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AVAILABILITY AND PERFORMANCE IMPROVEMENTS FOR A GE STAG™ 307E COMBINED-CYCLE POWER PLANT

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ABSTRACT

Massachusetts Municipal Wholesale Electric Company (MMWEC) is currently modernizing their GE STAG™ (Steam and Gas) 307E combined-cycle generating station at Stony Brook Energy Center. This project consists of upgrading both the gas turbine and steam turbine within the constraints of the existing combined cycle plant.

This modernization program will improve the availability of MMWEC's combined-cycle power plant primarily through doubling the combustion system inspection interval. Other benefits include increasing the present combined-cycle power output by approximately ten (10) megawatts with less fuel required per generated megawatt. These benefits are a result of new technology components developed by General Electric (GE) and engineered for retrofit to earlier steam and gas turbines such as MMWEC's.

This paper represents the thought process and motivation that MMWEC has followed to justify modernization of their ten (10) year old power plant. This paper also represents the specifics of the GE advanced technology components, including their impact on steam and gas turbine unit performance and reliability.

PLANT BACKGROUND

In the mid-1970s, MMWEC (a joint action power supply agency for over thirty [30] municipals in Massachusetts) decided it needed an intermediate and peaking plant to satisfy its power supply needs. The intermediate plant had to be capable of reliable daily cycling with low start up and shutdown costs, while meeting rigorous environmental regulations because of the then pending New Source Performance Standards. Heavy emphasis was placed on high operational efficiency since it was initially decided to be a fossil/fuel plant.

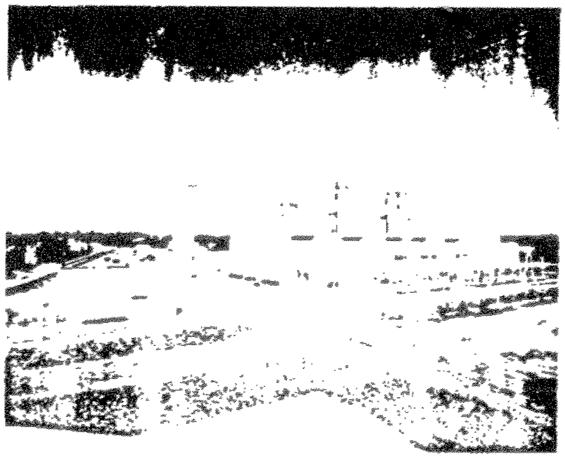
Extensive study was done and it was decided that the GE STAG™ 307 Plant came the closest to meeting all the requirements. Engineering began on the basis that the intermediate plant would be a combined-cycle plant built to the highest possible efficiency and reliability standards for cycling operation. The major components of this plant would be supplied by GE and the heart of the plant would be the GE Frame 7001E model gas turbine. The overall plant rating was to be in excess of 343MW net at 20°F ambient with a higher heating value heat rate of approximately 8,200 BTUs per KWH.

The Stony Brook intermediate plant began commercial operation on December 1, 1981 and at that time was the most efficient fossil fuel fired power plant in the world. In addition, Stony Brook consistently exceeded its target availability goals with the most recent four (4) years of operation experiencing well over 90% availability factor.

STONY BROOK - OPERATION IN THE 1990s

During the 1980s the Stony Brook maintenance staff concentrated its efforts on reducing demand maintenance, which increased planned maintenance to a certain extent. The overall program was so successful that in 1990 Stony Brook maintenance activities were largely preventive in nature. In order to achieve even higher availability factors, the staff shifted its interest of concentration from demand maintenance to outage maintenance planning. Careful study determined that the major cause of outage maintenance was gas turbine related as opposed to steam turbine, HRSG or balance of plant-related items.

There are three (3) major gas turbine outage activities (combustion overhaul, hot gas inspection, and major inspection). With the cooperation of GE, it was determined that with new technology it was possible to double the interval



MMWEC – Stony Brook Energy Center

between combustion overhauls with the ultimate goal of making them concurrent with hot gas path and major inspections.

When Stony Brook was constructed, the New England Power Pool was a winter peaking pool, therefore, all power plant ratings were based on winter standards. During the 1980s it became evident that the summer peaks experiences were rivaling and, in some cases, exceeding the winter peaks. In 1986 the Pool decided that all power plants would have both a summer and a winter rating. The summer rating for internal combustion engines would be based on a 90°F ambient; as a result MMWEC lost a significant amount of capacity credit during the summer period. Various options were evaluated that would recover some of the lost capacity.

MMWEC also realized that part of the summer derating and efficiency loss could be recovered by utilizing new gas turbine and steam turbine materials and technology. The higher efficiency attained would increase summer power output, and improve summer economics, as well as lower environmental emissions on a KW per hour basis.

In order to demonstrate that obtaining the above availability and performance improvement goals were justified, a detailed cost analysis was performed. The result indicated an expenditure of approximately $325/KW (1991 dollars) would be cost effective. Although the detailed assumption and results of the cost analysis of this nature would vary from utility to utility and region to region, MMWEC's analysis was able to demonstrate that this plant renewal effort would be cost-effective based on the following:

1. Current spares in inventory were approaching the end of their useful life and needed to be replaced. A significant percentage of the proposed $325/KW would be needed just to replace the old parts with components of old technology design.
2. Availability improvement of approximately 2% (points) would lower costs for capacity credit and maintenance.
3. Less frequency of plant gas turbine maintenance outages would reduce replacement power cost and critical component refurbishing costs.
4. Total plant output capacity during the summer would be increased by greater than 10MW which would recover a portion of the summer derated capacity. This would lower all power supply costs during the summer peak periods.
5. A projected increased efficiency of 1% for each gas turbine during the summer months lowers operating costs.

In order to keep implementation costs to a minimum, all renewals and modifications are to be performed during normally scheduled outages. Thus, the Availability Improvement Program (AIP) will not be completely implemented until 1993.

PRODUCT BACKGROUND

The GE pre-engineered STAG™ combined-cycle power generation systems consist of factory-packaged components, including an integrated control system. Introduced in the late 1960s, STAG™ systems may include from one (1) to six (6) gas turbines, including the MS5001, MS6001, MS7001, or MS9001, and one (1) steam turbine matched to the gas turbine exhaust heat. STAG™ designations starting with the numeral "1" (e.g., STAG™ 107E) employ one (1) gas and (1) steam turbine. They can be on a single shaft, driving one (1) generator, or on separate shafts, each with its own generator. All other designations (e.g., STAG™ 307E) are for multi-shaft configurations where the first digit is the number of gas turbines per steam turbine, while the last digit and letter(s) are the gas turbine frame size and model designations, respectively. Current fourth-generation STAG™ systems have now evolved to the introduction of larger, more efficient gas turbines, utilizing combustion system and hot gas path designs which have increased the time between scheduled shutdown inspections such that the objective of achieving combined-cycle availability greater than 95% is obtained. Table 1 lists all the GE Power Generation STAG™ combined-cycle systems currently in operation or on order.

The GE Frame 7001 model gas turbine was introduced in 1970. Design changes made to compressor, combustion, and hot gas path components have been implemented through the years resulting in the performance improvements shown in Figure 1. As of June 30, 1991, there are 513 Frame 7001 gas turbines either installed or shipped with a total of approximately 8,000,000 operating hours.

Steam turbines for STAG™ operation incorporate a number of special features for optimum performance, high reliability, and minimum operating and maintenance costs. Turbine configurations have included single-, double-, and four-flow arrangements, utilizing last stage bucket lengths from 10" to 26". During the past 23 years, GE has built in excess of 70 steam turbine-generator units totaling over 3,500 MW of capacity for application in combined-cycle power plants.

ADVANCED TECHNOLOGY COMPONENTS

The following GE advance technology gas and steam turbine components are being implemented in MMWEC's STAG™ 307E AIP. Projected availability and performance improvements are as follows:

- Double combustion system inspection interval to 8,000 fired hours/800 fired starts
- Increase summer month output of each gas turbine by 6.1% while improving heat rate by 1.1%
- Improve both output and heat rate of the steam turbine by 1.5%
- Improve summer month combined-cycle output and heat rate by 5.7% and 0.4%, respectively

COMPRESSOR IMPROVEMENTS

Inlet Guide Vanes

The inlet guide vanes (IGVs) that were originally on the MMWEC 7E gas turbines are the 403 stainless steel, "high flow" design. This design offered an improved airfoil design compared to the IGV design originally on the MS7001B gas turbines.

The IGVs that are supplied as part of the AIP are the "reduced camber" "high flow" IGVs. The "reduced camber" airfoil permits increased inlet air flow. This airfoil was designed as part of the MS7001F Development Program and applied across the product line since it provided a significant performance improvement. The redesigned airfoil can increase output by 1.5% and decrease the heat rate by 0.3% on a MS7001E turbine, like MMWEC's. The new IGVs are made of GTD-450, a precipitation-hardened martensitic stainless steel that provided increased tensile strength and superior corrosion resistance because of its higher concentration of chromium and molybdenum. There have also been substantial increases in high cycle and corrosion fatigue strength. Figure 2 shows a summary of the design improvements of the new IGV.

Country	Utility	No. GT's	No. ST's	Total MW	Commercial	Total GT Hours
USA	Wolverine Electric	1*	1	21	1968	148,000
USA	City of Ottawa	1*	1	11	1969	100,000
USA	City of Clarksdale	1*	1	21	1972	117,000
USA	City of Hutchinson	1*	1	11	1972	68,000
USA	Duquesne Power & Light	3	1	330	1974	25,500
USA	Houston Light & Power	8	2	574	1974	596,200
USA	Salt River Project	4*	4	290	1974	187,300
USA	Ohio Edison	2	1	225	1974	100,000
USA	Jersey Central Power & Light	4	1	340	1974	135,200
USA	Arizona Public Service	3*	3	250	1976	70,600
USA	Iowa Illinois G&E Company	4	1	105	1977	50,000
USA	Puerto Rico EPA	8	2	606	1977	203,500
USA	Western Farmers Electric	3*	3	278	1977	207,200
USA	Portland Gas & Electric	6	1	550	1977	15,000
Korea	Korea Electric	8	1	640	1979	190,000
USA	MMWEC	3	1	343	1981	71,700
Taiwan	Taiwan Power Company	6	2	570	1983	49,500
Mexico	CFE Mexico	4	1	375	1984	201,000
Argentina	EMSA	2	1	65	1984	33,000
USA	SCE Cool Water IGCC	1	1	120	1984	27,000
Trinidad	Trinidad & Tobago	2	1	198	1985	30,000
Japan	TEPCO-Group 1	7*	7	1,115	1986	144,124
Japan	TEPCO-Group 2	7*	7	1,155	1988	74,342
China	MPI Lama Dien II	1*	1	50	1986	10,000
Pakistan	WAPDA	4	2	623	1986	20,400
Japan	Chubu Electric Power Company	5*	5	577	1988	42,500
USA	Fayetteville	6	1	189	1988	40,200
Egypt	Egyptian Electric Authority	8	2	300	1988	54,000
USA	Ocean State Power	4	2	480	1990	Construction
USA	Virginia Power Company	2	2	420	1990/92	400
Thailand	EGAT	4	2	700	1990	Construction
Japan	TEPCO-ACC	8*	8	2,600	1995	Design
Korea	KEPCO	4	4	900	1992	Design
USA	TECO Power System	2	1	250	1992	Design
Other Related Experience		137	76	15,339		3,011,866
Cogeneration Including MS6000 and MS7000 GTs		140	34	8,213		2,313,900
Single Shaft		277	110	23,552		5,235,766

Table 1. Power Generation STAG™ Combined-Cycle Systems

MODEL	SHIP DATES	ISO PERFORMANCE* KW	FIRING TEMP°F	AIR FLOW (10⁶ LBS/HR)	HEAT RATE (BTu/KW-HR)	EXHAUST TEMP°F
A	1970-71	47,260	1650	1,851	11,910	844
B	1971-72	51,800	1800	1,851	12,090	944
	1972-1978	60,000	1840	1,905	10,960	947
	1978	61,750	1850	1,967	10,920	944
C	1974-1977	68,500	1950	2,129	10,970	986
E	1974-75	71,700	1985	2,040	10,800	992
	1976-78	73,200	1985	1,125	10,530	974
	1978-81	75,000	1985	2,176	10,590	977
	1981-84	76,900	2020	2,210	10,590	1000
EA	1984-87	80,080	2020	2,313	10,650	989
	1987	81,760	2020	2,343	10,620	987
	1988	83,310	2020	2,373	10,470	982
F	1988-91	147,210	2300	3,307	9,960	1100
FA	1992-	158,090	2350	3,307	9,520	1092

*BASE LOAD DISTILLATE INCLUDES 0/0 INCHES H20 INLET/EXHAUST PRESSURE DROPS

Figure 1. MS7001 Performance History

HOT GAS PATH IMPROVEMENTS

First Stage Bucket

Three (3) major improvements have been made to the new first stage buckets supplied as part of the AIP. First, the new bucket has a blunt leading edge airfoil, as opposed to the sharp leading edge airfoil that is on the original first stage bucket. Figure 3 shows a comparison of the two (2) airfoil shapes. The new design allows more air to the leading edge, reduced thermal gradients and associated cracks with increased power output.

The second improvement involved a change of material. The MS7001B and early MS7001E first stage buckets were made from IN-738, a precipitation-hardened, nickel-base super alloy, which for many years was the industry standard for corrosion resistance. The current first stage bucket is made from GTD-111, also a precipitation-hardened, nickel-base super alloy, with the added benefits of a 35°F increase in rupture strength and greater low-cycle fatigue strength.

Third, because of its location, it is essential to coat the first stage bucket to prevent oxidation and corrosion. Since 1975, there has been a progression of coating changes. In 1989, Plasmaguard Plus™ was developed, satisfying both oxidation resistance and hot corrosion resistance criteria.

Second Stage Bucket

The second stage bucket has been redesigned to reduce the outward radial creep deflection of the bucket tip shrouds.

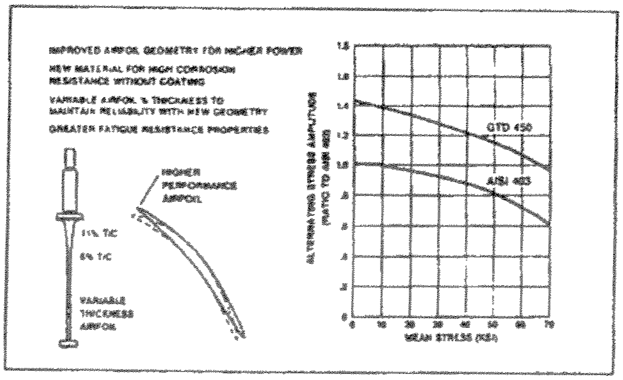


Figure 2. Design Improvements With GTD-450 High Flow IGV Designs

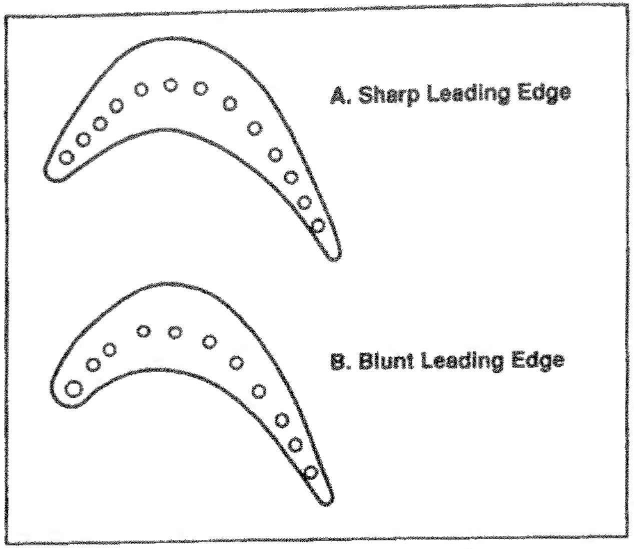


Figure 3. Sharp and Blunt Leading Edge Bucket Design Comparison

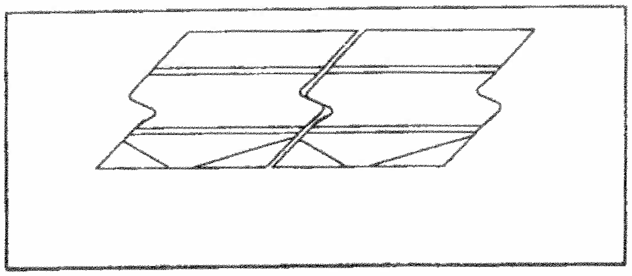


Figure 4. Scalloping of the Bucket Shroud

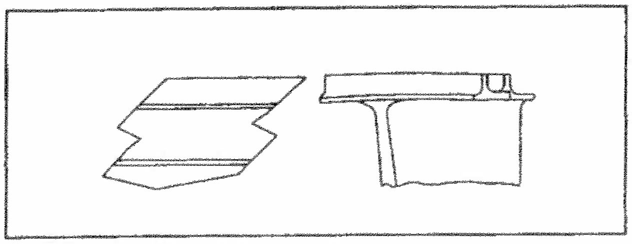


Figure 5. Final Configuration of Bucket Shroud

The deflection can lead to rubbing of the radial seal on the stationary shrouds and possibly cracking of the bucket tip shrouds. The principal cause of the deflection is elevated gas temperature in the region of the bucket tip.

The redesign involved the "scalloping" of the upstream side of the tip shroud to reduce the operating stress level and increase the creep life. Figure 4 shows the area of the tip shroud that was removed due to the "scalloping". Also, to further reduce the tip shroud stresses, the area between the seal teeth was thickened and the underside of the shroud was tapered. The final configuration, shown in Figure 5, reduced stress levels by more than 25% and increased creep life 80% over the original design.

First Stage Nozzle

To help improve the overall reliability of the gas turbine, an inner sidewall tangential support was added to the first stage nozzle. The tangential support consists of an integrally cast side support lug and milled radial slot on each nozzle segment that has a mating bushing-pin-retainer assembly as shown in Figure 6.

Second and Third Stage Nozzle

The second and third stage nozzles in MMWEC's turbines are made of FSX-414, the same material used in the first stage nozzle. GE has developed a new material for the second and third stage nozzles due to the problem of tangential deflection, indicating creep in the vane. The new GTD-222 material is a GE patented, nickel-based allow with a 150°F improvement in creep strength compared to FSX-414. This alloy also has enhanced low temperature hot corrosion resistance, and is weld repairable. This new material nozzle is expected to double the rework interval. At the present time, MMWEC has not replaced their second and third stage nozzles with GTD-222 nozzles.

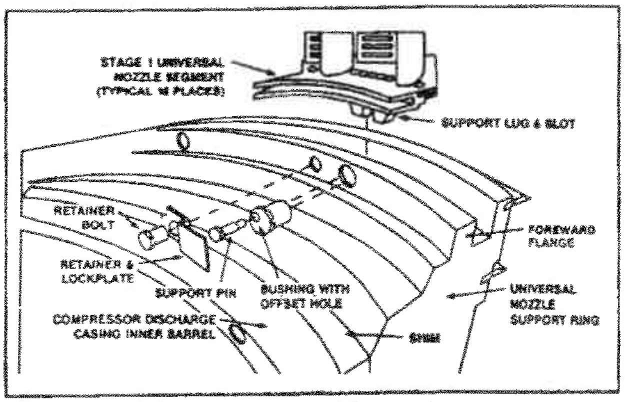


Figure 6. First Stage Nozzle Inner Sidewall Tangential Support

COMBUSTION SYSTEM IMPROVEMENTS

Significant efforts to advance the combustion system are driven by the need for higher firing temperatures. What originally were simple parts in the early gas turbines are now highly complex pieces of hardware with sophisticated materials and processing requirements. There are ten (10) combustion chambers on the MS7001 gas turbine. Figure 7 shows the arrangement of a typical chamber.

Combustion Liner

The combustion liners have been made of Hastelloy-X, a nickel-base alloy, since the introduction of the MS7001 in 1970. However a thermal barrier coating (TBC) now applied to the liners provides an insulating layer which reduces the underlying base material temperature by approximately 100°F, and mitigates the effects of uneven gas temperature distribution. The TBC consists of two (2) materials applied to the hot side of a component: the first provides a bond coat that is applied to the surface of the part, and the second, an insulating oxide which is then applied over the bond coat. Total thickness of the coating is approximately .015 inches.

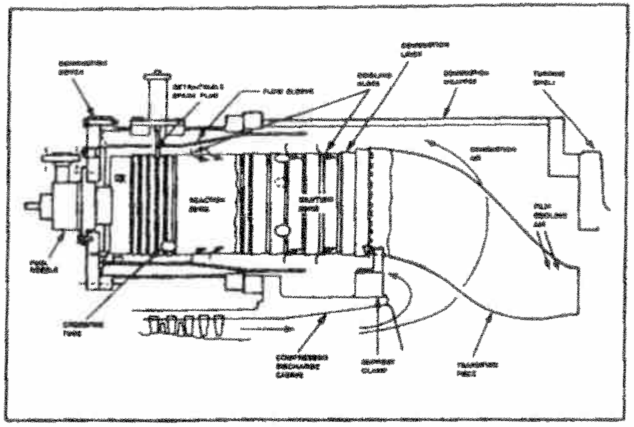


Figure 7. Combustion Chamber Arrangement

Transition Piece

The transition pieces originally supplied with the MMWEC gas turbines were the heavy wall Block III transition pieces made from Hastelloy-X material. The Block III transition pieces were an improvement over the thin wall transition pieces shipped on earlier MS7001 gas turbines. The new transition pieces that are part of the AIP are the HTP784 transition pieces. The HTP784 transition pieces were introduced to the GE MS7001 product line in 1984.

The HTP784 transition piece is made of Nimonic 263, a nickel-base alloy, which provides superior creep resistance, oxidation resistance, and fatigue strength over Hastelloy-X. Nimonic 263 has been used successfully in aircraft gas turbines for over 25 years.

Like the new combustion liners, the new transition pieces are being coated with TBC, reducing the metal temperature and improving creep resistance. The aft support has been redesigned to incorporate a cooled cylindrical mount welded to the body which eliminates cracking in the body-to-mount weld region. Cooling air is admitted to the cylinder mount via cooling holes and an impingement plate to film cool the mount area. This film cooling in conjunction with the thermal barrier coating significantly reduces the transition piece metal temperature. The aft bracket is hinged from the cylinder mount and has a two-bolt mounting arrangement to the nozzle retaining ring. This minimizes mounting loads, enhances low-cycle fatigue capability, increases torsional stability, and reduces aft frame seal wear. Figure 8 shows a comparison of the aft brackets. The aft frame is of one-piece wrought Nimonic 263 construction with machined slots for the end and floating seals. This aft frame sealing design reduces the relative motion between the end seals and floating seals and greatly reduces the wear rate.

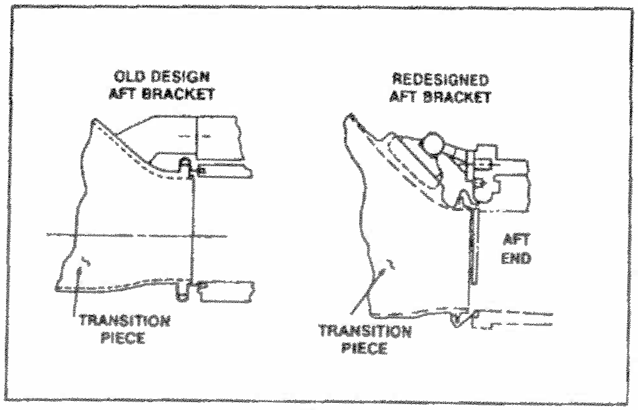


Figure 8. Comparison of Transition Piece Aft Bucket

STEAM PATH IMPROVEMENTS

Last Stage Bucket

The original 23" last stage bucket was first introduced into service in 1948. Initially used in utility units, this bucket has been primarily used in industrial and combined-cycle units during the last 20 plus years.

The original 23" design consists of individual buckets coupled together into discrete groups using a peened tenon cover connection at the vane tip and a brazed tie-wire located at mid-vane (Figure 9). The bucket is attached to the rotor wheel through the use of a finger dovetail design, which was first applied in 1947 and has been proven in over 24,000 wheel-years of satisfactory service on various last stage designs.

Figure 9. Current 23" Last Stage Buckets

Last stage buckets are one of the most challenging components of steam turbine design. The last stage (bucket and diaphragm):

1. Passes the largest volumetric flow in the turbine
2. Carries the highest stage loading at design conditions, producing up to 10% of the turbine output
3. Operates in a wet steam environment
4. Must operate in a variable load, flow, and exhaust pressure environments

In 1987, a development project was undertaken to redesign the 23" last stage bucket using modern state-of-the-art technology (Figure 10). The redesigned 23" last stage bucket (Figure 11), which can be retrofit into existing units, has design features that are beneficial for utility, industrial, and combined-cycle applications as follows:

Aerodynamic Design

The redesign has accomplished the same high level of efficiency found on GE's modern longer stage bucket through

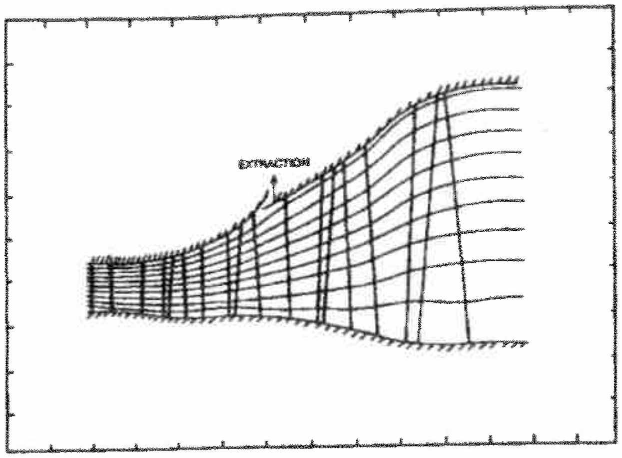


Figure 10. 23" Low Pressure Turbine 3-D Flow Analysis

Figure 11. Redesigned 23" Last Stage Buckets

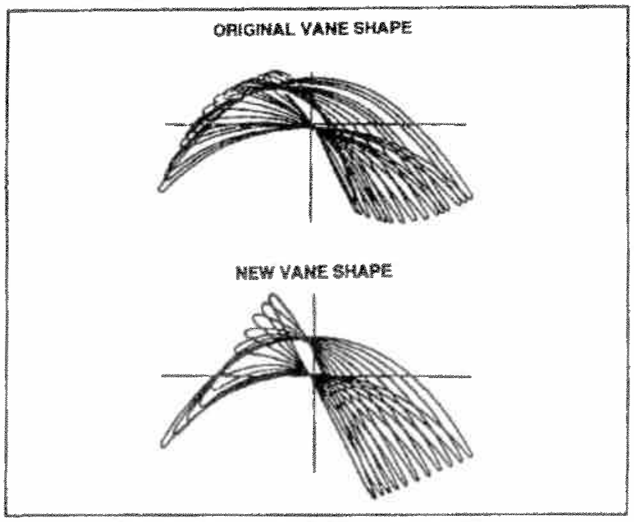


Figure 12. New Redesigned 23" Last Stage

bucket vane section aerodynamic design, raising root reaction, and better tip leakage control, while optimizing stage radial flow distributions. Heat rate improvements as much as 0.9% are predicted when replacing the original 23" last stage bucket.

Advances in manufacturing technology since the 23" bucket was first introduced allow use of an improved bucket dovetail design, which in turn permits improved bucket flow passage geometry (Figure 12). Current analytical techniques permit more accurate determination of, and reduction in flow incidence angle losses, and also result in a more efficient transonic tip design, minimizing shock losses (Figure 13).

Vane tip leakage control currently used on in-service 23" last stage buckets is shown in Figure 14. The redesigned tip (Figure 15), provides sealing against steam leakage while permitting moisture to flow out over the bucket tip in a film along the end wall. Much of the moisture is contained in this film; therefore, the tendency to erode the bucket covers and outer vane sections has been sharply reduced. This is of particular value for nonreheat application found in combined-cycle plants.

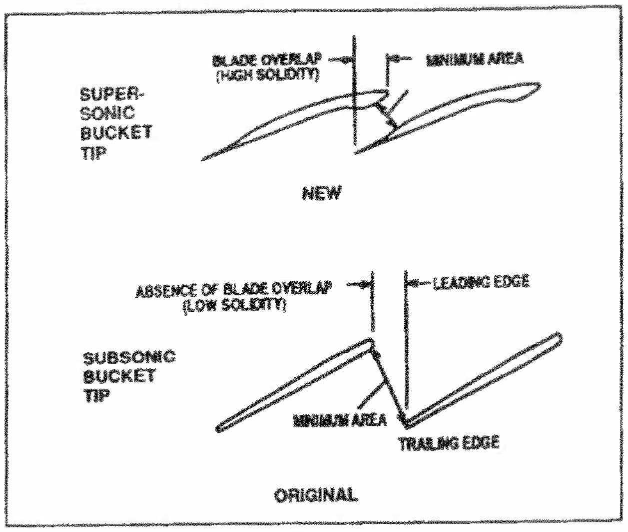


Figure 13. New Redesigned GE 23" Last Stage Bucket Tip Comparison

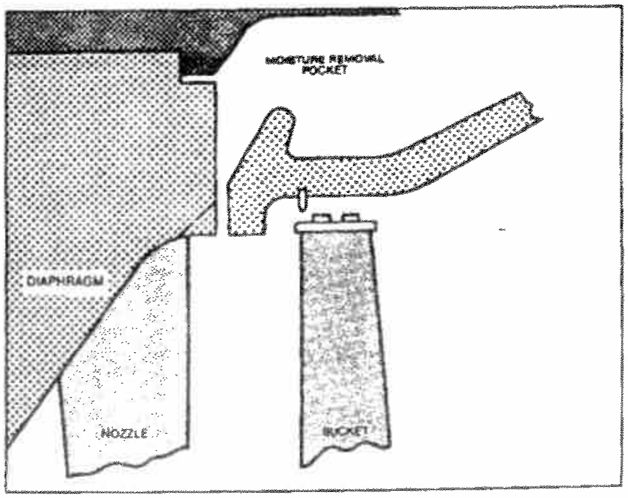


Figure 14. Typical Current 23" Tip Leakage Control and Moisture Removal

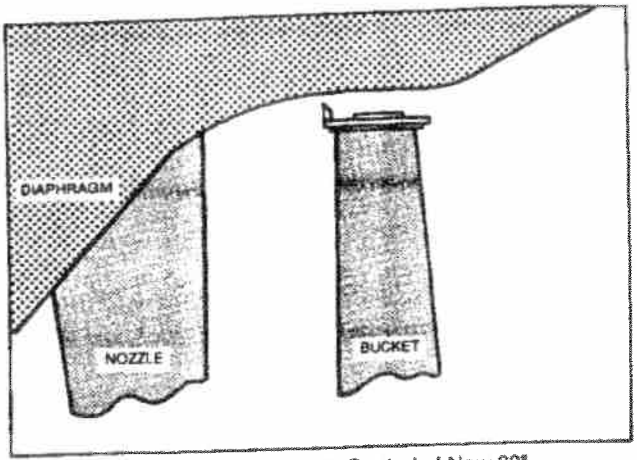


Figure 15. Tip Leakage Control of New 23" Bucket and New Diaphragm

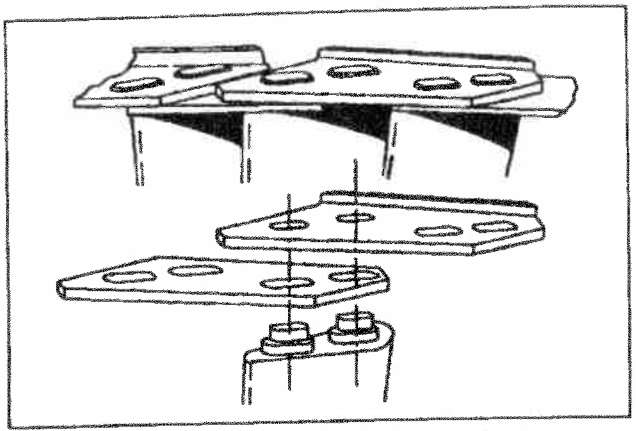


Figure 16. New Redesigned GE 23" Last Stage Bucket Cover Design Continuous Over-Under Construction

Mechanical Design

Last stage buckets experience a wide range of exhaust pressures and loads in service. This wide variety of operating conditions occasionally exposes the bucket to strong dynamic forces. Bucket stiffness, damping, and coupling must prevent strong bucket response to these forces. The redesigned 23" last stage bucket uses a continually-coupled cover design (Figure 16) and a three-piece loose tie-wire to achieve bucket response suppression and mechanical damping. These features minimize the risk of damaging responses during off-design point operation.

The larger tip chord length and continuously-coupled over-and-under cover design increases the bucket and dovetail centrifugal loads. To minimize this effect and yet maintain satisfactory cover strengths, the cover is made from titanium material. In addition, the bucket is made from high-strength, erosion-resistant bucket material.

Last Stage Nozzle

The redesigned 23" last stage nozzle can be retrofit into existing turbines. This nozzle can contribute an additional 0.1-0.4% heat rate improvement when used in conjunction with the redesigned 23" last stage bucket. More precise estimates can be predicted on a unit-by-unit basis.

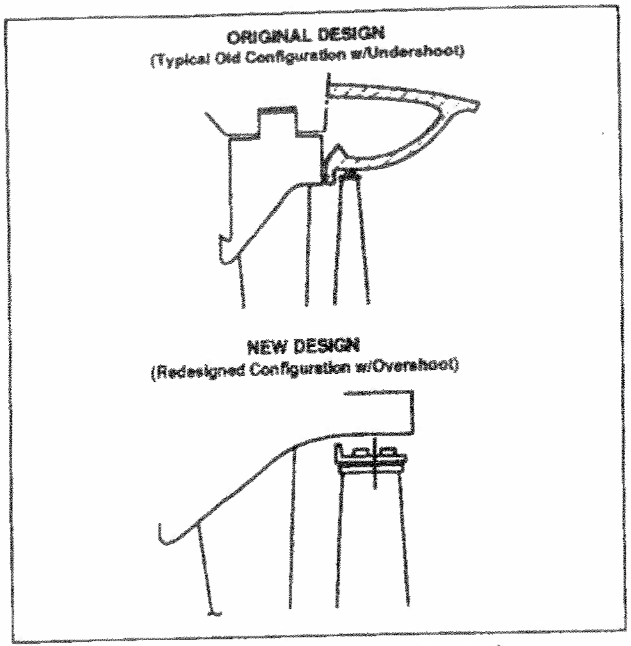


Figure 17. New Redesigned GE 23" Last Stage

The new nozzle redistributes the low-pressure turbine energy in order to improve last stage root reaction. The original 23" last stage has a nearly flat radial flow distribution, while the new design shifts more flow to regions of the stage where efficiency is the highest. This provides a major part of the contributions of the nozzles to heat rate improvement. The use of the nozzle design was verified by 3-dimensional through-flow calculations, as shown in Figure 10.

This nozzle design, together with overshoot construction in the outer wall (Figure 17), permits use of a sealing rib on the bucket cover (Figure 15) which greatly reduces tip leakage loss when compared with the older design (Figure 14). The redesigned nozzle configuration together with the overshoot construction of the outer wall is also predicted to reduce erosion at the bucket leading edge.

SUMMARY

Retrofit of GE advance-technology steam and gas turbine components into MMWEC's Stony Brook Energy Center GE STAG™ 307E Combined-Cycle Power Plant (AIP) began in March, 1991. This program is expected to improve plant availability by approximately 2% (points) and improve combined-cycle power plant summer month output by 5.7% when completed in 1993.

Performance testing completed for MMWEC gas turbine unit 1C after March, 1991 retrofit with gas turbine AIP components, demonstrates more than the expected summer month output and heat rate improvement of 6.1% and 1.1%, respectively. MMWEC is expecting to retrofit a second of their gas turbines and their steam turbine with AIP components in spring, 1992.

MMWEC's modernization of their combined-cycle power plant will result in availability approaching those of now fourth-generation STAG™ power plants.