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INDUSTRIAL GAS TURBINE UPRATES: TIPS, TRICKS AND TRAPS

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ABSTRACT

After industrial gas turbines have been in production for some amount of time, there is often an opportunity to improve or "uprate" the engine's output power or cycle efficiency or both. In most cases, the manufacturer would like to provide these uprates without compromising the proven reliability and durability of the product. Further, the manufacturer would like the development of this "Uprate" to be low cost, low risk and result in an improvement in "customer value" over that of the original design. This paper describes several options available for enhancing the performance of an existing industrial gas turbine engine and discusses the implications for each option. Advantages and disadvantages of each option are given along with considerations that should be taken into account in selecting one option over another.

Specific options discussed include dimensional scaling, improving component efficiencies, increasing massflow, compressor zero staging, increasing firing temperature (thermal uprate), adding a recuperator, increasing cycle pressure ratio, and converting to a single shaft design. The implications on output power, cycle efficiency, off-design performance engine life or time between overhaul (TBO), engine cost, development time and cost, auxiliary requirements and product support issues are discussed. Several examples are provided where these options have been successfully implemented in industrial gas turbine engines.

INTRODUCTION

High on every gas turbine manufacturer's priority list are "Continuous Improvements". "Continuous Improvements" apply to every phase of the business process; technologies, products, processes and business relationships. This paper will discuss "Product Improvements" and specifically those programs that improve engine output power and/or efficiency. These engine improvements are often referred to as engine "Uprates", but are also referred to as "Product Improvements" or "Product Improvement Programs" (PIP's). Regardless of what name they go by, these programs have always been and will continue to be a major part of the gas turbine engine business.

The authors earlier personal experience working on aircraft engine designs, indicated that aircraft power requirements tend to increase with time. This seemed to happen in the aircraft design and development phase when the total drag and total weight inevitably came out higher than projected and even after the aircraft was in production when mission requirements were expanded. Even after an aircraft was in service and mature, competitive and economic forces always dictated a need for more power and improved fuel efficiency while not compromising cost. A similar trend seems to exist with industrial gas turbines. Regardless of the power size or application, customers' power needs tend to increase with time. Also, every user's need to improve profits puts pressure on industrial gas turbine suppliers to reduce fuel consumption and improve cost per unit of power, both on first cost and life cycle cost basis. This paper describes several methods for improving the performance of a mature industrial gas turbine engines. Both the advantages and disadvantages are discussed along with general comments on relative risks and impact on costs. Some modifications such as steam injection are not covered believing that these options are well understood.

For comparison purposes a fictional industrial gas turbine engine, which will be called the "Base Engine", is described and used as a basis for comparison between the different uprate methods. This will allow the performance improvements to be quantified and the different methods to be compared. Quantitatively, these improvements cannot be translated directly to other engines but their trends in performance improvements, cost impacts and risk should apply to most of todays industrial engines.

The incentive behind most engine uprates is to be able to offer more value to the gas turbine end users. In evaluating a performance uprate to an engine with an established reputation, customers will first want to know how engine durability will be effected. In most cases, customers are not willing to accept noticeable reductions in either reliability, availability or maintainability (RAM). Therefore, uprates that are perceived as putting established durability at risk will be more difficult to get accepted in the market place. This is why maintaining or improving existing durability is a key goal in all uprate programs.

BASE ENGINE

To help make the discussion more meaningful, a fictional engine will be defined which will be called the "Base Engine". We will assume that

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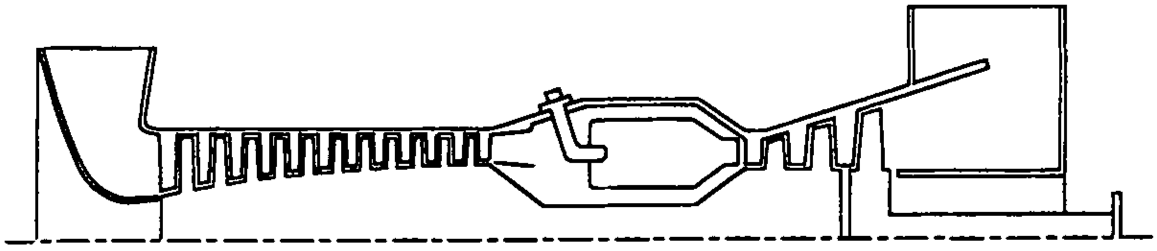

FIG. 1 - SCHEMATIC OF FICTIONAL BASE ENGINE

this engine is a mature product that was designed about 15 years ago with a good durability record and a good initial cost basis. As with most engines of this type, it can be assumed that it does not have state-of-the-art component or cycle efficiencies, and that it does not take advantage of the most recent materials and manufacturing developments. A schematic of this base engine is shown in Figure 1. The main cycle parameters for this "Base Engine" are listed below in Table 1.

With this base engine defined, the various options available to provide uprates can now be evaluated.

TABLE 1 - MAIN CYCLE PARAMETERS FOR BASE ENGINE

Cycle Parameter	Value
Compressor Airflow (ω)	50.0 lb/sec (22.7 kg/sec)
Compressor Pressure Ratio (P/P)	10:1
Compressor Efficiency (η_c)	85%
Gas Producer Speed ($N_{G/P}$)	13,500 RPM
Turbine Rotor Inlet Temp. (TRIT)	1900°F (1038°C)
Gas Producer Turbine Efficiency ($\eta_{G/P}$)	88%
Power Turbine Efficiency ($\eta_{P/T}$)	89%
Power Turbine Speed ($N_{P/T}$)	13,000 RPM
Cycle Efficiency (η_{cy})	31.5%
Shaft Output Power (Hp_s)	7800 HP (5816 Kw)

DIMENSIONAL SCALING

One popular method of expanding a product line is "Dimensional Scaling" which has been used successfully by several engine manufacturers. The goal of dimensional scaling is to get a different size engine, usually larger (but can be smaller), that requires minimal development and retains the proven durability of the existing design. In its simplest form, "Dimensional Scaling", means that all the linear dimensions of an existing design are scaled (usually up) by a constant factor. The general rules of scaling are shown in Table 2.

TABLE 2 - RULES OF SCALING

1. Linear dimensions scale directly with the scale factor.
2. Rotor speeds scale inversely with the scale factor.
3. Flows scale with the square of the scale factor.
4. Power scales with the square of the scale factor.
5. Weight and volume scale with the cube of the scale factor.

When these rules of scaling are followed, most of the original aerodynamics and most of the original mechanical safety margins are not changed. This means that the original aerodynamic values of Mach numbers, velocity triangles, gas temperatures and gas pressures are maintained in the new design. It also means that the original stress margins and the percent vibration and critical speed margins are maintained.

It would be nice if scaling would be as sample as adding a multiplier to all the drawings, dimensions, but it is not that simple. One important area of the design that doesn't scale is heat transfer characteristics, especially in the turbine cooling system. This area always has to be reanalyzed and usually requires some design modifications. However, these modifications can usually be limited to slight changes in the cooling flow percentages and with small to moderate changes to the airfoil cooling passages.

The combustion system may also require some modifications. The scaled combustor case and combustor liner will usually work fine, but the amount and size of the liner dilution holes may require further modifications if the radial temperature profile entering the first blade is to be maintained. In order to maintain or improve the original combustor exit pattern factor, the design of and the number of fuel injectors may also need to be changed. Scaling up a Dry Low NOx (DLN) combustor may require a significant amount of redesign.

Any area of the design that uses standard hardware such as fasteners, tubing, connectors, etc. will usually need to be modified to accommodate available standard parts that are close to the scaled sizes.

From the rules of scaling, one would expect the power to be changed by the square of the scale factor and the cycle efficiency to remain unchanged. In practice, however, there are size affected dimensions that will have small effects on performance. Mechanical tolerances and surface finishes usually don't scale. Mechanical tolerances can usually be improved as a design is scaled up and airfoil surface finishes can usually be kept the same as airfoils are scaled up. Tip clearances and seal clearances may or may not scale depending on what mechanism sets the minimum values. Also, airfoil leading and trailing edge thicknesses usually have a minimum value in order to maintain adequate material properties. When airfoils are scaled up there is often a chance to reduce leading and trailing edges as a percentage of chord, thus improving airfoil efficiencies. Just the opposite happens when airfoils are scaled down. Often the scaled down leading and trailing edge values are too small to maintain adequate material properties during casting or they become very expensive to manufacture and must be increased which usually results in a slight performance penalty.

This leads to one of the subtle traps of dimensional scaling. It is nearly impossible to complete a scaled design without finding things in the design that can to be improved. Many of these changes are legitimate and some are "Must Do's", but the design team must be careful not to take on

TABLE 3 - APPROXIMATE PERFORMANCE FOR A 1.5X BASE ENGINE

	Original	1.5X Scale (Direct)	1.5X Scale (Improved)
Output Power	7800 Hp (5816 Kw)	17,550 Hp (13,087 Kw)	17,900 Hp (13,348 Kw)
Cycle Eff.	31.5%	31.5%	32.0%
Airflow	50.0 lb/sec (22.7 Kg/sec)	112.5 lb/sec (51.0 Kg/sec)	113.0 lb/sec (51.3 Kg/sec)

so many "Design Improvements" that they lose the proven integrity of the original design and at the same time exceed their design and development schedule and budget.

If we were to apply a 1.5 scale factor to our base engine we would expect to get an engine that is 50% longer with 50% larger diameters that would have performance of 17,550 Hp (13,087 Kw) and 31.5% cycle efficiency as shown in Table 3.

If we make some allowances for size effects (reduced tip clearances, constant surface finish and reduced leakages through improved tolerances) on performance, we should be able to get around 17,900 Hp (13,348 Kw) at a cycle efficiency of 32.0%.

Figure 2 shows an isometric view of a 1.5X scaled airfoil and Figure 3 shows a schematic view of the original engine and a 1.5X scale of that schematic. These figures are included to point out that the volume of a part like the volume of an engine increases by the cube of the linear scaling factor.

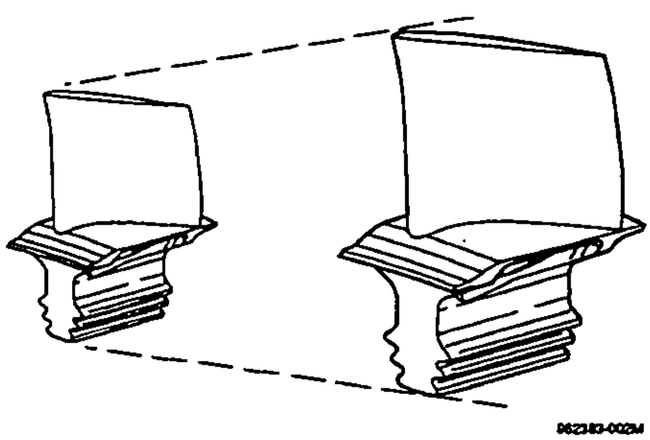

FIG. 2 - COMPARISON OF A BASE AIRFOIL AND A 1.5X SCALED AIRFOIL

One additional factor that doesn't scale is the manufacture's recurring engine cost. This cost is a very difficult factor to predict and each project will have to be evaluated independently. It stands to reason, however, that by scaling an engine up, the cost per unit of power (dollars per horsepower) should decrease. Figure 4 can be used to understand the trends in engine cost as a given design is scaled up or down. This figure indicates that for a given design, (i.e. fixed complexity and technology level) the cost per unit of power decreases as the engine gets larger. The rate at which cost decreases will depend on the technology level or complexity of the design. Figure 4 also helps explain why we see the most advanced technologies in the largest engines. When new but expensive technologies become available, it is usually more cost effective to apply these technologies in the larger engines first.

COMPONENT EFFICIENCY IMPROVEMENTS

As analytical tools, design methods and manufacturing processes advance, it is often possible to improve the efficiency of one or more components of a mature design. Referring back to our "Base Engine", we can examine the results of various component improvements. If we assume a 1.0% efficiency improvement in the compressor, the gas producer turbine and the power turbine we can generate the values shown in Table 4. This table gives the performance improvements of our "Base Engine" if these improvements were made individually and if they were made concurrently.

For these methods of increasing performance to be attractive the components in the existing design must first of all have room to be improved. Also, the cost of these improvements must be justified by the performance gains. If, for example, a completely new compressor must be designed and developed just to pick up one point in efficiency, this effort would be hard to justify. On the other hand, if one point in compressor efficiency could be gained just by reducing tip clearances and seal leakages, this might be easy to justify.

A good example of the latter is what Solar Turbines Incorporated did with their latest Taurus™ 60 uprate (Van Leuven, 1994). This engine was uprated from the T6500 model to the T7000 model with a power increase of 7.1% from 6500 Hp (4847 Kw) to 6960 Hp (5190 Kw) and with a 3.1% reduction in heatrate. This was accomplished primarily by tip clearance reductions in the compressor and turbine sections plus about a 3.4% increase in flow obtained by slightly untwisting the first compressor blade. This uprate was successful because it provided improved performance while maintaining the engine's proven durability. The recurring cost was kept low because minimal changes were made to only a few parts. The products durability was maintained because there was no change in firing temperature and other operating conditions remained essentially the same.

INCREASED AIRFLOW

If the airflow of an engine can be increased without a significant falloff in component efficiencies, the engine's power will increase and the engines durability can usually be maintained. This is usually done by increasing the flowpath height in the first few compressor stages. This may also be accomplished by other means such as redesigning the first stage airfoils, untwisting the compressor first stage blades, setting the first stage blades at an increased broach angle and sometimes by simply opening up the compressors inlet guide vanes (IGV's). These procedures are sometime referred to as "High-Flowing" a compressor.

These types of uprates are usually limited to under 10% flow increases. These uprates are usually successful because minimal amounts of parts are changed and the core part of the engine operates at conditions very near to those of the original engine. There are some conditions, however, that can restrict the use of this uprating method.

First of all, the compressor must have adequate surge margin to accommodate the increased pressure ratio that goes with the increased

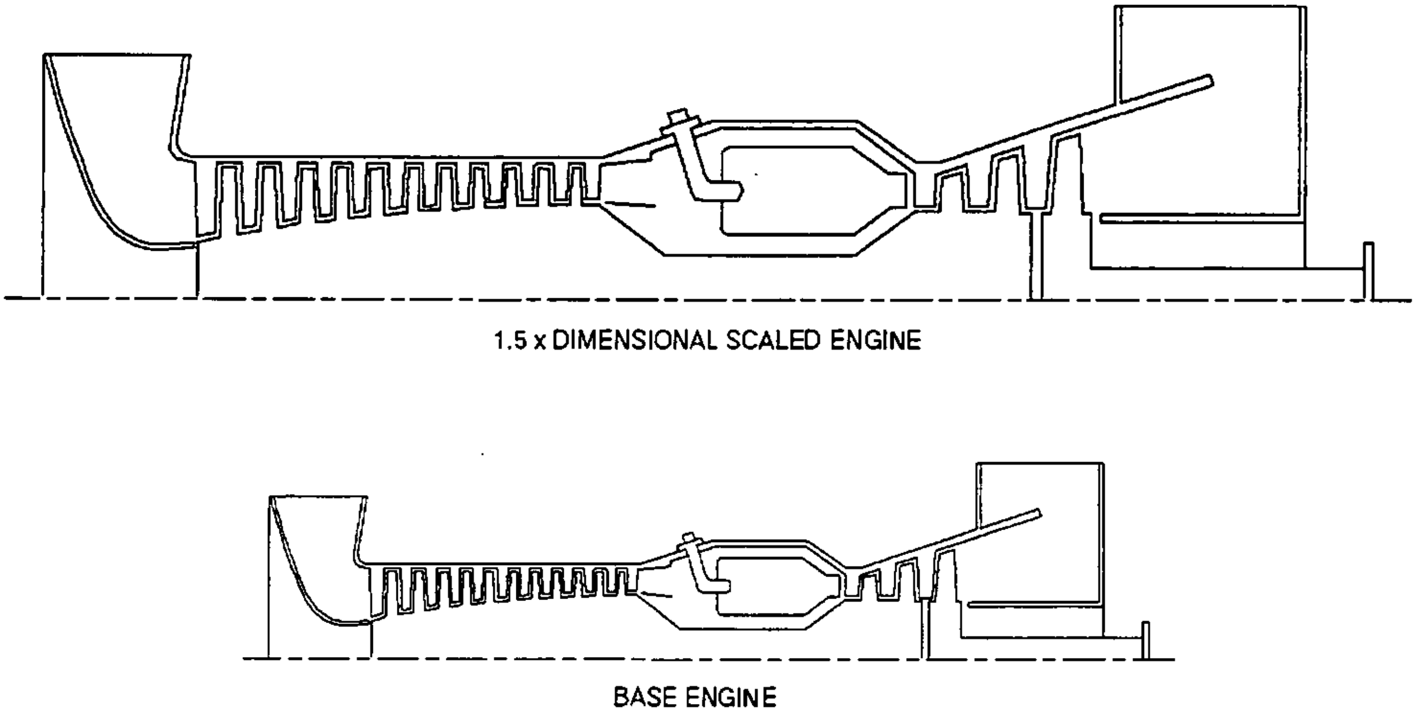

FIG. 3 - RELATIVE COMPARISON OF THE BASE ENGINE AND A 1.5X SCALED UP VERSION

TABLE 4 - BASE ENGINE IMPROVEMENTS WITH COMPONENT EFFICIENCY IMPROVEMENTS

Component	Eff. Improvement	Power Increase	Cycle Eff. Incrse.
Compressor Eff.	1.0% Point	+1.4%, 113 Hp (84 Kw)	0.31 points (1.0%)
G/P Turbine Eff.	1.0% Point	+1.1%, 84 Hp (63 Kw)	0.34 points (1.1%)
Power Turbine Eff.	1.0% Point	+1.1%, 88 Hp (66 Kw)	0.35 points (1.1%)
All Three Improvements Combined		+3.6%, 285 Hp (213 Kw)	1.00 points (3.2%)

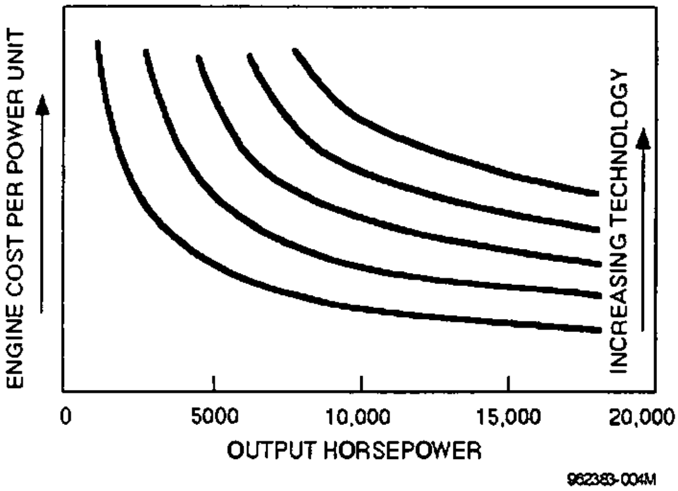

FIG. 4 - ENGINE RECURRING COST TRENDS

airflow. If the gas producer turbine remains unchanged and the firing temperature is kept the same, then the engine pressure ratio will increase proportional to the airflow increase. This could reduce the compressor's surge margin to an unacceptablelevel. Other results of the increased pressure ratio are increased loads on the thrust bearings and a slightly higher cooling air temperature.

Another often overlooked effect of this "High Flowing" method of uprating engines is the impact on performance at high ambient temperatures. Usually the front end of a compressor can be redesigned to provide the additional flow without a major loss in compressor efficiency at design point but not at all off design points. A typical compressor map is shown in Figure 5. With this type of map, it is easy to see that we would expect compressor efficiencies to increase slightly as we move down the operating line. The compressor map shown in Figure 6 shows what tends to happen when the front end of a compressor is redesigned for increased airflow but the remaining stages are not redesigned and must operate off-design. With this type of compressor map, efficiency actually drops slightly

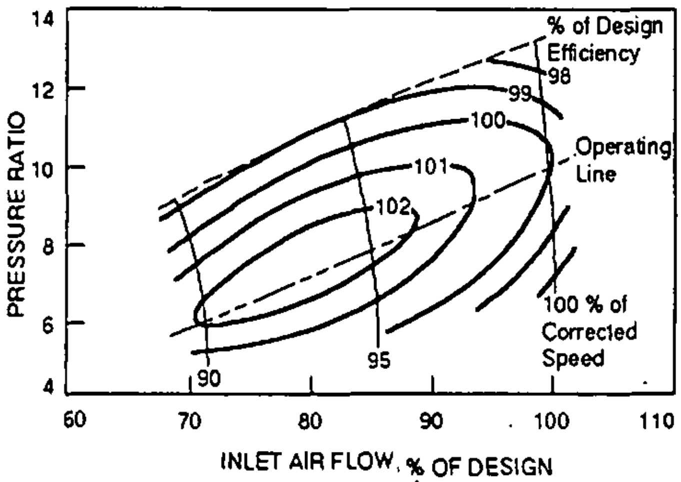

FIG. 5 - TYPICAL COMPRESSOR MAP

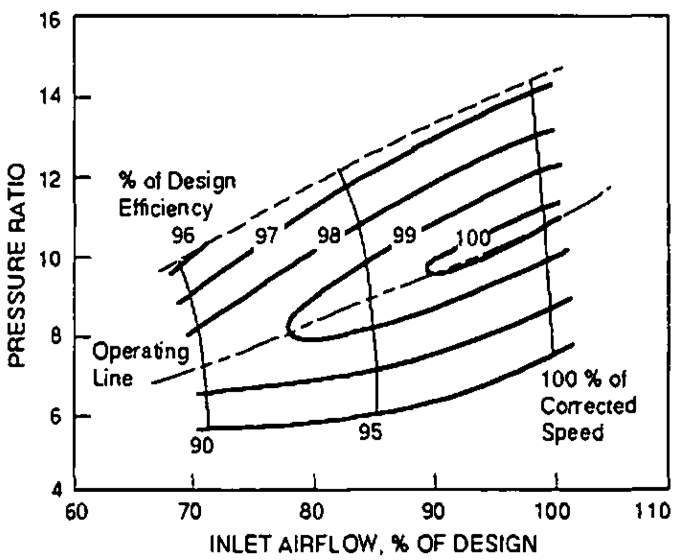

FIG. 6 - TYPICAL HIGH FLOWED COMPRESSOR MAP

as we move down the operating line. Figure 7 shows how the compressor efficiency curves of a typical compressor and a "High Flowed" compressor tend to compare. What this means is that uprated engines with a "High Flowed" compressor may not produce the same percentage improvement in engine performance at 122°F (50°C) ambients as they do at 59°F (15°C) ambients. Solar Turbines has been successful in recovering most of the extra falloff in high ambient performance by using a variable guide vane control system. This control system keeps the gas producer speed up near 100% mechanical speed at ambients above 59°F (15°C).

A "High Flowed" compressor will also have an effect on the turbine section. The flow rate entering the gas producer turbine will go up but the pressure will go up by the same proportion and since the firing temperature remains unchanged, the Mach number entering this turbine will be essentially unchanged. Almost all of the increased pressure ratio available for the full turbine section will be required by the gas producer turbine to provide the extra power required to drive the higher pressure ratio compressor. The results is that this turbine will operate at a slightly higher

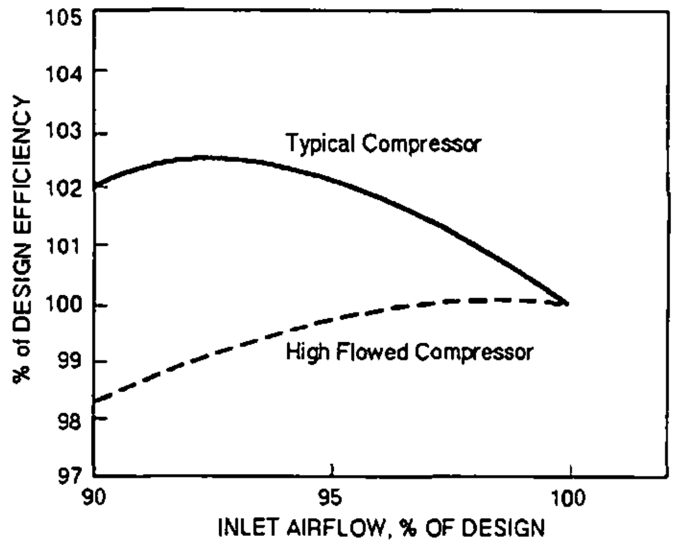

FIG. 7 - COMPARISON OF COMPESSOR OPERATING LINE EFFICIENCY

pressure ratio but shouldn't experience a large drop off in efficiency at its new operating conditions.

The power turbine will see the increased flow at almost its original pressure levels since the gas producer turbine requires most of the cycles increased pressure ratio. Also, since the engine's firing temperature stays the same, the temperature entering the power turbine will only be slightly reduced due to the increased pressure drop through the gas producer turbine. As a result, the Mach numbers throughout the power turbine will increase and the power turbine efficiency levels will usually drop off more than for the gas producer turbine. Increased losses may also be experienced in the exhaust diffuser and collector section due to the increased velocities.

Anytime the pressure ratio of an engine is increased without increasing the firing temperature, the temperature of the exhaust gas will be reduced. In this uprate option, the engine exhaust conditions will change to reflect the increased airflow but at a slightly reduced temperature.

In evaluating this "High Flowed" concept for a performance uprate, the design team must decide how much additional airflow can be designed for before the component losses reach the point where the uprate doesn't make sense.

Looking at a possible "High Flowed" compressor uprate for our base engine we might try to increase the airflow by 5.0% by redesigning the first two compressor stages with a slightly opened up flowpath. We should be able to hold the design point efficiency of the compressor but we could loose 0.1% efficiency in the gas producer turbine and 0.5% in the power turbine. With these assumptions, our base engine performance should increase by 340 Hp (254 Kw)/ (4.4%) with a slight improvement in heatrate (0.5%). The exhaust gas temperature would be decreasd by 11°F (5°C).

This is the uprate method that was selected by Solar Turbines for the latest Mars™ 90 and Mars 100 uprates. In this case, the first two compressor airfoil stages and the IGV were redesigned for a slightly more open flowpath and no other parts in the engine were changed. For the Mars 100 engine, the T14000 model was uprated to the T15000 model. This resulted in almost 9% more flow and a performance increase of 900 Hp (671 Kw)/(6.4%) and a heatrate improvement of 1.5%. The compressor efficiency in the uprated engine actually increased by 0.6 percentage points as a result of using more modern aerodynamic design tools. The overall turbine efficiency dropped by 0.25 points and the compressor pressure ratio increased from 16:1 to 17.4:1. This engine did not get the same percentage improvement at the high ambient conditions as it did at 59°F (15°C) but by implementing compressor variable guide vane controls, the engine achieved a power gain of 5.0% at 122°F (50°C) ambients.

ZERO STAGING

The process of adding an axial compressor stage in front of an existing compressor has commonly been referred to as "Zero Staging". To avoid having to rename many existing parts and changing even more drawings, this new stage has usually been called stage zero or the "Zero Stage".

The main principal behind this type of uprate is to try to increase the output of an existing engine with few or no changes to the center core of the engine. The center core is almost always the most expensive, the most development intensive and the most durability limiting section of a turbine engine. The aircraft engine industry has used this basic principle very successfully by using a well proven, high pressure core and matching it with several different size fans and low pressure turbines.

By the use of "Zero Staging", an engine's performance can usually be increased with minor or no changes to the existing compressor, the combustor and the gas producer turbine. This is usually done by adding a single axial stage in front of the compressor and opening up or completely redesigning the power turbine. This approach results in an engine program that needs to develop a single axial compressor stage and a new or modified power turbine. Both of these tasks are usually fairly predictable and relatively low risk. When these new components are applied to the existing engine, the results can be a new engine that has a large number of parts in common with the original engine and a percentage cost increase that is much less than the percentage increase in power.

The durability of the new engine can usually be maintained close to that of the engine being uprated. This is done primarily by keeping the firing temperature unchanged. Even though the pressure levels in the high pressure area of the engine will be increased and thrust loads will go up, the Mach numbers will stay about the same and the temperature levels in the high pressure turbine area will stay about the same. This helps maintain the proven durability of the original design because the high pressure and high temperature sections of the engine (the engine core) are relatively unchanged and this is the engine's most durability sensitive section.

When adding a zero stage to an existing compressor, it would be ideal if the mechanical speed of the gas producer shaft could be increased so that the corrected speed (RPM/ $\sqrt{\text{Temp}}$) at the inlet to what was originally the first stage remained unchanged. This would keep all the velocity triangles and corrected conditions throughout the compressor unchanged. This would require that the original design have a 3 to 4% speed margin in the gas producer spool. This usually isn't available unless the original design took into account the need for a "Zero Stage" uprate at some future date. Even if no increase in mechanical speed is possible, a "Zero Stage" design should be able to increase the compressor's airflow by about 20% without a significant falloff in compressor design point efficiency.

When a "Zero Stage" is applied to an existing engine, the original components react in the same manner as they do with the "High Flow" option described above but to an even greater extent. With the original compressor stages running at the original mechanical speed but with the increased flow they will be running off-design and some drop in compressor efficiency should be expected.

With the gas producer turbine unchanged and with the same firing temperature, the cycle pressure ratio will increase in proportion to the airflow. This means that the combustor will operate at a higher pressure but the Mach numbers will be about the same. The combustor may work in the new engine cycle with only modifications to the fuel injectors. DLN combustors, however, will probably require further modifications.

The aerodynamic conditions entering the gas producer turbine will be about the same as in the original engine but with an increased pressure ratio across the turbine. With this increased loading in the gas producer turbine section, the efficiency will probably decrease somewhat but not drastically. The power turbine, however, will be heavily impacted. The velocities throughout the power turbine will increase and the velocities entering the diffuser/collector section will increase almost in proportion to the flow increase. It is unrealistic to expect the efficiency of the power turbine not to fall off.

When an engine is uprated by "Zero Staging", the power turbine will usually have to be redesigned. At least the flowpath annulus area needs to be increased to get low loss velocities through the turbine and the diffuser/collector section. In some cases an additional turbine stage may need to be added and the shaft speed reduced in order to get reasonable power turbine efficiencies. The reduced output shaft speed may actually help since driven equipment at a higher power range usually wants to run a bit slower.

To see what a "Zero Staged" uprate option could do for our "Base Engine", we can assume that the "Zero Stage" will increase airflow by 20% but must run at the original mechanical speed. Under these conditions, the compressor efficiency may drop by 1.0%. The gas producer turbine will also drop in efficiency but only about 0.3%. We will assume that the power turbine can be redesigned and opened up so that the total-to-static efficiency of the power turbine and diffuser/collector system will not change. If these assumptions can be met, we should have an uprated engine with a 1350 Hp (1007 Kw)/ (+17.3%) increase in power with a little over 2.0% improved heatrate. The exhaust conditions would have 20% more massflow but the gas temperature would be reduced by 50°F (28°C).

The Taurus 60 product was created at Solar by "Zero Staging" the Centaur™ 50 engine. In addition to the "Zero Staged" compressor, the only other major modification to the Centaur 50 engine was a new power turbine. A lower speed, two-stage power turbine was designed for the two-shaft Taurus 60 and a single, more open, third turbine stage was designed for the single-shaft version. The last eleven compressor stages, the combustor section and the gas producer turbine are all identical on these two engines.

The "Zero Staged" compressor provided an increase in airflow of approximately 17%. This increased airflow and the corresponding cycle pressure ratio increase from 9.5:1 to 11:1 combined with a more efficient power turbine to produce a power increase of 1000 Hp (746 Kw)/(+18.2%) and a heatrate reduction of 5.3%.

By keeping the firing temperature of these two engines the same, it was felt that the durability of the "Zero Staged" Taurus 60 engine would be as good as it was on the developed Centaur 50 engine and this turned out to be true.

INCREASED FIRING TEMPERATURE

Probably the most common way of uprating gas turbine engines is by increasing the firing temperature (thermal uprate). The main attraction of this method is that the increased performance usually comes with no change in external dimensions. This makes the uprate very attractive for retrofitting into existing installations.

From a manufacturer's point of view this can be one of the more difficult uprates to develop. In many cases a manufacturer will introduce a new engine at a derated firing temperature to build up field experience to identify any weak areas in the hot section. After the engine has enough field experience to identify any weakness in the hot section design and these weaknesses, if any, have been corrected, it is then easy to increase the firing temperature to the original design level. This should not be considered a true thermal uprate.

In other cases the firing temperature of an existing engine may be increased by upgrading the material of the life limiting part or parts of the hot section. For example, if the first stage turbine blade is the life limiting part of an existing design, it may be possible to change from a normally cast material to a single crystal alloy and then allow a higher firing temperature. These types of uprates can usually be done with low risk to the durability of the engine as long as temperature increase are small and the other hot section parts have adequate life margins.

For a substantial increase in firing temperature of a mature engine, the gas producer turbine and its airfoil cooling system usually have to be redesigned. This type of uprate usually carries extra cost, risk and development time. In most cases, the turbine aerodynamics have to be redesigned, additional airfoil rows require cooling, the airfoil cooling schemes have to be redesigned, materials often have to be upgraded, the gas producer turbine flowpath may have to be changed plus the power turbine has to be modified or even redesigned.

As an example, we could look at what would be involved in doing a thermal uprate for our "Base Engine". For this example we will assume that we want to increase the turbine rotor inlet temperature (TRIT) from 1900°F (1038°C) to 2100°F (1149°C). To retain the engine retrofitable option we will assume that we want to keep the engine outside dimension unchanged. With this amount of change in TRIT, the gas producer turbine and power turbine will need to be redesigned. In addition to cooling the first turbine nozzle and rotor, the second turbine nozzle will now have to be cooled. The combustor case can probably be saved, but the combustor liner will have to be redesigned or at least modified.

With new state-of-the-art design tools, we should be able to improve the aerodynamics of the turbine section. In the gas producer turbine section however, the increased amount of cooling air will hurt efficiency so we will probably end up with no gain in gas producer turbine efficiency. Similarly with the power turbine, we should be able to improve the total-to-total efficiency at optimum speed, but most likely the optimum aerodynamic speed will be beyond the maximum mechanical speed for this single stage power turbine. Figure 8 shows an extreme case of what can happen to the efficiency of a single stage power turbine due to a thermal uprate. We could solve the problem by going to a two stage power turbine, but this would need to run slower and would probably change the engines outside dimensions, both of which would impact our retrofitable options. Also, with the higher firing temperature, the velocities leaving the power turbine will probably be increased which will go against the total-to-static efficiency of the power turbine and diffuser/collector system. For this example, we will assume that we end up with the same total-to-static efficiency for the power turbine and diffuser/collector system. Making some reasonable assumptions for the amount of additional cooling air required we could expect this thermal uprate option to produce performance improvement of 1100 HP (820 Kw)/(14.1%) with a reduction in heatrate of about 2.0% plus an increase in exhaust gas temperature of about 85°F (29°C) to aid in heat recovery applications.

Thermal uprates in one form or another have been applied to almost all of Solar Turbine's mature engine products. Over the years probably the most aggressive thermal uprate program at Solar was in uprating the Centaur 40 engine to the Centaur 50 model (Padgett, 1985). In this program, the compressor sections remained relatively unchanged but the combustion and turbine sections were redesigned to allow the TRIT to be raised from 1660°F (904°C) to 1850°F (1010°C). This major redesign job of the combustion and turbine sections required new materials, the addition

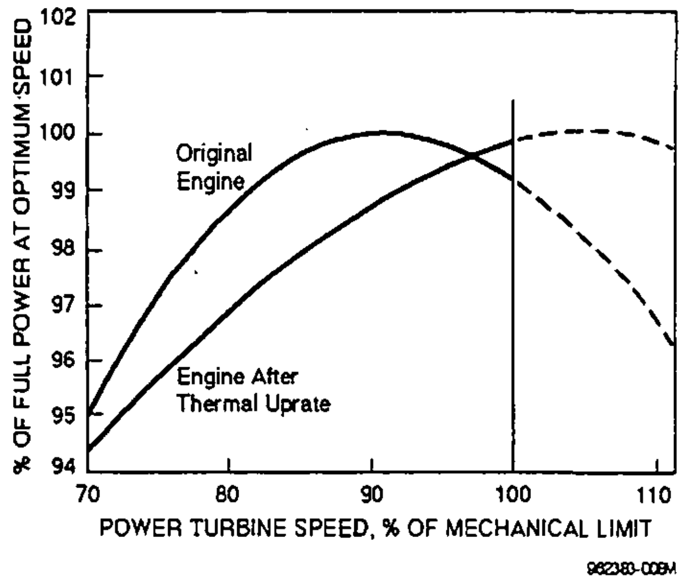

FIG. 8 - COMPARISON OF POSSIBLE FULL LOAD VS SPEED CURVES

of a cooled first stage turbine blade row, and a much more complicated secondary cooling system. The payoff for this effort, however, was a new Centaur 50 engine at almost exactly the same size as the Centaur 40 engine but with improved power output of almost 1000 HP (746 Kw)/(21%) and a 3.9% reduction in heatrate with a 120°F (49°C) increase in exhaust gas temperature.

ADDING A RECUPERATOR

Some engines lend themselves to being fitted with a recuperator to increase cycle efficiency. For this to work, the turbine exhaust temperature must be higher than the compressor exit temperature since the recuperator uses the turbine exhaust to pre-heat the compressor exit air before it enters the combustor. In very high pressure ratio engines, this might not be the case.

If the cycle conditions allow a recuperator to be added, the compressor section and the turbine section can usually be used as is. The major changes happen in the middle of the engine. A collector must be added at the compressor exit, a recuperator must be designed, and piping must be added to get the air from the compressor collector to the recuperator and from the recuperator back to the combustor. The combustor will usually have to be modified or redesigned since the temperature entering the combustion section will be hotter than in the original design. The turbine exhaust system will have to be redesigned to best transport the turbine exhaust gas to the recuperator face and provide a near uniform profile. One system redesign that is often overlooked when considering adding a recuperator is the secondary flow system. With a recuperator, cooling air can no longer be drawn from the plenum outside the combustor liner without redesigning the cooling system to operate with higher flows and higher temperature cooling air. In most cases it will be easier to route compressor discharge air around the recuperator and combustor through external pipes.

Most simple cycle engines operate at a pressure ratio that is too high for an optimum recuperator cycle. While many engines can have improved cycle efficiency when a recuperator is added, the efficiency level will usually be far less than the 40%+ level that is possible with an optimum recuperator cycle design.

Because the recuperator adds pressure losses to the cycle, a simple cycle engine usually sacrifices some power when a recuperator is added due to the lower pressure ratio available for the turbine section.

The "Base Engine" has a turbine exit temperature that is about 320°F (160°C) higher than the compressor exit temperature so a recuperator should improve the efficiency of this cycle. A 90% effective recuperator can be assumed with 2% pressure loss on the air side and 4% on the gas side. To this, 1% loss should be added for piping to and from the recuperator. With these assumptions, the new engine would lose 620 Hp (462 Kw)/(7.9%) but the engines cycle efficiency would increase from 31.5% to 36.8%.

Solar has used this uprate option on versions of the Saturn and Centaur engines. On the Centaur engine, the T3000R version has a recuperator and it gets 14% better heatrate than the simple cycle version but it has 11% less power.

INCREASED CYCLE PRESSURE RATIO

If improved cycle efficiency is needed, adding stages to the back end of the compressor may be considered. An increased cycle pressure ratio is one of the best ways to improve the cycle efficiency of a simple cycle engine. Aerodynamically, adding additional stages to the back end of an existing multiple stage axial compressor is not usually a large risk. Asaft stages are added the flowpath annulus area must decrease leading to smaller airfoil heights. This may cause a compressor efficiency problem if the new airfoil heights get too small to maintain adequate tip clearances.

The engine changes required to increase the cycle pressure ratio by this method can be considerable. When stages are added to the aft end of an existing engine's compressor, the following changes are usually required: a) the compressor shaft gets longer and may cause shaft dynamic problems, b) the velocities in the combustor will be reduced due to the higher operating pressures requiring a new or modified combustor and c) the gas producer turbine will have to be redesigned or extensively modified to accommodate the higher pressure.

We could consider adding three stages to the aft end of our "Base Engine". For this example we will assume that the compressor pressure ratio will increase from 10:1 to 14:1 and that by redesigning the gas producer turbine all our component efficiencies stay the same. If we also assume that we can keep the cooling flow amounts the same, then we should end up with an engine with 7683 Hp (5729 Kw)/(a drop of 1.5%) but with an increase in cycle efficiency from 31.5% to 33.8%. This means that if we can live with the 1.5% drop in maximum power, our heatrate or specific fuel consumption will be reduced by 6.8%.

Solar has never used this uprate option except in combination with some other option because of the large amount of engine parts that must be changed. Not only does this get expensive but any proven durability is usually lost.

CONVERSION TO SINGLE-SHAFT

While not normally done to improve power or heatrate, converting a two-shaft engine to a single-shaft design could be considered an uprate for some applications.

When this is done, it might also be possible to convert to a cold end drive arrangement and eliminate the engine exhaust collector. This can be attractive for generator drives because it simplifies the engine controls and the overall system package.

An ideal engine for this type of conversion would have a one or two stage gas producer turbine and a single-stage power turbine capable of running at or above the speed of the gas producer. If these conditions are met, it should be relatively easy to lock the power turbine rotor to the gas producer rotor, take the power out through the front of the engine and design a straight out turbine diffuser without a collector. The performance of the new single shaft engine, in this case, should be 1% to 2% better than the original two shaft engine due to the reduced diffuser/collector losses.

Converting a two-shaft design to a single-shaft design becomes more difficult with an engine that has a high speed, high flow gas producer section. With this type of gas producer section, it is usually not possible to design the last turbine stage rotor with enough annulus area to get decent efficiency from that stage and reasonable recovery in the turbine diffuser section. For a high efficiency level in the last turbine stage and minimal total pressure loss in the turbine diffuser section, the axial Mach number leaving the turbine should be in the 0.3 to 0.4 range. With a high speed, high flow gas producer section, mechanical limits on the last row of turbine blades restrict the amount of turbine exit area that can be designed for. In some cases, a mechanically sound design could result in turbine exit Mach numbers of 0.7 and higher. Even though the last turbine stage can be designed for these conditions and a longer turbine diffuser can increase the amount of velocity head recovery, the resulting turbine/diffuser section will probably not perform as well as the original turbine/diffuser/collector section on the two-shaft engine. When this happens, the amount of performance loss associated with converting from a two-shaft to a single-shaft design could make the project unattractive.

For our "Base Engine", a conversion to a single-shaft arrangement should be an attractive option. With the power turbine already running at 96% of the gas producer speed, it should only require minor design modifications to allow it to be attached directly to the gas producer turbine. Assuming that the shafting and compressor section can take the additional torque of a cold end drive arrangement, the turbine exhaust collector can be removed and the engine performance should be about 1% better than that of the originating two-shaft design.

COMPLEX CYCLE UPRATES

As the industrial gas turbine suppliers start producing complex cycle engines, the question of how to best provide uprated versions will need to be addressed. There doesn't seem to be enough experience in the industry yet to definitely answer this question. Most recuperated engines in the industrial field are being designed with little or no temperature margin in the high pressure turbine section or in the recuperator section. In these cases, a thermal uprate of the gas producer turbine section would require that additional temperature capability be added to the recuperator section or that the compressor pressure ratio be increased in order to keep the temperature entering the gas side of the recuperator at an acceptable level (Ragland, 1995). This in turn could require that additional pressure capability be added to the recuperator.

As these complex cycle engines become more popular, the industry will be challenged to come up with uprate options that help add value to the product. Variations of the popular uprate options for simple cycle engines will probably emerge. For instance, the high pressure section of a recuperated engine might be used as the core section for an intercooled and recuperated (ICR) engine.

COMPARISON OF OPTIONS

What an uprate program is trying to accomplish and the characteristics of the particular engine being uprated will be the primary factors in deciding what uprate method to choose. There is no one best uprate option that will apply in all cases but several options should be evaluated before a final selection is made.

Our fictional "Base Engine" was used to provide examples of approximate performance improvements that could be obtained with the

TABLE 5 - BASE ENGINE PERFORMANCE IMPROVEMENTS FROM DIFFERENT UPRATE OPTIONS

Uprate Option	Output Power	Cycle Efficiency
Base Engine	7800 Hp (5816 Kw)	31.5%
1.5X Dimensional Scaling	+128%, 17,800 Hp (13,273 Kw)	32.0% (+1.5%)
Component Eff. Improvement	+3.7%, 8085 Hp (6029 Kw)	32.5% (+3.2%)
Increased Airflow	+4.4%, 8140 Hp (6070 Kw)	31.7% (+0.5%)
Zero Staging	+17.3%, 9150 Hp (6823 Kw)	32.1% (+2.0%)
Increased Firing Temperature	+14.1%, 8900 Hp (6637 Kw)	32.1% (+2.0%)
Add A Recuperator	-7.9%, 7180 Hp (5354 Kw)	36.8% (+16.8%)
Increased Pressure Ratio	-1.5%, 7683 Hp (5729 Kw)	33.8% (+7.3%)
Single-Shaft Conversion	+1.0%, 7878 Hp (5875 Kw)	31.8% (+1.0%)

TABLE 6 - SUBJECTIVE RISK AND COST EVALUATIONS FOR DIFFERENT UPRATE OPTIONS

Uprate Option	Development Risks	Development Costs	Change in Cost Per Power Unit
1.5X Dimensional Scaling	Low	Low	Small Reduction
Component Eff. Improvement	Low/Moderate	Low/Moderate	Reduced
Increased Airflow	Low	Low	Reduced
Zero Staging	Low/Moderate	Low/Moderate	Reduced
Increased Firing Temperature	Moderate/High	Moderate/High	Reduced
Add A Recuperator	Moderate/High	Moderate/High	Increased
Increased Pressure Ratio	Moderate	Moderate/High	Small Increase
Single-Shaft Conversion	Low	Low	Small Reduction

various uprate options. The performance improvements from the different uprate options that were studied for the "Base Engine" are tabulated in Table 5. The quantitative values derived for these examples may not hold up when applied to some other engine, but the trends should be of help when trying to decide what uprate option to select.

While the values in Table 5 are all dependent on the assumptions that we made about what could be done to our fictitious "Base Engine", they can be of some help in understanding the advantages and disadvantages of each option.

Other factors must also be considered when deciding which uprate option to pursue. Table 6 is an attempt to relate the development risk, the development costs and the increased engine costs of the various uprate options for our "Base Engine". Any attempt to generate a table like this must, by nature, be subjective and the evaluations might change for engine configurations that are significantly different from that of our "Base Engine".

The dimensional scaling option is probably best suited for expanding a product line. It is dependent on having an existing engine with good durability and acceptance in the market place. Scaling up an existing design saves design time and reduces the amount of development testing required. There should be some reduction in cost per unit of power and the durability of the original engine should be maintained. The scaling factor can be selected to produce a wide range of engine power sizes, but the cycle efficiency will change very little from that of the original design. The scaled engine will usually have no parts in common with the original engine, but since the design of the two engines will be the same, any improvements developed for one engine can usually be applied to the other.

If existing engines have room for component efficiency improvements, this can be an attractive way of improving the engine's performance without significantly increasing the recurring cost of the engine. For example, if improved aerodynamics can be developed that can be retrofit into the existing flowpath, this will improve both power and heatrate and shouldn't increase recurring costs significantly.

Increasing airflow can be a low risk way of providing additional power by changing a minimal number of engine parts. There is usually minimal if any improvement in heatrate but the engines exterior dimensions typically don't change which makes the new engine interchangeable into existing installations. Some adjustments to thrust bearings, inlet filtering system and engine accessories may be required.

Zero staging an existing engine's compressor can produce a significant increase in power and usually some heatrate improvement. This is usually a very predictable and relatively low risk development program. This type of a program can allow a manufacturer to offer two engines at different power levels with more than 80% parts commonality. This may be attractive to users with large engine fleets because personal trained to operate and maintain one engine can easily learn to take care of the other. Also, the number of spare parts required to support two engine types can be reduced. The increased airflow will usually require a larger inlet filtering and exhaust system. The starter, fuel and lubrication systems may have to be upgraded and the thrust bearing capacity may have to be increased.

The most popular performance uprate option is through increased firing temperature. This option is popular because it provides additional power and improved heatrate without changing the engine's envelope. On the negative side however, increased firing temperature can be a major cost driver plus the development programs can be risky and costly. The durability of the engine can also be compromised if the cooling system design is not adequate.

On some engines, adding a recuperator can produce a significant improvement in cycle efficiency with some loss in maximum power. The compressor and turbine sections can usually be held the same but in addition to the recuperator, the collectors and ducting must be added and the combustor usually has to be redesigned.

If improved heatrate is the main goal of an uprate program, then increasing the cycle pressure ratio could be considered. This option requires several changes to existing engine hardware and is usually hard to justify unless combined with other uprate options.

Some two-shaft engines may lend themselves to being converted to a single-shaft arrangement. If the power turbine can run at or near the speed of the gas producer section, this conversion may be relatively easy. If the engine can be converted to a cold end drive configuration at the same time, the controls and overall package can be simplified and it may be possible to gain 1% to 2% in performance.

These uprate options have been discussed mainly from a performance and aerodynamic perspective. The implementation of any of these options will require a great deal of structural analysis. Anytime additional power is provided, existing parts must be analyzed under any new loads resulting from new values of mechanical forces, torque, pressure or temperature. Also, these performance uprates can have an impact on auxiliaries such as the starter, the fuel and lube system, enclosures, silencers, inlet filtration and exhaust systems.

SUMMARY

Providing performance uprates to existing industrial gas turbine engines has been a time honored method of providing additional value to gas turbine end users. This paper has tried to present some of the implications of the different options available for providing performance uprates.

When possible, there is a significant advantage in keeping the high pressure section of the engine and the firing temperature unchanged. This greatly reduces the size and cost of an uprate program and greatly reduces the risk of the uprated engine having less durability than the original design.

In any uprate program, it is easy to get locked into only one method for getting the additional performance. As shown here, there are several options for providing extra performance, all with advantages and disadvantages. Several options should be evaluated before a final program direction is selected to see which one best provides additional value to the user community.

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