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ECONOMICS AND DESIGN APPROACHES FOR SMALL COMMERCIAL TURBOGENERATORS

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ABSTRACT

The successful development of small commercial turbogenerators for automotive and other applications presents a major economic challenge. Current aerospace turbogenerators in the 60 kilowatt power range sell for around $500 per kilowatt. Volume automotive turbogenerators prices must be $30 per kilowatt, or less - a 94% reduction. Turbogenerators for aerospace applications have drastically different requirements on almost all important criteria from automotive turbogenerators. The production of commercial turbogenerators requires a radically different organizational setting, mindset, and overhead structure from that necessary for the aerospace industry. Ground up designs which take an integrated approach to material selection, method of operation, fabrication techniques, supplier base, assembly methods, and low cost overheads will be necessary for commercial success. Significant innovation and simplification, and the natural effects of high volume production are also required. Success will likely require lean, agile, innovative, and specialized organizations.

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TURBOGENERATORS - DEFINITION AND DESCRIPTION

The term "turbogenerator", as used in this paper, and as commonly becoming accepted, is a gas turbine connected directly to a generator. In this paper, we are further restricting the definition to include only Brayton Cycle gas turbines. While various configurations are possible, generally the turbogenerators we are discussing, and as being considered for commercial vehicle use, are single shaft machines with the generator on the same shaft and running at the same speed as the gas turbine section. Usually the turbogenerator is recuperated for added efficiency, and it may or may not have catalytic combustion. The machines can be designed to run on a variety of liquid or gaseous fuels. Multiple fuel machines are feasible, but add significantly to cost, and to a lesser extent to size and space requirements. Turbogenerator power ratings for main engine automotive applications are typically 50 to 60 kilowatts at maximum sustained power output. They typically run at 70,000 to 100,000 rpm. Hot sections of the engine may be either high temperature stainless steels, or ceramics.

AEROSPACE TURBOGENERATORS VERSUS COMMERCIAL ONES

Major differences exist between turbogenerators used for aerospace versus commercial applications, such as for autos and other vehicles. There are a number of criteria that are important for the evaluation and consideration of turbogenerators, and these are given immediately below, in Table 1.

It can be seen that these differences are major and frequently extreme between the aerospace applications and the commercial ones. Development efforts, to be successful, must be geared to these differences. The organizational settings and structures must also be different, and fully take these considerations into account.

ADAPTATION OF EXISTING DESIGNS VERSUS GROUND UP DESIGNS

As should be clear from the examination of the criteria for aerospace versus commercial applications, there are numerous and sometimes drastic differences. Both logic and experience strongly indicate that the entire development process must similarly be different. The required characteristics for the commercially successful turbogenerator require a design approach and design goals that meet the commercial criteria.

Table 1 - Comparison of Aerospace and Commercial Criteria for Turbogenerators

Important Criteria	Aerospace	Commercial
Cost/unit	Relatively Unimportant	Critical
Reliability	Critical	Important
Weight	Extremely Important	Of moderate importance
Volume	Extremely Important	Reasonably important
Operating Environment	Harsh and extreme	A reasonable range
Volumes/production run	Tens to hundreds	Thousands to millions
Fuel Efficiency	Extremely Important	Very Important
Air pollution effects	Relatively Unimportant	Extremely Important
Government regulations	Extremely Important	Of overall importance
Paperwork/Documentation	Onerous and extreme	Largely irrelevant
Cost to O.E.M. Customer/Kw	$500/Kw	$30/Kw
Time in Production	30 to 40 years	Not yet in production

Of all of the criteria, cost is the driving characteristic for automotive applications. Those familiar with automotive economics understand that cost realities are harsh and relatively inflexible. The old adage that "a buyer for the big three will slit his own mother's throat to save a mill per car", still pertains. With the effects of inflation, this adage has been adjusted to being a "penny" per car nowadays. It is a major challenge to meet the stringent cost targets of $30 per kilowatt. Our company technical executives, and our team of world class technical experts have concluded unanimously and strongly that there is no practical possibility of meeting the cost targets by taking an expensive aerospace design, and attempting to adapt it. Furthermore, there is virtually nothing in the literature of product development to suggest that such an adaptive approach would have any reasonable likelihood of success.

An examination of the history and literature of defense conversion efforts since the end of the Second World War indicate only a tiny percentage of successes. In the United States, it has been an unfortunate fact of life that successful defense companies are driven inexorably to adapt to Federal procurement practices and regulations. These practices and regulations generate gross inefficiencies in such companies, and large bureaucratic structures. Paperwork requirements and regulatory compliance become onerous and extremely expensive. Large amounts of executive time must be spent, diverting such companies from other productive efforts. Overhead structures in such companies frequently require overhead charges of three to one or more compared to direct costs. Successful commercial companies cannot exceed one to one overhead ratios. The only notable exceptions to successful conversions have been for companies that made commercial airliners. However, in those cases, the requirements for the commercial aircraft were nearly identical to those for comparable military aircraft. Thus, Boeing could easily convert the U.S. Air Force's C-135 aircraft into the nearly identical Boeing 707. As seen above, few comparabilities exist between aerospace and commercial turbogenerators.

It can be furthermore observed that there are almost no known successes of major defense contractors developing commercially successful products in the same lines of their business. High overheads and defense procurement mentalities do not lend themselves at all to such success. Commercial approaches require a totally different environment and mindset. Speed of development, low cost, production efficiency, and market appeal of the product are paramount requirements. Promotion, advertising, and selling efforts are critical. Channels of distribution and other marketing issues have major importance. None of these are important for defense oriented products. There is no apparent reason to believe that aerospace companies will be any more successful in adapting aerospace turbogenerator designs to commercial applications.

THE MANUFACTURING ECONOMICS OF QUANTITY PRODUCTION

A widely applicable rule of production economics is that costs per unit drop in half for every tenfold increase in production quantities per unit of time. This rule has been observed to be applicable to products produced in a wide range of volumes, up to the billions per year, such as consumer products like napkins, diapers, and pencils.

For illustrative purposes this can be shown in the case of turbogenerators, starting with production of a particular unit that sold for $30,000 each, and for which ten were produced per year of the same model.

The highlighted line of 100,000 units per year is close to the cost target for the auto industry. But that number will not be achieved by observing the effects of quantity production economics. For these to be achieved in the real world requires a major commitment to producing such economics.

Table 2. Cost Reductions As A Function of Annual Production Quantities

Annual Production Quantity	Cost per Unit
10	$30,000
100	$15,000
1,000	$ 7,500
10,000	$ 3,750
100,000	$ 1,750
1,000,000	$ 938

MANUFACTURING BENCHMARKS WITH AEROSPACE TURBOGENERATORS

Table 3 compares the manufacturing methods for producing turbogenerators within the aerospace and the automotive industries. Because of the high risk to engine failure and possible catastrophic results, and because of different operating conditions, the methods for the aerospace industry are very costly in comparison to those in the automotive industry. The result of these and other differences shown in Table 3 are a radical reduction in production costs. This is clearly needed, if the turbogenerator is going to be commercially practical for the automotive industry.

Carrying this comparison forward, Table 4, on the following page, shows the differences in the manufacturing processes for aerospace versus automotive turbogenerators. As can be seen by an examination of individual assemblies and subsystems, the overall impact is dramatic. As a function both of volume economies and major changes in both the product and process, manufacturing costs can be reduced from $15,000 per unit, to as low as $900, in production quantities of 100,000 per year or more. That radically reduced cost target will be difficult to reach, but must be attained for the turbogenerator to be a commercially successful product in the automotive industry.

Another approach to obtaining an estimate for the volume production cost for a 60 Kw turbogenerator is to the use the experience of the automotive industry in making turbochargers. Turbochargers are very similar in design to the turbogenerator, except that they lack a generator, combustion chamber, associated controls, and a recuperator. These important additions add to cost and complexity, but do not invalidate the comparison. For this comparison, we have started with the estimated cost for a 15 Kw turbocharger used in production vehicles, and scaled it up to 60 Kw, for cost estimating purposes. Cost estimates and requirements are then added for the additional subsystems. These comparisons are shown in Table 5. It can be seen that the total manufacturing cost for the 15 Kw turbocharger is in the vicinity of $200. An estimated $50 is added for scaling this turbocharger up to 60 Kw. The additional subsystems are then estimated to show how a $900 volume production cost is reached. It should be emphasized that these estimates are based upon preliminary manufacturing studies, and may not hold up in actual production experience. Differences in allocation of expense may occur, or the total may be different. However, the manufacturing cost target needs to be very close to $900 to meet the delivery sale price targets of $30 per kilowatt, or $1,800 total to the auto companies, in large volumes of 100,000 per year or more.

OVERALL REQUIREMENTS FOR SUCCESS

Our company believes that these results can only be achieved early on with a totally dedicated effort. Such effort must and has included the following:

- A fundamental analysis of what functions for the turbogenerator are really required, and how they can most simply and cheaply be achieved

- Innovative and creative design approaches for the overall system, as well as each subsystem and component

- The use of advanced computer modeling and computer aided design to allow rapid and flexible design development and evaluation

Table 3. Comparison of Aerospace and Automotive Manufacturing Methods

Aerospace Turbogenerators	Automotive Turbogenerators
Large number of components	Small number of components
Project based production assembly	Production lines or cells
Low volume production (100/yr)	High volume production (100,000+/yr)
High inspection and test cost	Low inspection and test cost
High liability insurance cost	Low liability insurance cost
Mentality in $/pound	Mentality in cents/piece
Exotic materials used	Traditional materials used
High liability cost built into product	Low liability cost

Table 5 - Manufacturing Cost Estimates Based on Automotive Turbochargers

Assembly	Manufacturing Cost
Current Production - 15 Kw Turbocharger	
Turbine wheel	included
Compressor wheel	included
Shaft	included
Housing	included
Final assembly	included
Subtotal	$200
Additional Cost for 60 Kw Turbogenerator	$ 50
Energy supply & control	
Burner can and igniter	$ 50
Recuperator	$100
Fuel control	$ 30
Subtotal	$180
Generator & Controls	
Generator	$220
Longer shaft	$ 5
Power electronics	$ 90
Subtotal	$315
Final Assembly	
Misc. components	$ 30
Larger housing	$ 55
Final assembly and test	$ 70
Subtotal	$155
Total	$900

Table 4 - Turbogenerator Manufacturing Processes - Aerospace Versus Automotive

ASSEMBLY	AEROSPACE PROCESS	AUTOMOTIVE PROCESS	IMPLICATIONS
Turbine Wheel	Hundreds of blades Precision machined 5-10 stages, individually cast Super alloy materials High assembly cost-complexity	Blades integrally cast Minimum machining 1 stage Cast stainless Assembly cost low	Far fewer components Lower manufacturing cost Lower assembly cost
Compressor Wheel	Same as for the turbine wheel	Same as for the turbine wheel	Same as for the turbine wheel
Main shaft	2" diameter shaft Machined, mounted, and balanced	.75" diameter shaft Machined, mounted, and balanced High volume, low margin mfg.	Much lower cost
Burner can	Made from titanium	Made from stainless steel allows	Much lower cost
Generator	Low volume of 100/yr for 60 Kw	High volume auto style production	Much lower cost
Recuperator	None, due to space and weight	Simple & of stainless steel	Efficiency boost of 10% Somewhat higher cost
Housing	Cast and machined titanium	Pressed steel	Lower material, fab cost
Power electronics	Low volume, high reliability	High volume, auto reliability Auto style mfg. process	Much lower cost
Final Assembly and Test	Low volume, project oriented mfg. Major testing	High volume cellular mfg. Similar to IC engine mfg.	Reduced assembly time Much lower cost
Mfg. Overhead	Huge overhead - government procedures, inspection techniques, reporting	Low overhead - high volume mfg., built-in inspection, lean management	Radical reduction in cost
Total System	**Est. $15,000 mfg. cost**	**Est. $900 mfg. cost @ 100,000/year production volumes**	**Overall radical reduction in cost**

- The use of rapid prototyping to cut development time and cost, and allow more designs to be evaluated within reasonable cost and time parameters

- Careful consideration to the choice of materials to keep them as low cost as possible

- Manufacturing processes and techniques best geared to low cost volume production, with high quality maintained

- The seeking out and reliance on existing high volume manufacturers of analogous components as suppliers. This can provide the low cost incident to already high volumes of production, and minimize capital investment and consequent cost

- Constant attention to simplification, cost reduction, and quality improvement

- The organization of a manufacturing and corporate structure which is very lean, flexible, and low cost, to minimize overhead cost components

The automotive industry has achieved the incredible result of manufacturing complex products for only double the cost of the raw materials. And they buy these materials in the millions of tons per year. The same goal must be sought for the production of turbogenerators if they are to be a commercially successful product for the automotive industry. This will require highly creative and innovative approaches. Those companies that are up to the difficult task can be highly successful. Those that cannot will never crack the market.

CONCLUSIONS

A major challenge faces those companies that seek to develop successful commercial turbogenerators. Costs must be reduced from the current aerospace level of $500 per kilowatt to $30 per kilowatt. The adaption of existing aerospace designs to produce this drastic cost reduction offers virtually no chance of success. Logic and experience indicate that ground up design approaches must be used. Such approaches will require highly focused attention to simplifying the turbogenerators, and drastically reducing the cost of subsystems and components. Low cost materials, production processes, and lean, agile manufacturing approaches must all be employed. This will also require creative and innovative approaches. Volume production economics will help, but these must be created since they will not occur by magic. Given the expected demand for commercial turbogenerators, the payoff for successful efforts will be enormous.