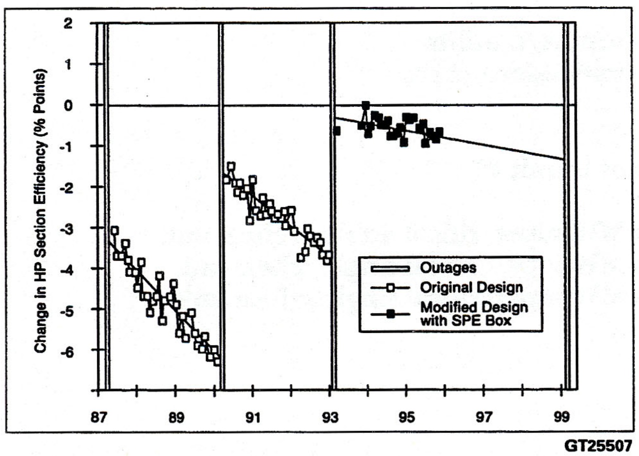

Figure 26. HP section efficiency deterioration of a 800 MW supercritical single reheat unit

Long term heat rate and HP section efficiency data, presented in this paper, confirms the ability of GE's steam path designs to sustain efficiency.

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LIST OF FIGURES

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