



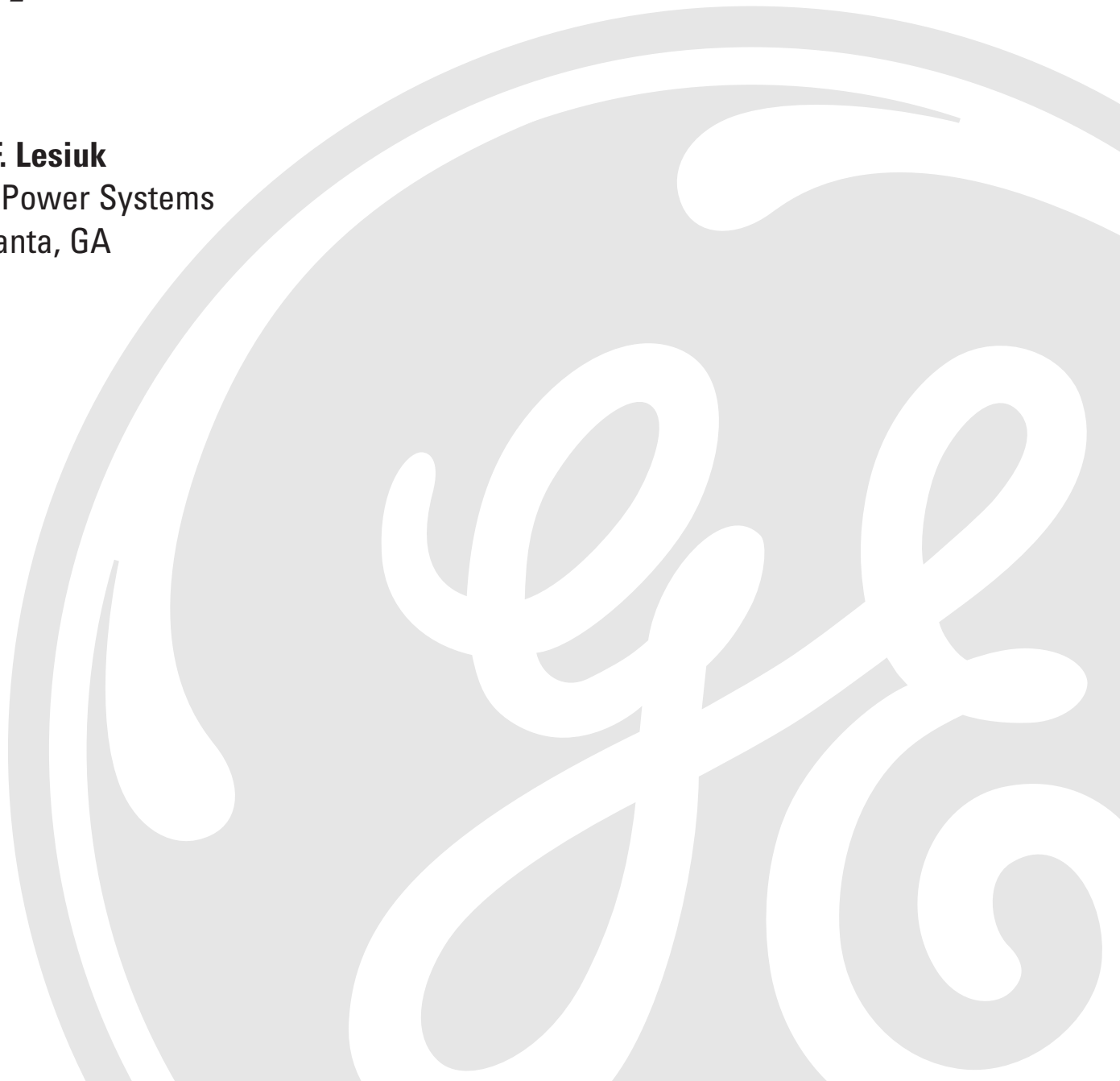
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***GE Power Systems***

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# ***Steam Turbine Upgrades***

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# Steam Turbine Uprates

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# *Steam Turbine Uprates*

## Summary

The thermodynamic performance of a steam turbine is primarily determined by the steam path components. Because the efficiency of the entire power plant cycle is largely dependent on the efficiency of the energy conversion in the turbine, it is important to minimize aerodynamic and steam leakage losses in the steam path.

Nozzle and bucket aerodynamic-profile losses, secondary-flow losses, and leakage losses account for roughly 80-to-90 percent of the total stage losses. In order to ensure high-efficiency turbine designs without sacrificing turbine reliability, it is necessary to use both highly-efficient nozzle and bucket designs to minimize profile and secondary losses, and advanced clearance controls to minimize leakage flows.

GE's development effort has been underway for more than a decade in order to reduce these losses. The objective of this long-term program is to develop specific design features for both new turbines and retrofits of existing units that maximize overall turbine efficiency and maintain a high degree of reliability and cost effectiveness. The development program has included activities conducted for all of the steam turbine product lines in cooperation with other company components such as Aircraft Engines, Gas Turbine, and Corporate Research & Development. The result of this development effort was the introduction of the Advanced Design Steam Path, ADSP, in 1995.

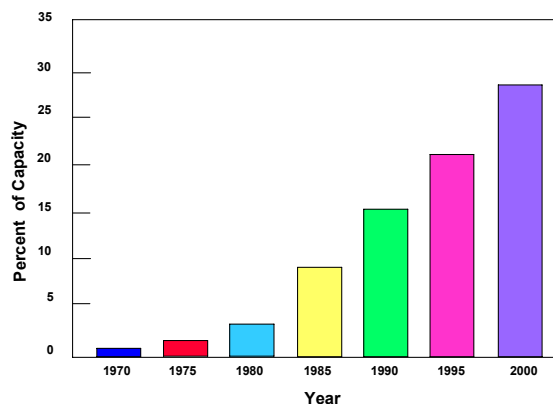
Since 1995, GE has installed over 40 first- and second-generation ADSP retrofits on a variety of units. Field test data from these units has indicated steam path efficiency improvements ranging from 1.5 percent to 3.0 percent. Along with this, GE has been developing new NPI features, such as enhanced advanced-vortex designs, integral cover buckets, and brush seals. These

features achieve additional improvement in efficiency.

As a natural progression from the ADSP experience, GE introduced the "Dense Pack" redesign approach to achieve additional section efficiency improvement.

## Background

During the mid-1980s and early 1990s the principle reason for making steam turbine uprate decisions was the aging of power plants, (see *Figure 1*), and the attendant poorer reliability of older equipment, as shown in *Figure 2*.

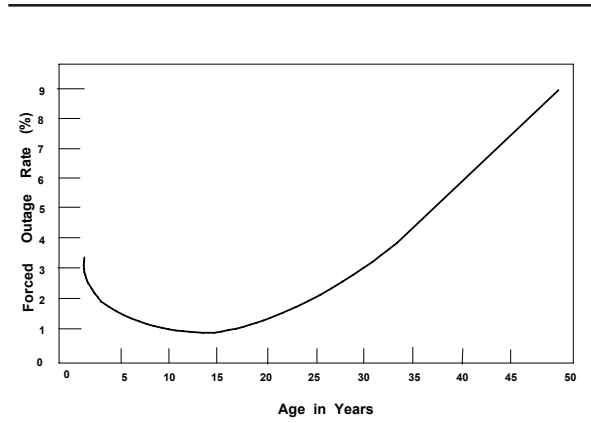


**Figure 1.** Utility dependence upon units greater than 30 years old

Utilities evaluated their aging fleet and concluded it was more economical to extend the life of the equipment than to retire the unit. This resulted in turbine life extension evaluations to identify equipment that needed repair or replacement in order to operate beyond the generally-accepted design life of 40 years.

Talk of deregulation of the power industry during the mid-1990s created considerable uncertainty among the utilities. Decisions regarding the sale of generating and/or transmission and distribution assets were analyzed. One clear conclusion from the deregulation discussions

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**Figure 2.** Typical aging reliability trend

was that the utilities were going to be in an extremely competitive environment in the future.

The initial reaction to deregulation within the utility industry was to take a “wait and see” position. As decisions regarding the retention or selling of assets were made, new drivers in the cost model developed. Evaluations for replacement power during peak periods soared and it became clear that additional capacity and improved efficiency were the principle objectives for the future. The low cost producer of

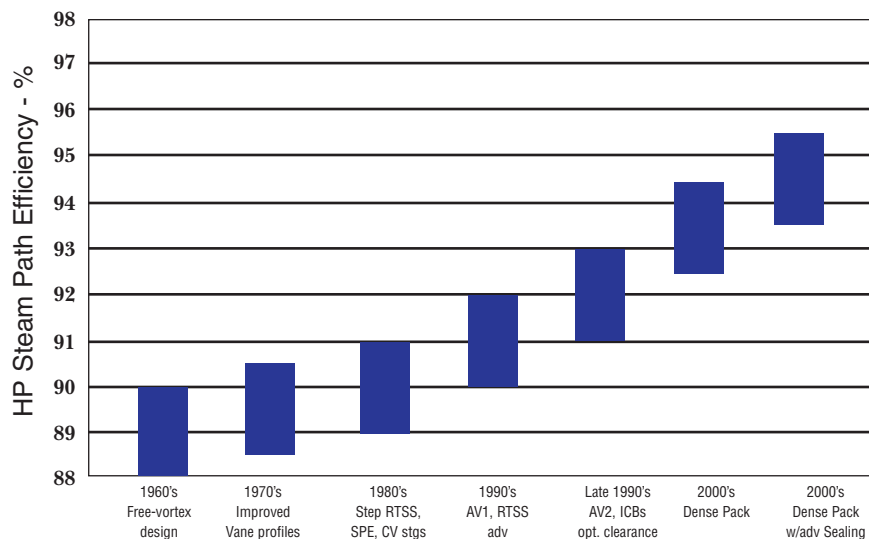
electricity with additional capacity would be the victor in the new, unregulated market.

Today, in addition to addressing the aging fleet issue, utilities are looking for the competitive edge that additional capacity and better performance will provide. Other factors that enter into the economic model are the desire for sustained performance with minimal degradation over period of at least ten years and the desire to extend time between major overhauls to at least ten years. The balance of the paper discusses the technologies and product solutions developed to address these utility needs.

## Dense Pack Section Replacement

The Dense Pack turbine section performance, as shown in *Figure 3*, is the latest evolution of GE steam design that began in 1903 with a 5000 kW turbine. The design limits, operational experience, and rugged dependability synonymous with GE turbine design is not changed with a Dense Pack.

The design goal of a Dense Pack retrofit is to put the most efficient steam path into an exist-



**Figure 3.** Efficiency evolution of a single HP stage

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ing high-pressure outer shell. The high efficiency steam path will produce a lower heat rate and increased output for the same steam flow. In designing the most efficient steam path, two interesting by-products also resulted. The design parameters utilized to increase efficiency, such as bucket and nozzle solidity and reduced rotor diameters, also had the benefit of reducing solid particle erosion. This led to a steam path that not only is more efficient but also has a greater, sustained efficiency. Coupled with the supply of a solid rotor (elimination of the rotor bore), the sustained efficiency results in a turbine section that should not require internal repair or inspection for ten or more years. These complementary, interacting benefits produce additional megawatts at a lower life-cycle cost.

## High Efficiency Steam Path

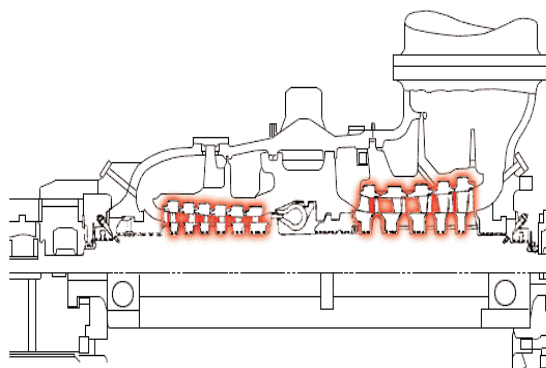
In the early 1990s, GE produced an Advanced Vortex bucket and diaphragm retrofit known as Advanced Design Steam Path (ADSP), *Figure 4*. Although ADSP remains a cost-effective efficiency retrofit, the potential efficiency benefit of ADSP is limited because the retrofit is

installed onto the existing steam turbine rotor and inner shell. This limited the designers' flexibility because the number of turbine stages and rotor diameters was fixed.

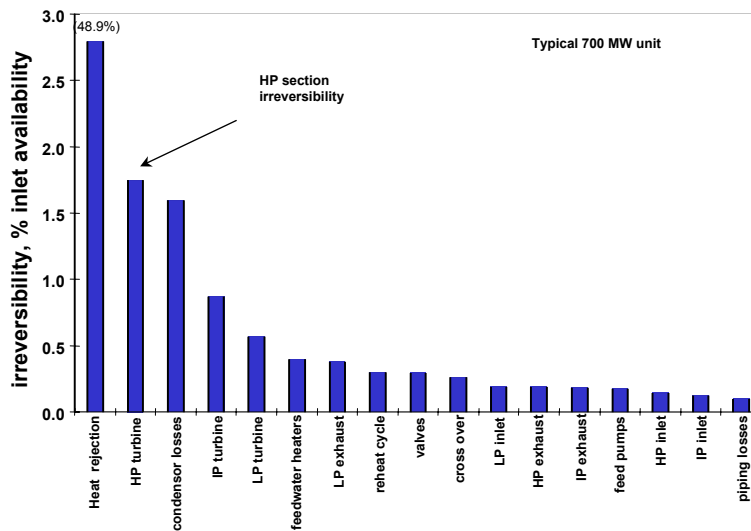
With more than 40 ADSP packages currently in operation, the ADSP program provided a good experience base for the Dense Pack. ADSP incorporates some of the features to be included in Dense Pack such as steam flow management, optimized packing clearances, and advanced shaft sealing. Pending deregulation and decreasing reserve margin have driven the utility marketplace to seek ever more aggressive methods of lowering bus bar cost and increasing capacity. Armed with the experience gained from the ADSP program, improved turbine design and modeling tools, shared technology from GE's aircraft engine and gas turbine product lines, and customer desire for steam path enhancements, the Dense Pack team was formed.

The Dense Pack team began by reviewing the turbine to determine where to focus design efforts to improve efficiency. *Figure 5* is a Pareto chart of unrecoverable turbine losses by turbine

- |                          |  |
|--------------------------|--|
| Advanced aero buckets    | All stages, with advanced bucket tip sealing   |
| Advanced aero partitions | All diaphragms   |
| Additional               | Diffusion coated 1st stage nozzle with SPE Profile Partition                                       |
|                          | Diamond Tuff™ HVOF coating (stage 1 buckets, 1st reheat diaphragm, 1 <sup>st</sup> reheat buckets) |



**Figure 4.** Advanced design steam path



**Figure 5.** Efficiency loss by system

section. Unrecoverable losses are essentially inefficient use of the steam energy. A review of the Pareto chart shows that except for the heat losses of the condenser, the HP and IP turbine sections have the greatest amount of irreversibility.

The efficiency upgrade focused on HP and IP sections and attacked the tip leakage and steam path secondary and profile losses.

The Dense Pack team drew on cross-functional GE engineering resources from steam and gas turbine design, Aircraft Engines, and Corporate Research and Development (CRD). Their objective was to design the most efficient steam path that could be installed into an existing outer shell that included incorporating additional staging into the turbine section. Hence, the name “Dense Pack,” for additional staging in the same axial spacing.

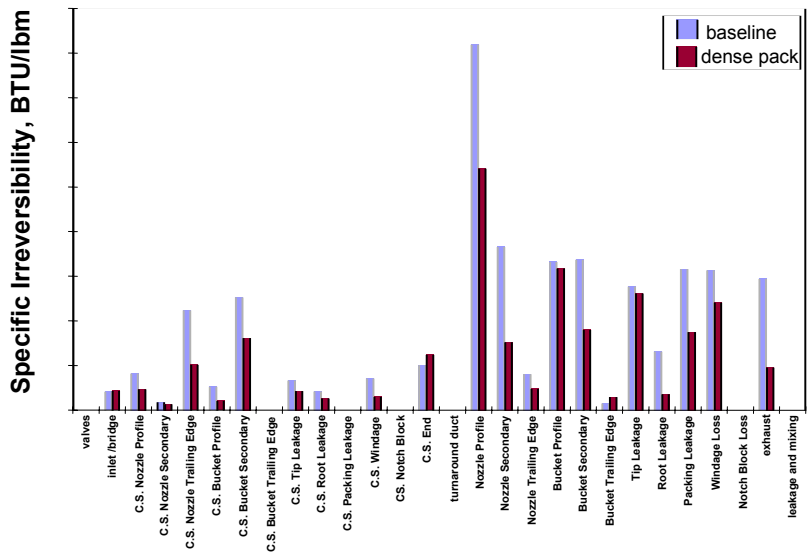
Given the latitude of supplying a new steam turbine rotor and inner shell, the team capitalized on adding staging and reducing the rotor stage diameter. Both of these concepts result in an inherently more efficient steam path. By adding stages, the energy may be extracted in smaller,

more controlled, and more efficient increments. Reducing the stage root diameter results in increased bucket and nozzle partition heights. Secondary losses decrease as the partition height increases. In addition, reducing the rotor diameter results in a reduction in shaft sealing leakage area, further improving efficiency. The smaller steam path diameter also results in lower steam velocity and reduces the effect of any solid particle carryover.

The steam path design incorporates reduced solidity concepts or less buckets and nozzles per row. The reduction in steam velocity coupled with fewer partitions results in lower profile losses per stage. Typical efficiency gains vs. sources of irreversible losses for a conventional and Dense Pack steam path are shown on *Figure 6*.

The first step in the steam path redesign is to establish the mechanical constraints. The minimum rotor diameters are determined through an analysis of the torsional stress requirements and a rotor dynamics investigation including a rigorous review of rotor stability. Once the minimum rotor packing diameters are determined, the minimum steam path diameter can be established from the known radial height



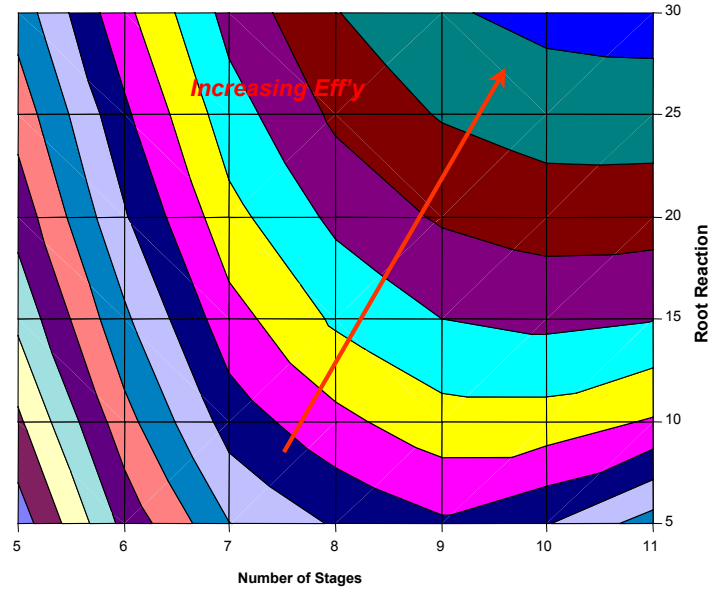


**Figure 6.** Typical loss mechanism comparison

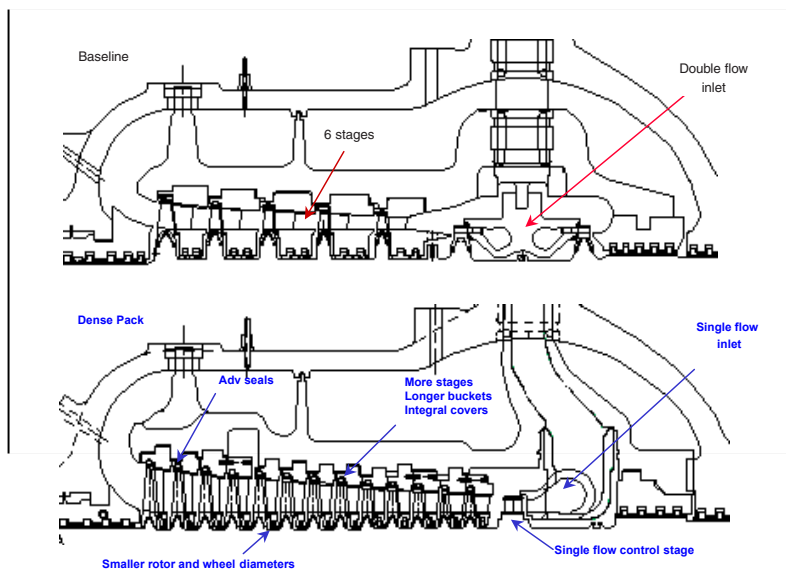
requirements for the various bucket attachments available to the turbine designer. This allows the steam path optimization to proceed. GE has always utilized some reaction levels in the design of high-pressure steam turbine buckets. Building on ADSP experience, the Dense Pack increases the bucket reaction to approximately 20-25 percent. Modern design and modeling tools allow the computational iterations necessary to individually optimize both the

stage number and bucket reaction levels for each steam path. *Figure 7* shows a typical optimization contour plot of stage count vs. stage root reaction. Additional parameters are compared in order to arrive at the optimum value for the key parameters that define the Dense Pack steam path.

*Figure 8* shows the results of the Dense Pack optimization approach as applied to the redesign of a single-flow, high-pressure section. The base-



**Figure 7.** Optimization contour plot



**Figure 8.** Dense Pack redesign of a single-flow high-pressure section

line design employed a 6-stage section with a double-flow first stage. By lowering the steam path diameters and increasing the stage reaction, a more efficient 14-stage steam path results. The major components affected by this redesign include replacement of the bucketed rotor, diaphragms, inner shell, and end packing heads. In addition, the original double-flow, first-stage nozzle box is replaced with either a single-flow nozzle box, a nozzle plate, or a noz-

zle diaphragm, depending on unit size and number of control-stage admissions.

*Figure 9* is a photograph of an 11-stage, single-flow high-pressure rotor that was redesigned from a baseline configuration of 7 stages including a double-flow first stage.

Once the high efficiency steam path is fundamentally designed for the number of stages, has solidity and has sufficient rotor root diameter,



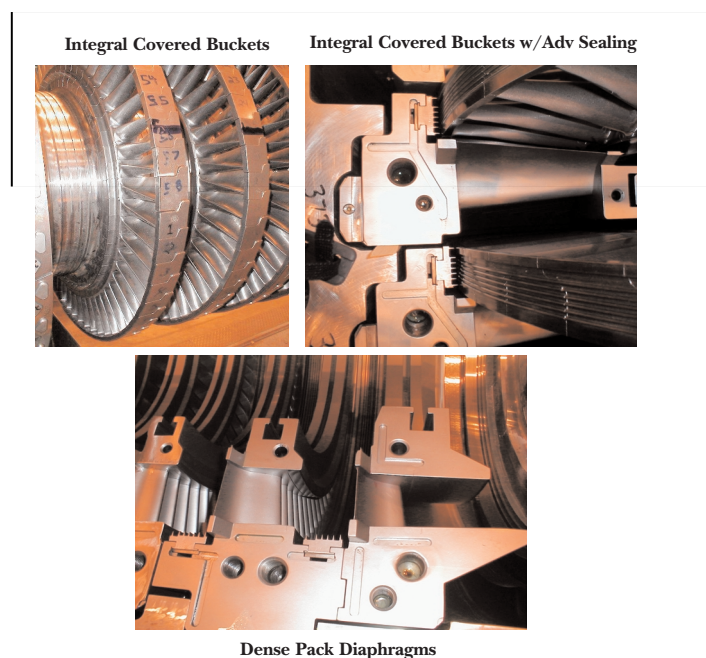
**Figure 9.** Dense Pack redesign of a single-flow high-pressure rotor

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then design engineering adds sealing features such as optimized packing clearances, integral covered buckets, and advanced tip sealing (See *Figure 10*). Bimetallic seal rings complete the offering and maximize steam efficiency.

### **Sustained Heat Rate and Solid Particle Erosion (SPE) Resistance**

Another GE design objective with the Dense Pack redesign was to supply a steam path that would be resistant to SPE degradation. In the

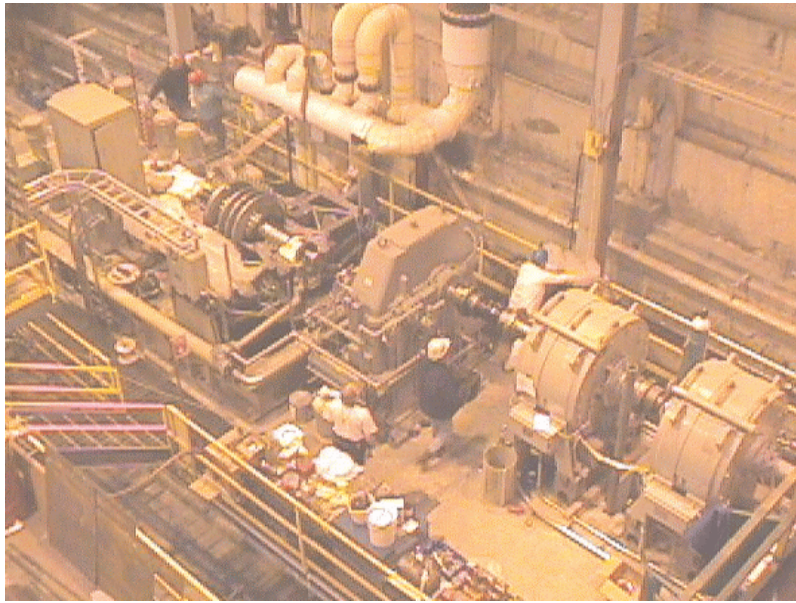


**Figure 10.** Dense Pack features

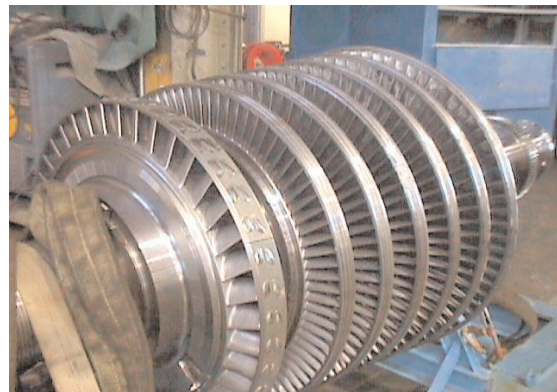
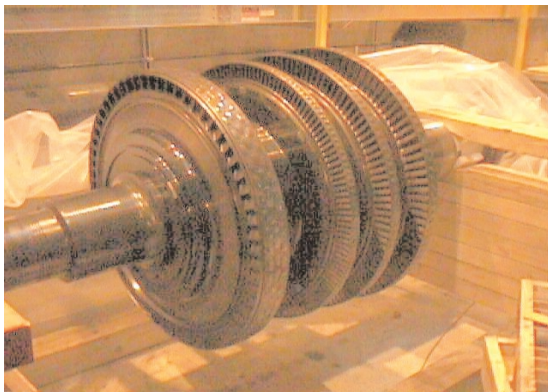
The Dense Pack design approach has been verified through a rigorous Six Sigma Design of Experiment process in GE's Steam Turbine Test Vehicle (STTV) located in Lynn, Massachusetts. This state-of-the-art test facility was completed in 1999 and the first test was completed in April of that year. The STTV is a fully-instrumented, multi-stage test turbine using high-pressure steam. The initial test in April of 1999 was to establish a baseline representing the installed fleet designs. This was followed by a series of tests using the Dense Pack design approach applied to the same steam conditions. *Figure 11* shows the test facility and *Figure 12* shows the test rotors for the baseline and one of the Dense Pack tests.

1980s GE performed extensive computer modeling and analysis of solid particle trajectories in the steam path. The comprehensive development effort resulted in the following:

- A fundamental understanding of the erosion mechanism in the steam turbine steam path.
- Development of plasma spray and diffusion coatings that significantly enhanced the SPE resistance of the steam path.
- A combination of design changes identified by the trajectory analysis and SPE-resistant coatings that led to minimizing particle carryover damage.



**Figure 11.** Steam Turbine Test Vehicle



**Figure 12.** Baseline and Dense Pack test rotors

These design changes included increased axial clearance between the stationary nozzles and rotating buckets for the reheat section, increased nozzle scale factor for all stages, and redesigned nozzle profiles that allow smoother and less damaging passage of solid particles through the steam path.

The study resulted in the redesign of the high-pressure nozzle partitions to distribute the solid particle impact over a broader area of the partition. Customer experience indicated a 75% reduction in the degradation attributed to solid

particle erosion. Clearly, the model and the GE analysis were on target. The high-efficiency steam path of the Dense Pack will virtually eliminate solid particle erosion. *Figure 13* depicts the solid particle erosion of a conventional steam path nozzle partition. The severity of the erosion varies from zero, shown in blue, to the highest shown in red.

*Figure 14* shows the benefits of the reduced nozzle count, lower solidity, and the redesigned nozzle partition. These features (lower nozzle and bucket solidity, redesigned partitions,

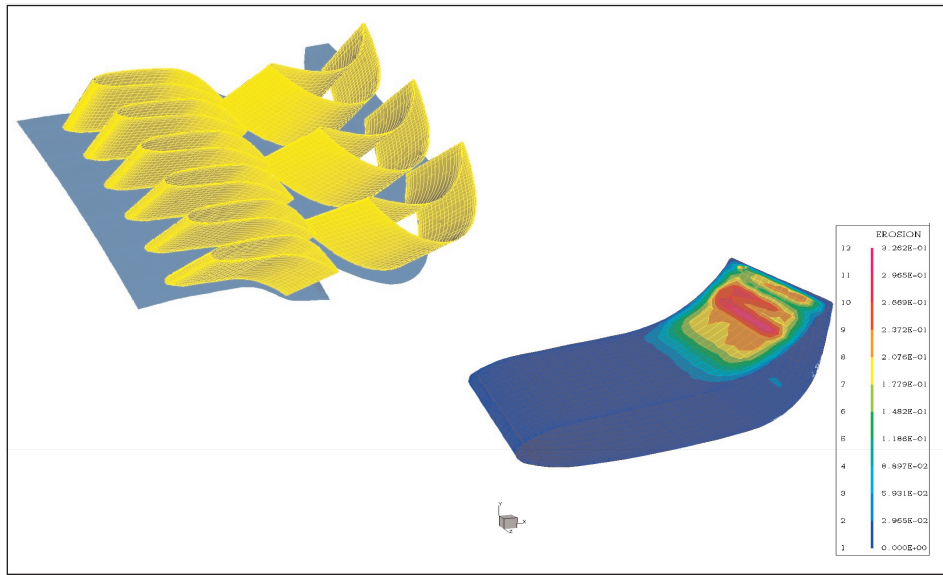


Figure 13. Solid particle erosion on conventional steam path

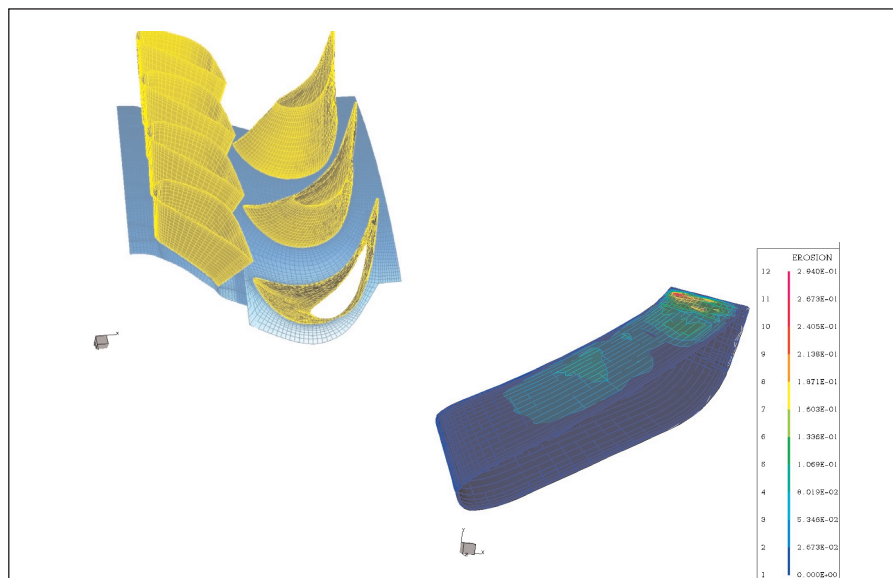


Figure 14. Solid particle erosion on Dense Pack steam path

reduced steam velocities, and solid coatings) yield a steam path that is more resistant to solid particle carryover. This will allow units to be operating for longer periods between major overhauls because the rate of performance degradation will be significantly reduced, if not virtually eliminated.

## Conclusions

The Dense Pack section replacement is the latest option in GE's long history of steam path efficiency improvements. Incorporating technologies from gas turbine, Aircraft Engines, and Corporate Research and Development, the

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Dense Pack provides an alternative to the Advanced Design Steam Path design. The Dense Pack alternative supplies the user with a redesigned steam path including a new bucketed rotor, diaphragms, and inner shell. The increase in output and the reduction in heat rate address the two major competitive issues facing the utility industry today.

The inherent features of Dense Pack, including a lower solidity design steam path, and fewer nozzles and buckets per row, combined with GE's

proven solid particle erosion protection features, address a utility concern of sustained performance. The resultant damage to the steam path from particle carryover is virtually eliminated, enabling utilities to extend the time between major overhauls and reduce life-cycle costs.

### ***Acknowledgement***

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The author wishes to acknowledge the contributions of the Dense Pack team led by James Maughan.

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