Rampressor Turbine Design

Topical Report

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Abstract

The design of a unique gas turbine engine is presented. The first Rampressor Turbine engine rig will be a configuration where the Rampressor rotor is integrated into an existing industrial gas turbine engine. The Rampressor rotor compresses air which is burned in a traditional stationary combustion system in order to increase the enthalpy of the compressed air. The combustion products are then expanded through a conventional gas turbine which provides both compressor and electrical power. This in turn produces shaft torque, which drives a generator to provide electricity. The design and the associated design process of such an engine are discussed in this report.

This effort was funded in part by the Department of Energy under the cooperative agreement #DE-FC26-00N7 40915, awarded between the period of March 1, 2003 and September 30, 2003.

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1.0 Executive Summary

This report summarizes the results of Rampressor Turbine engine development design efforts. This effort was funded by Department of Energy cooperative agreement number DE-FC26-00N7 40915.

The Rampressor Turbine Rig represents a configuration where the Rampressor rotor is integrated into an existing or a new industrial gas turbine engine. The Rampressor rotor compresses the air which is burned in a traditional stationary combustion system in order to increase the enthalpy of the compressed air. The combustion products are then expanded through a conventional gas turbine which provides both compressor and electrical power. This in turn produces shaft torque, which drives a generator to provide electricity.

The high efficiency, low cost potential of the Rampressor Turbine engine product is key to the DOE vision of Distributed Energy for the future. Ramgen plans to advance the development of a 500KW class Rampressor Turbine to readiness for Field Demonstration. Based on improving knowledge of the physics of the engine, and limitations on funding it is believed that the proposed plan strikes the best balance between risk, cost and schedule.

This report describes how Ramgen evolved the supersonic shock inlet technology from the Ramgen Engine configuration to the Rampressor Turbine configuration. The goal of the Rampressor Turbine program is to eventually demonstrate a cost effective high efficiency industrial gas turbine utilizing a Rampressor compressor. The potential to generate higher efficiency is because of the inherently better performing Rampressor rotor. The successful development and commercialization of the Rampressor will lay the foundation for Ramgen to pursue development of the Rampressor Turbine product. To minimize the risks of the development of an engine, it was decided by Ramgen to stage the development of the engine by first pursuing the Rampressor Turbine design in stead of the Ramgen Engine.

An important consideration was how to proceed with the first Rampressor Turbine Rig. The rig could be designed and built

1) from scratch utilizing conventional combustor and expander (turbine) technology,
2) to incorporate advanced vortex combustor (AVC) technology with a conventional turbine,
3) or to integrate the Rampressor to an existing industrial gas turbine, thereby leveraging some of the known factors of the existing gas turbine engine

This report describes the analysis work completed on the AVC configuration and the insertion of a Rampressor on an existing gas turbine engine.

After due consideration, it was decided that in order to support a successful demonstration of the first Rampressor Turbine engine rig, it was prudent to integrate a

Rampressor to an existing gas turbine engine. Creating a complete Rampressor Turbine engine design from scratch would result in enormous costs to develop a one-off combustor and turbine. To design AVC into the engine from the start would be unnecessarily risky since the development of AVC is a complete program in itself. A delay or set-back in the development of either the Rampressor Turbine or AVC would delay both in a combined development scenario.

Other decisions that followed involve choosing a single spool gas turbine engine and a moderately sized engine at or below 1MW that had an overall pressure ratio at or below 10:1. These decisions were made methodically so as to give Ramgen the highest chance of success at demonstrating the Rampressor Turbine 1 technology. Once such a technology demonstration is made, an engine where performance becomes a key factor will be incrementally targeted in future Rampressor Turbine programs.

The design of the first Rampressor Turbine Rig, which combines a Rampressor with an off-the shelf combustor and turbine engine represents the integration of the Rampressor compression technology to an established industrial gas turbine engine design. Currently the Rampressor Turbine Rig configuration is designed to demonstrate the viability of this particular engine and does not particularly emphasize the performance metrics of the engine. At maturity, the production engine will have a thermal efficiency rivaling and surpassing conventional gas turbines, with highly competitive CO and NO_x emissions through its operation in a lean premixed mode.

Accomplishment of the completed design tasks has led to a greater understanding of what is required to adapt the Rampressor technology to an existing industrial gas turbine engine. Based on the efforts to date, it is clear that a great deal of work is yet to be done in order to match the various components of the Rampressor Turbine engine from an aero and mechanical perspective, for the successful operation of this engine. Significant design and analysis milestones towards answering the many challenges will be made in the following contract periods. Future efforts will build on the foundation of this research and development effort.

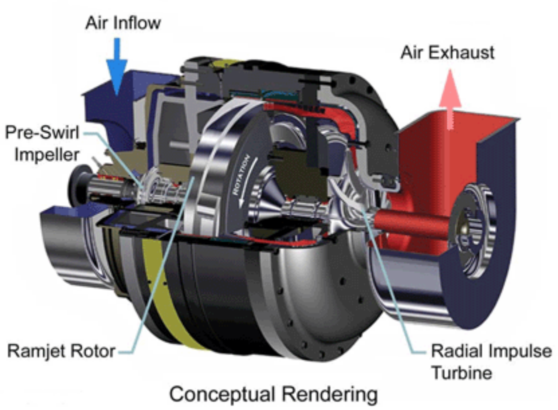
2.0 Introduction

This document presents the early stage design of a new kind of power generation device known as the Rampressor Turbine Engine. These efforts have been aided by the Department of Energy, as part of an initiative to bring viable and innovative energy technologies to market.

This document is split into two major sections. The first section details the planned evolution of this technology over a period of time to include an Advanced Vortex Combustor and how Ramgen's technology development in other programs feed into the Rampressor Turbine technology advancement. The second section of this document details the process by which one particular industrial gas turbine engine was selected as the best possible fit for demonstrating this configuration from many different existing engines. A variety of factors including cost, design, resources and schedule were considered before the selection was made.

The Rampressor Turbine configuration was born from the challenge of creating a viable energy producing product based on superior Rampressor compression technology. The first power producing engine configuration was the Ramgen Engine. See Figure 2-1.

Figure 2-1. Ramgen Engine



Description of Ramgen's Technology Evolution

The design of the Ramgen engine represents a unique application of well-established ramjet technology to electric power generation. In both the Ramgen Engine and the Rampressor Turbine the ramjet thrust modules are mounted on the perimeter of an enclosed rotor, which revolves at supersonic rim speeds. Similar to the increased Mach number for ramjets used in aerospace applications, the faster the rotor spins, the more efficiently the compression process, which is a significant factor affecting engine efficiency. Ramgen projects that the technology can be scaled to produce electrical output ranging from 800 kilowatts ("kW") to at least 10 MW and arranged in configurations for larger outputs. Ramgen's development plan will target the 1MW class in engine size. The Ramgen Engine technology is at an early stage in its development evolution. Just as the gas turbine engine significantly increased its efficiency over its 60 years of development, it is realistic to expect that significant improvements will take place with the Ramgen engine and with the Rampressor Turbine engine during the ongoing process of technological improvement.

The first pre-prototype Ramgen Engine was assembled in 1998, at the Ramgen Company's test site in Tacoma, Washington. On February 2, 1999, the Ramgen Engine was ignited for the first time. Ramgen engineers continued to improve the pre-prototype Ramgen engine's combustor, fuel injection, ignition, and air film cooling systems in the Tacoma pre-prototype Ramgen engine. In the third and fourth quarter of 2000 the prototype engine was rotated to Mach 1.1.

Several improvements have already been conceptualized by Ramgen to increase efficiency, lower costs, and further reduce emissions. The extensive design work and component testing that was required to achieve these advances in the next demonstration rig were executed during Budget Period 2 and 3. In addition, it is projected that the single most important factor to achieve higher efficiency in future generations of Ramgen engines will be advances in materials, which will permit higher rotational speeds. Advances in high strength/light weight materials have been occurring steadily and there is every reason to believe that such advances will continue.

In April, 2002, the DOE conducted a two day Design Review of the Company's technology at the NASA Glenn facility outside Cleveland, Ohio. This Design Review involved approximately 20 prominent scientists from the DOE, Department of Defense, and NASA, as well as a team of Ramgen scientists. At the time of this Design Review in Cleveland, Ramgen estimated that the development costs to demonstrate an advanced Ramgen Engine were in excess of $30 million.

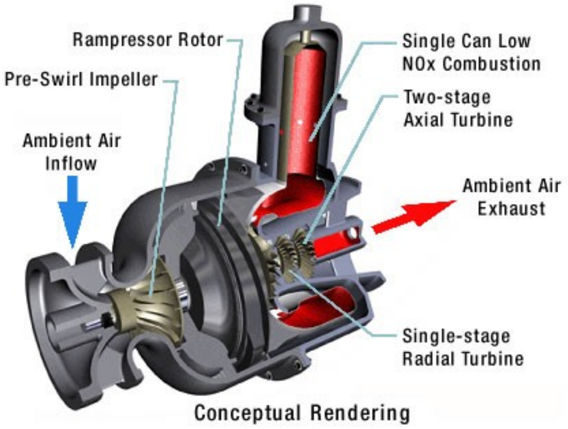
One of the most significant conclusions Ramgen brought back from the Review was that a deterministic component level validation approach was the best path to successfully develop the technology. Additionally, the National Energy Technology Lab (NETL) stated that the testing of the Tacoma engine should have been "more aggressive" with further subcomponent testing planned in the future. The new phase of subcomponent tests of the next generation Ramgen engine (i.e., inlet compression, combustor, rotor dynamics, nozzle expansion, control logic, etc.) will provide increased understanding of the mechanical challenges and aerodynamic flow-field characteristics.

As a result of that Design Review, Ramgen management concluded that most of the advantages and value of the technology could be realized at a fraction of this cost (and within probable DOE support levels), in a shorter time period and with less technical risk. Consequently, Ramgen has focused its resources on demonstrating the Rampressor and designing the Rampressor Turbine in the near-term. The technology required for the Rampressor and the Rampressor Turbine are also important components of the Ramgen Engine under development on a longer timeline.

Rampressor Turbine

In placing a Rampressor on the front end of a stationary combustor and turbine stage, Ramgen has developed what it calls the Rampressor Turbine. The conceptual rendering of Figure 2.2 represents a potential Rampressor Turbine product for commercial sale. As shown in the rendering a Rampressor compressor is configured to flow into a conventional silo style burner and then a conventional axial turbine.

Figure 2.2 Rampressor Turbine



The Rampressor Turbine simplifies the engine technology development by removing the hot combustor from the spinning Ramgen Engine rotor. By separating the combustor from the rotor the technical issues are significantly reduced. The Rampressor Turbine engine uses the ramjet technology to capture the projected advantages in efficiency, cost, and fuel flexibility of the original Ramgen engine, while significantly reducing the time, risk, and money required to complete the design and manufacture of the first commercial engine.

The design for the Rampressor turbine system as shown in Figure 2.2 was to use the high efficiency of the Rampressor compressor in a small simple cycle engine system that would have potential application into the distributed generation market.

The result was a conceptual system layout for a ~500 kW system. Two derivatives were considered at pressure ratios of 10 and 15:1. To achieve these pressure ratios, a centrifugal pre-compressor was coupled with the Rampressor wheel. The discharge from the Rampressor stage fed a reverse flow “can type” combustor that could, eventually utilize a trapped vortex flame holding scheme. The flow was then collected and routed into a centrifugal expansion stage to achieve a decrease in flow-path mean line radius prior to being completely expanded through two additional axial flow turbine stages.

The turbine and combustor stages of both designs were based on the Kawasaki S2A-01 which is a 700 kW system with a pressure ratio of ~ 9:1. The Kawasaki components were scaled to correct for mass flow and pressure ratio. Having estimated the size and speed of the turbine stages, the Rampressor wheels were sized to develop the appropriate inflow Mach numbers for the two different pressure ratio options.

The two systems considered are summarized below in Table 2.1:

Design Rating	10:1 Design	15:1 Design
Shaft Power	485 kW	485 kW
System Efficiency	30.8%	32.7%
Pressure Ratio	10:1	15:1
Air flow	4.1 pps	4.3 pps
Shaft Speed	44,800 rpm	54,870 rpm
TRIT	1700 F	1700 F
Exhaust Temp	885 F	885 F

Table 2.1 Rampressor Turbine Layout Options

This conceptual design iteration highlighted the importance of the designing the turbine stages to provide good mass flow and speed matching with the compressor. In order to ensure proper turbine matching, subsequent Rampressor turbine conceptual design iterations involved the evaluation of multiple existing system candidates. These evaluations were based on many factors and ultimately led to the initial hybridized Rampressor turbine system that was proposed for further design.

3.0 The Rampressor Turbine Engine Design with Advanced Vortex Combustor and Matched Conventional Turbine

3.1 Integration of Rampressor Technology to a Gas Turbine

The approach to developing a Rampressor Turbine utilizing Advanced Vortex Combustion (AVC) technology would consist of several steps in the process of eventually combining the Rampressor compressor and AVC burner technologies into a Rampressor AVC Turbine. As shown in Fig. 3.1, the separate development of commercial applications of the Rampressor, Rampressor Turbine, and AVC technologies naturally leads to their eventual combination in a Rampressor AVC Turbine. The primary challenges to achieving this outcome are technology development coordination, timing, and funding levels. In addition, determining the specific application or set of related applications of the Rampressor AVC Turbine will be critical in assembling the appropriate technology development path.

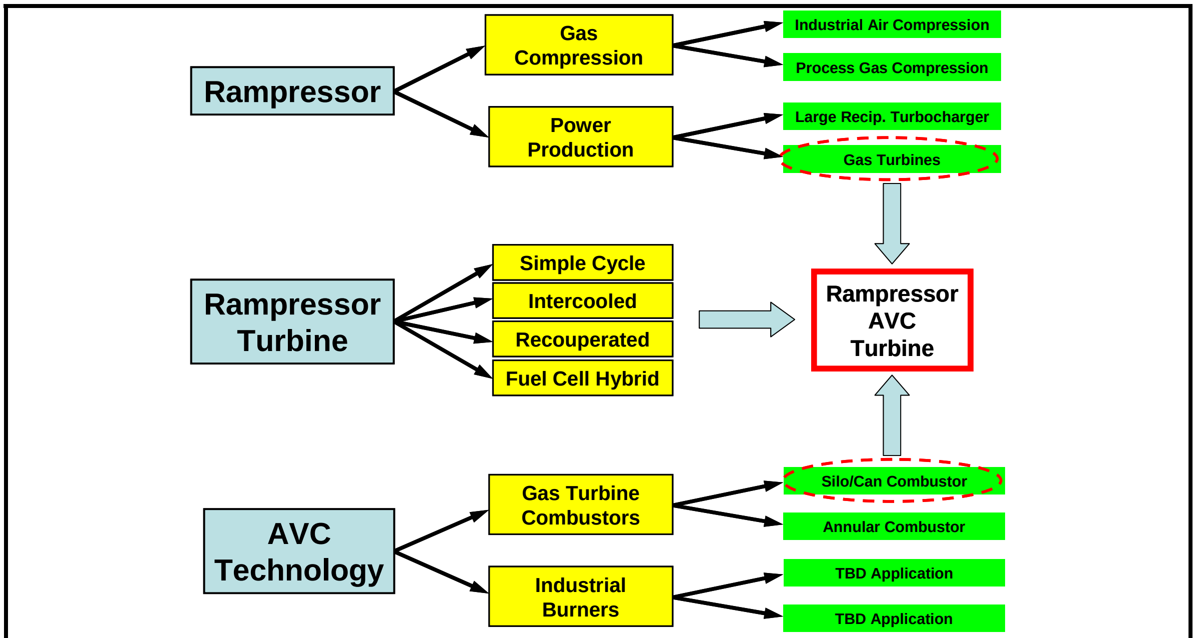


Figure 3.1: Relationship between Rampressor and AVC

The technology development path to reach a Rampressor AVC Turbine would consist of parallel development paths of a Rampressor Turbine and AVC technology that would eventually be combined after sufficient demonstration of each technology. This is shown schematically in Fig. 3.2.

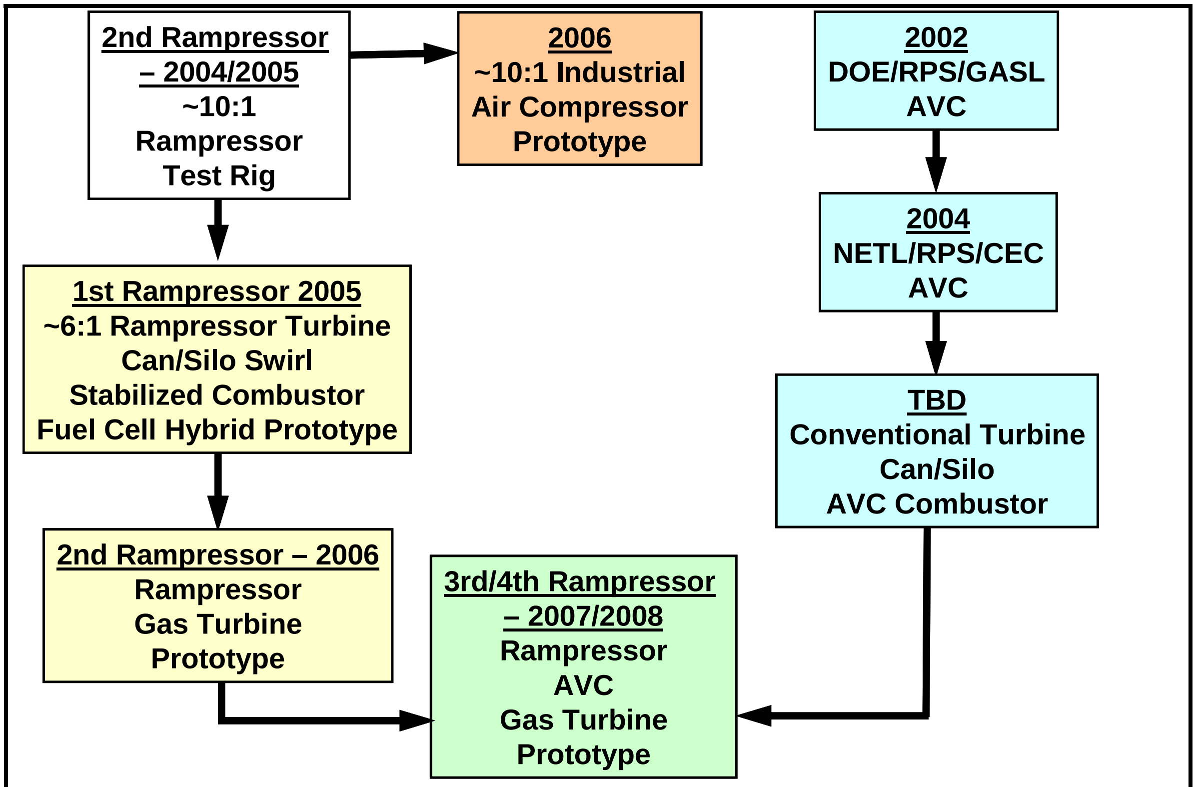


Fig. 3.2: Development Paths of the Rampressor Turbine and AVC technologies

The first stage in progressing towards a Rampressor AVC Turbine would be to combine for the first time a Rampressor, conventional combustor, and turbine for power production. The Rampressor compressor would leverage from the technology base produced by demonstrating a 10:1 Rampressor rotor test rig (Rampressor-II). The initial Rampressor Turbine application would require a lower pressure ratio than 10:1 and would likely be near 6:1, thus reducing the development risk.

The 1st prototype Rampressor Turbine would demonstrate the combination and operating capability of a Rampressor adapted to a conventional combustor (most likely a silo combustor) and power turbine. This prototype system would not likely be the correct size or configuration for an eventual Rampressor AVC Turbine application, but would serve to demonstrate the integrated operation of the components and provide many lessons learned.

The configuration for the 1st Rampressor Turbine scope of supply includes: Compressor, compressor motor, inverter, burner, turbine, turbine generator, inverter, rig skid, controls, rig oil supply, rig water, fuel, cooling air, vacuum, etc. The scope of supply of the entire project includes fuel cell, fuel cell support systems, heat exchanger, plumbing and valves between the Rampressor Turbine rig, fuel cell, and heat exchanger. See Figure 3.3; Notional Fuel Cell / Rampressor Turbine Rig Schematic.

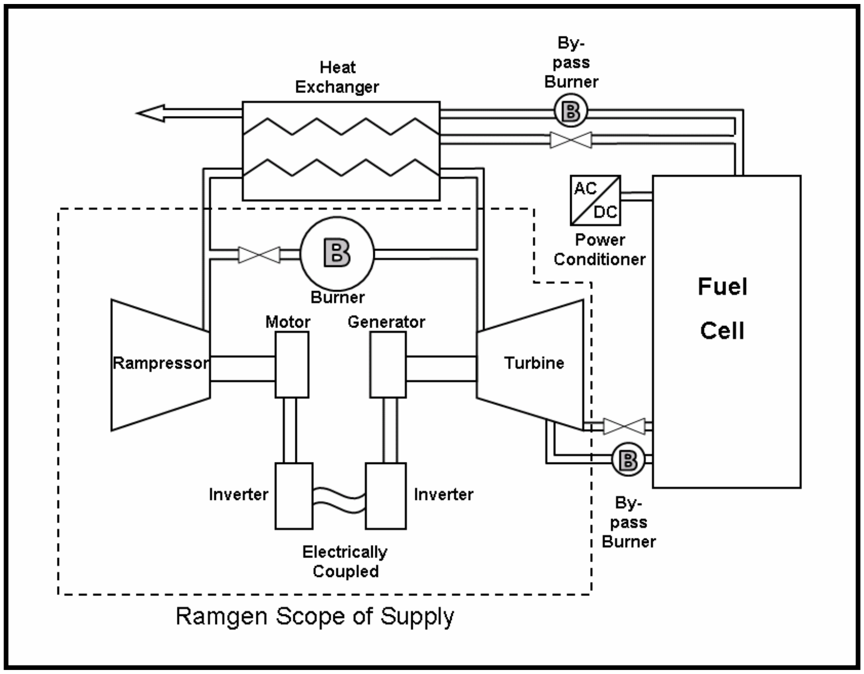


Figure 3.3. Notional Fuel Cell / Rampressor Turbine Rig Schematic

The Rampressor Turbine concept currently envisioned is a 4:1 to 6:1 pressure ratio Rampressor compressor with an available industrial combustor and turbine. This assumes an Indirect System (un-pressurized) will be optimal. The test rig compressor and turbine will be electrically coupled to eliminate matching issues between the components. This configuration will provide the lowest risk, the lowest cost and the quickest path to demonstrating the potential of an optimized Fuel Cell/Rampressor Turbine Hybrid system.

The second Rampressor Turbine prototype would be dedicated to a specific application and would look functionally like the early Rampressor Turbine design shown in Fig. 3.4 that has a Rampressor compressor, conventional silo combustor, and an expander turbine. For comparison, a Kawasaki small gas turbine which utilizes a similar design is also shown. This device would demonstrate full operation of a Rampressor compressor with a conventional combustor and expansion turbine and would not be restricted to limitations imposed by a hybrid fuel cell system.

In parallel, the AVC technology development path would consist of taking the ongoing NETL/RPS AVC program results and designing an AVC combustor to retrofit into an existing small gas turbine that utilizes a silo combustor. This approach would reduce risk by only modifying the combustor and not the compressor. This gas turbine test rig would then fully characterize the application of an AVC combustor in a proven gas turbine configuration. The results from the Rampressor Turbine and AVC silo combustor demonstrations would then allow integration of the Rampressor and AVC technologies into a single prototype Rampressor AVC Turbine unit.

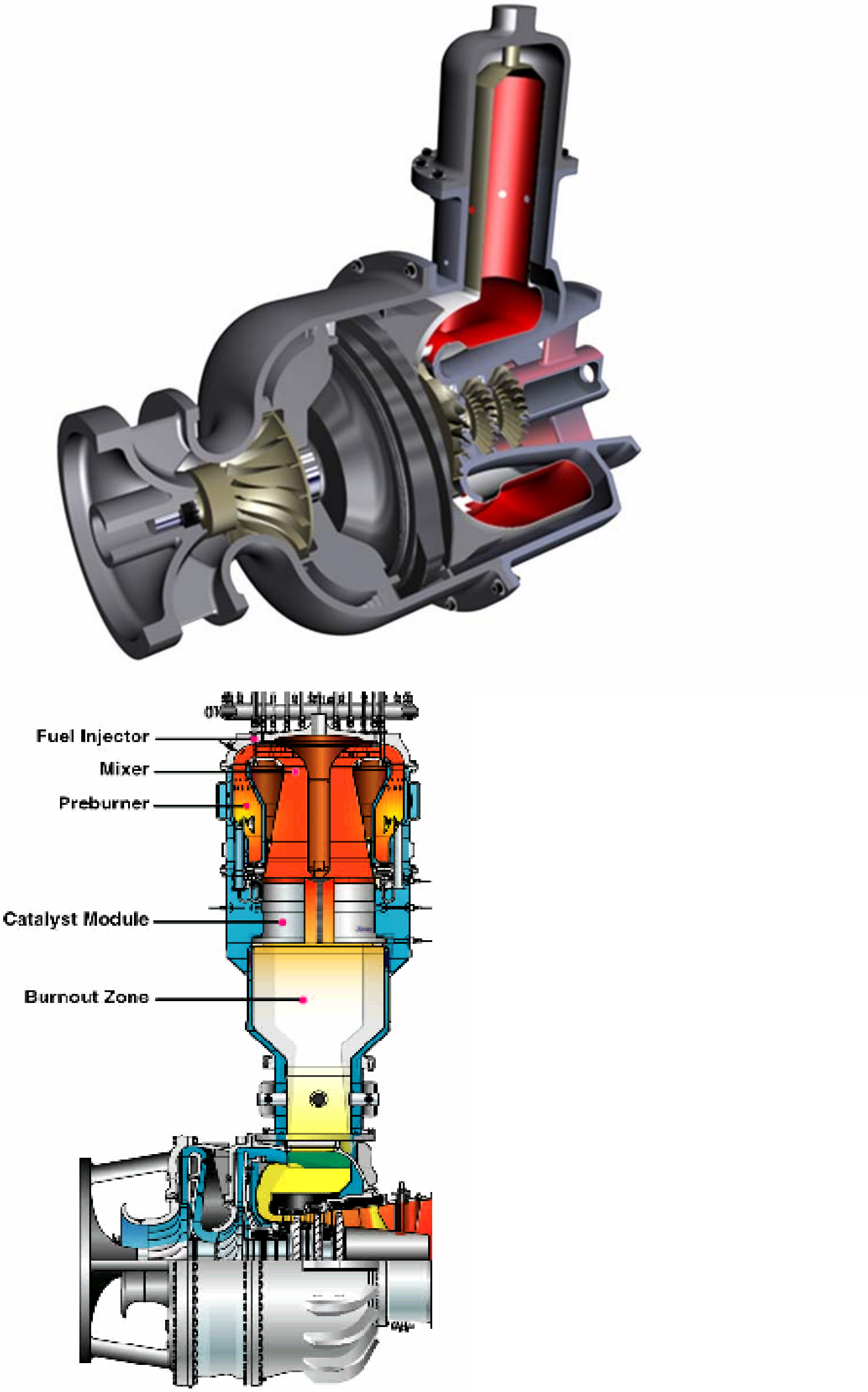


Figure 3.4: Early conceptual rendering of a Rampressor Turbine and Kawasaki small gas turbine

4.0 The Rampressor Turbine Engine

4.1 Integration of Rampressor Technology to a Gas Turbine

The compressor part of the Rampressor Turbine Engine is based on aero propulsion supersonic flight inlet technology which can accomplish high compression with high efficiency in a single stage. This makes the Rampressor the simplest mechanical air-compression device to date through its minimal use of moving parts.

The compressed air then goes through a stationary combustor (single can, can annular etc.,) where it mixes with the fuel in the combustion chamber. The fuel-air mixture is burned in this chamber following which it is expanded in the turbine, which results in power generation. The generated power is converted into electric power using a generator, which is attached to the turbine shaft via a gear box.

The uniqueness of the Rampressor technology is that the compression is across a single stage. This leads to fewer moving mechanical parts, which reduces the cost of the product. In addition to these potential benefits, the Rampressor has a high compressrion ratio across an individual stage (i.e., 10:1 or greater). The overall efficiency of the Rampressor is expected to be equal or better than comparable centrifugal or axial compressors. The above characteristics lead to the big advantages of the Rampressor over centrifugal and axial compressors. The Rampressor is better than centrifugal compressors in that it maintains a relatively high efficiency even at high pressure ratios and it much more compact than an axial compressor. All of these characteristics lead to a much improved performance metric for a Rampressor integrated industrial gas turbine.

4.2 Ramgen's Technology Development Plan

This section deals with the integration of the Rampressor Turbine Program into Ramgen's technology development plan. As detailed in figure 4.1 , the Rampressor Turbine program trails the Rampressor technology development in its various complementary phases. This allows sufficient lessons learned in the Rampressor technology to be incorporated into the Rampressor Turbine program. As shown in figure 4.1, the Rampressor 1 & Rampressor 2 programs are to be tested and designed, respectively, by end of FY 2004. FYs 2005 & 2006 are dedicated to development of Rampressor 3 and Rampressor 4 programs. Simultaneously, the Rampressor Turbine 1 program is scheduled for test in FY 2005, thereby allowing the incorporation of all the lessons learned in the Rampressor 1 & Rampressor 2 programs into this, for a better chance at success.

Future Rampressor Turbine Programs are planned based on additional information from the Rampressor Technology development. Incrementally, these future programs will demonstrate increased performance, both from an emissions standpoint and from an aerodynamics perspective. The Rampressor Turbine 1 program, as indicated before, is principally concerned with demonstrating the concept of a Rampressor working in a power generation environment with no special emphasis on performance metrics.

The Advanced Vortex Combustion (AVC) program is being developed in fiscal years 2003 through 2004 and beyond, so that a combination of this technology along with the advancement of the Rampressor Turbine technology could be incorporated in the Ramgen Turbine program possibly as soon as fiscal year 2008 contingent upon funding and commercial interest.

4.3 Rampressor Turbine Applications

The Rampressor Turbine product is targeted for a variety of applications such as distributed generation (DG). The Rampressor Turbine product geared towards a distributed generation market can either be a high pressure ratio engine or a low pressure ratio engine. It can be operated in a simple cycle environment as well as in a recuperated cycle environment. Usually, the concentration of power outputs for this kind of system is below 1 MW.

In all applications, there is great pressure to reduce system costs, while maintaining high efficiencies. In order to satisfy these market demands and to make efficient use of the funds available, Ramgen decided to put more emphasis on engines that are smaller in size in terms of output power and lower in pressure ratio.

4.4 Methodology of Selecting Engines

The process of selecting the correct engine for the Rampressor Turbine 1 program was carefully considered and methodical. It was a balance between the resources available, cost and complexity of the program and the timeline available for demonstrating such an engine program. The flowchart of the overall process is shown in figure 4.2 and is briefly discussed in this section. The individual steps are later covered in more detail.

As shown in figure 4.2, the overall selection process included many steps. The first step was a study of the generic configurations and options available for the Rampressor turbine product. A decision about the configuration resulted in narrowing down the list of turbine engines that were suitable for the first test rig of Rampressor Turbine engine. The different gas turbines that were identified as being possible candidates were used for generating a list of the generic aerodynamic, mechanical and peripheral risk/issues. This general list was further refined, as shown in the third step, into a list of the important metrics by which different turbines were to be judged. The metrics were then weighted according to the importance that each of them carried to Ramgen's overall goals for the Rampressor Turbine 1 engine. This process helped in reducing the total number of identified engines to a more manageable list.

A further investigation of the list of engines that were left standing after the weighting process helped in reduction of the number of engines to 2. Finally, taking into consideration Ramgen’s resources and lessons learnt from the Rampressor 1 test rig, the list of 2 engines was further reduced to one engine. Once the engine was selected, the associated cross section layout was developed and an early design review of this layout was conducted. The next few sections detail each of the steps listed in the flowchart, shown in figure 4.2.

4.4.1 General Configuration Decisions

As mentioned earlier, the selection process for a suitable Rampressor Turbine 1 demonstration engine was started by trying to assimilate the different engine configurations within the constraints of the resources, cost, technical risk and time available. The gas turbine engines can be broadly classified as single spool or multi-spool engines. Also, since the Rampressor turbine product is ultimately targeted towards the distribution generation market an engine in the 400 KW class is a priority. The pressure ratio of the engine was a factor that was considered as well, because the higher the pressure ratio of the overall system, the greater the technical challenges for the Rampressor Turbine 1 engine.

Another important consideration was whether to build a new engine from scratch or integrate the Rampressor to an existing industrial gas turbine, thereby leveraging some of the known factors of the existing gas turbine engine. After due consideration for all of the above questions, it was decided that in order to support a successful demonstration of the Rampressor Turbine 1 engine, it was prudent to integrate a Rampressor to an existing gas turbine engine. Other decisions that followed involve choosing a single spool gas turbine engine and a moderately sized engine at or below 1MW that had an overall pressure ratio at or below 10:1. These decisions were made methodically so as to give Ramgen the highest chance of success at demonstrating the Rampressor Turbine 1 technology. Once such a technology demonstration is made, an engine where performance becomes a key factor will be incrementally targeted in future Rampressor Turbine programs.

4.4.2 Generic Aero/Mechanical/Peripheral Issues

This section deals with identifying the principal aero and mechanical issues as well as the major components of any Rampressor Turbine Engine. The idea behind identifying such issues is to ensure that during the gas turbine engine selection/ design process such issues are given due consideration. This helps in identifying the appropriate turbine for the Rampressor Turbine 1 program after considering the various risks involved with each of the issues.

4.4.3 Aerodynamic Issues

The major components that are required for this engine are the impeller in the front (to assist in self-aspiration), followed by a De-swirl vane (to remove the swirl from flow out of the impeller and align it axial for the Pre-swirl inlet) and a Pre-Swirl nozzle for the Rampressor rotor. All of the above mentioned components are upstream of the Rampressor Rotor. The components downstream of the Rampressor rotor are a De-Swirl vane (required to take out the swirl coming out of the rotor), a Diffuser (to diffuse the flow from the rotor to a low mach number flow so that is could be fed to the downstream combustion components), a bleed port (to assist in the starting of the engine), a combustor (to allow for combustion) and a turbine (to expand the high pressure gas so that power is generated). Since Ramgen decided to integrate the Rampressor rotor to an existing gas turbine engine rather than build a completely new engine, the design effort concerning the combustion system and the turbine system design is minimal.

The other two other issues that need to be dealt with. First, the starter motor size for the Rampressor Turbine engine. Second, the requirement of turbine maps of the chosen industrial gas turbine engine to which the Rampressor is to be integrated into (helps determine the starting process of the Rampressor Turbine engine).

4.4.4 Mechanical Issues

All the issues discussed so far pertain to the aero aspects of the engine. On the mechanical and structural side of things, the requirements/issue are a low loss transition piece from the impeller De-Swirl vane to the Pre-Swirl nozzle, struts in the flow path to allow for oil feed lines, buffer air feed lines and bleed air lines. This has a potentially detrimental effect on the performance of the engine because of the blockage created and hence needs to be carefully designed. The diffuser and de-Swirl components, if variable geometry, could be challenging tasks. Since the Rampressor rotor is to be integrated with an existing gas turbine engine, access to the cross section of the engine is an important factor in the design of the Rampressor Turbine 1 engine. The other potential mechanical issues are the rotor dynamics of the overall system, the integration of the Rampressor shaft to the existing turbine shaft and tip speed limitations of the rotor design.

4.4.5 Peripheral Issues

Among the various peripheral issues for this engine is a requirement for vacuum system for the bleed air. Since the Rampressor rotor requires certain percentage of air to be bled off from the mainstream flow for performance and starting reasons, a higher mass flow rate engine will require a bigger vacuum system, which could prove to be a hindrance to the performance of the overall design. In addition, the Rampressor is in its early developmental stage and efforts have not been made to optimize the bleed requirement. Future programs of this design are expected to concentrate on such issues, which will be incorporated in the future Rampressor Turbine products, as was discussed in the overall technology development section of this document. The other peripheral system requirements are a tip clearance control system, a thrust balance system, a generator or a load bank for using the power generated, a gearbox between the generator and the turbine/compressor. The connection between the starter motor and repressor shaft is yet another peripheral issue that needs due consideration during the design phase of the project.

The issues discussed in this section help in defining the important metrics that are to be considered for choosing an appropriate gas turbine engine for the Rampressor Turbine 1 program. These metrics are discussed in the following section

4.4.6 Important Metrics & Their Weighting Factors

This section deals with specifically identifying the important metrics by which different engines are to be evaluated. Following the identification of these metrics, they are weighted according to how critical they are for the overall engine design. The various metrics that are considered for evaluating these different engines are:

(i) Output Power of the system
(ii) Design Pressure Ratio
(iii) Mass Flow rate
(iv) Whether the turbine is cooled or uncooled
(v) Availability of the engine in the market
(vi) Starter Motor Size/Requirement
(vii) Compressor Tip Clearance Requirement
(viii) Availability of Access to Engine Cross Section
(ix) Access to Turbine Maps
(x) Access to Compressor Maps
(xi) Availability of Consultants
(xii) Cost of the chosen engine
(xiii) Industrial engine or an APU
(xiv) Type of fuel used, natural gas, liquid or dual fuel
(xv) Potential supplier of the same
(xvi) Technical Challenge of tip speed
(xvii) Rampressor centerline radius
(xviii) Flow path from the Rampressor to the combustor inlet

The metrics are weighted on a scale of 10 to 100 in steps of 5, 10 being the least important and 100 being the most important factor, relative to each other. The Ramgen team discussed these various parameters and assigned the weighting factors, as was seen appropriate to the overall design of the Rampressor Turbine engine. These are captured in Table 4.0. From the table, it is clear that among all the metrics considered, the team picked the availability of the engine, the complexity of the engine (whether cooled or uncooled) and the availability of consultants that understand the various components of the engine as the most critical parameters for this design. Access to compressor maps of existing engines, starter motor size and the number of suppliers available for each of the different engines was considered least critical for the design. These decisions and the corresponding weighting factors are made/assigned after considering that this rig was the first of its kind.

Table 4.0 Important Engine Metrics Versus Weighting Factors

Important Engine Metrics	Weighting Factors

Output Power of the system	40
Design Pressure Ratio	80
Mass flow rate	60
Whether the turbine is Cooled or Uncooled	100
Availability of the engine in the market	100
Starter Motor Size/Requirement	30
Compressor Tip Clearance Requirement	75
Availability of Access to Engine Cross Section	80
Access to Turbine Maps	70
Access to Compressor Maps	20
Availability of Consultants	100
Cost of the chose engine	50
Industrial Engine or an APUS	40
Type of fuel used, natural gas, liquid or dual fuel	60
Potential supplier of the same	30
Technical challenge of tip speed	80
Rampressor Centerline radius	70
Flow path from the Rampressor to the combustor inlet	70

4.4.7 Ranking Process of Different Engines

In the previous section, the important parameters and the corresponding weighting factors were discussed. This section discusses how individual scores are assigned to each of those weighted parameters. In general, the scores are assigned on a scale from 1 to 5. A higher score is usually considered good and a lower score is considered bad. For the different parameters, the respective scores breakdown is discussed below

4.4.7.1 Output power of the system

The output power of the system is one of the many critical parameters that Ramgen identified. This is because it affects the size of rotor that Ramgen needs to design. Since this directly relates to the Ramgen's design experience, a careful analysis of the same was conducted and scores associated with the generic engine's power rating is detailed below.

Table 4.1 Assigned scores for the Output power of the system

Output power of the system (Horse Power)	**Assigned scores**
< 300, > 1000	1
700 to 1000	2
600 to 700	3
300 to 350, 500 to 600	4
350 to 500	5

4.4.7.2 Design Pressure Ratio

The overall pressure ratio of the system affects the aero and mechanical system challenges. A low pressure ratio machine has fewer design challenges compared to a high pressure ratio machine. Taking this into consideration, the generic engine's pressure ratio and its associated scores is detailed below

Table 4.2 Assigned scores for Design pressure ratio

Design pressure ratio	**Assigned scores**
> 8	1
7 to 8	2
6 to 7	3
5 to 6	4
< 5	5

4.4.7.3 Mass flow rate

The mass flow rate of the system affects the rotor design of the Rampressor. A higher mass flow rate requires a bigger flow path and a lower flow rate requires a smaller flow path. Since this directly corresponds to the actual design of the rotor, due consideration for this parameter was given and the generic engine's mass flow rate and its associated scores is detailed below

Table 4.3 Assigned scores for Design mass flow rate

Mass flow rate (lbm/s)	**Assigned scores**
> 10	2
6 to 10	3
< 6	4

4.4.7.4 Turbine cooling configuration

A turbine that is cooled is more complex than a turbine that is uncooled. Not only does the design have to consider the routing of the secondary flows required for cooling the turbine, but also the tap off points from the Rampressor rotor need to be roped into the design as well. Since this entails a more sophisticated design analysis, a turbine with no cooling would be a highly preferred way of designing the Rampressor 1 turbine. The generic engine's cooling configuration and its associated scores is detailed below

Table 4.4 Assigned scores for Turbine cooling configuration

Turbine cooling configuration	Assigned scores
Cooled	1
Potentially Cooled	3
Uncooled	5

4.4.7.5 Availability of engines in the second hand market

The simplicity of the design does not matter if such an engine is unavailable in the market relatively easily. So, an engine that is readily available in the market, even if its slightly more complicated in design, is preferable to one that is not available in the second hand market. The generic engine's availability and its associated scores is detailed below

Table 4.5 Assigned scores for Availability of engines in the second hand market

Availability of engines	Assigned scores
Unavailable	1
Very Low Chance of Availability	2
Engines are available. Time of availability is in question	3
Manufacturers/ Overhaul places have dealt with it in the past and if asked for they can locate such engines	4
Readily available	5

4.4.7.6 Starter motor size

For starter motor size determination, the Rampressor Turbine has been assumed to require a starter motor that will be large enough to take it up to 50% (which is pretty typical for gas turbines) of its design speed. A smaller starter motor is preferable because of its compactness and simplicity in design. Based on this assumption, the generic engine's starter motor size and its associated scores is detailed below

Table 4.6 Assigned scores for Starter motor size

Starter motor size (Horsepower)	Assigned scores
> 1000	1
750 to 1000	2
500 to 750	3
250 to 500	4
0 to 250	5

4.4.7.7 Availability of the turbine cross section

One of the essential elements required for integrating a new front end to an existing design, is the availability of an existing engine cross-section. The easier it is to get an engine cross-section, the higher the assigned scores. The availability of the generic engine's cross section and its associated scores is detailed below

Table 4.7 Assigned scores for Availability of turbine cross section

Availability of turbine cross section	**Assigned scores**
Reasonably good chance of getting it	4
Currently available	5

4.4.7.8 Availability of the consultants

Another critical element for designing a front end for an existing engine is the availability of designers with expertise and experience on the selected engines. The availability of such consultants results in a high score whereas the unavailability of such consultants results in a low score, in our weighting model. The associated scores of the same is detailed below

Table 4.8 Assigned Scores for Availability of consultants

Availability of consultants	**Assigned Scores**
None available	1
Low probability of identifying	2
If looked around, consultants maybe available	3
Pretty Confident of consultants being available	4
Consultants Currently available	5

4.4.7.9 Access to Turbine Maps

One of the considerations while designing a front end for an existing engine is the operating characteristic of the turbine. A turbine map provides information regarding the operation of the engine. Getting this information is invaluable and the associated scores of accessing the turbine maps is detailed below

Table 4.9 Assigned Scores for Access to turbine maps

Access to turbine maps	**Assigned Scores**
Unavailable	1
Decent chance of availability	3

Currently Available	5

4.4.7.10 Access to Compressor Maps

The other principal characteristic that is required for designing the front end is the operating characteristic of the existing compressor of the engine. This is important because designing the Rampressor to have the same characteristic as that of the existing compressor will make running the overall turbine engine a much simpler job. Getting access to the compressor maps of the generic engine, by way of reverse engineering, and its associated scores is detailed below

Table 4.10 Assigned Scores for Access to compressor maps

Access to compressor Maps	**Assigned Scores**
Unavailable	1
Decent chance of availability	3
Currently Available	5

4.4.7.11 Used / Overhauled gas turbine cost

This relates to the funds available at Ramgen for purchasing a generic gas turbine engine. The cost of the individual engine package and its associated scores are detailed below

Table 4.11 Assigned Scores for Used / Overhauled gas turbine cost

Used / Overhauled gas turbine cost ($)	**Assigned scores**
> 200k	1
150k to 200k	2
100k to 150k	3
50k to 100k	4
< 50k	5

4.4.7.12 Type of engine

This relates to the whether the generic gas turbine engine is an industrial gas turbine or an APU or aero propulsion based. An industrial gas turbine is more rugged than a comparable aero engine. So, a natural preference for a first time demonstration is the industrial engine. This is reflected in the following table which matches the type of engine and its associated score as

Table 4.12 Assigned Scores for the Type of engine.

Type of engine	**Assigned scores**
Aero Propulsion	1
APU	3
Industrial	5

4.4.7.13 Type of fuel used

This relates to the type of fuel used in the generic gas turbine engine. The fuel type that the engine uses confines the testing location to a certain number of test cells. In order to give Ramgen the most flexibility in identifying the test cells, an engine that supports dual fuel is most preferred and is reflected in the table below. The type of engine and its associated scores are detailed below

Table 4.13 Assigned scores for the Type of fuel used

Type of fuel used	**Assigned scores**
Gas	1
Liquid / Dual	5

4.4.7.14 Number of overhaul engine suppliers

This relates to the number of suppliers available to supply the generic engine either in a used state or in an overhauled state. Having more than a single supplier gives Ramgen the flexibility to negotiate on prices as well as the engine package. So the engines that have more suppliers in the secondary market are preferable. This is reflected in the table below and the associated scores for the same is detailed below

Table 4.14 Assigned scores for the Number of overhaul engine suppliers

Number of Suppliers	**Assigned Scores**
No Suppliers currently identified	1
1 supplier currently identified	3
2 supplier currently identified	4
More than 3 supplier identified	5

4.4.7.15 Rampressor rotor tip speed

This relates to the technical challenge of the design of the Rampressor rotor for the generic gas turbine engine. The higher the tip speed the more challenging the design gets. Since Ramgen is committed to developing a Rampressor turbine 1 demonstration unit the risk is to be kept at a minimum. This indicates that lower tip speed engines would be preferable to higher tip speed engines and is reflected in the table below. The associated scores for the tip speeds is detailed below

Table 4.15 Assigned scores for the effect of Rampressor rotor tip speed

Tip Speed (ft/s)	**Assigned Scores**
> 2050	1
1950 to 2050	2
1850 to 1949	3
1750 to 1849	4
< 1750	5

4.4.7.16 Rampressor centerline radius

This also relates to the technical challenge of the design of the Rampressor rotor for the generic gas turbine engine. This parameter was evaluated against the existing design experience at Ramgen and a design similar to an existing design was given a higher score, largely because of familiarity. Having a smaller sized rotor makes for a challenge to get the secondary systems around the main rotor. The associated scores for the same is detailed below

Table 4.16 Assigned scores for the Rampressor centerline radius

Rampressor centerline radius (inches)	**Assigned scores**
< 3	1
3 to 3.5	2
3.5 to 4.0	3
4 to 4.5	4
4.5 to 7	5

The abovementioned tables and the scores allotted to each of the different parameters were done based on what Ramgen considered to be important design considerations. An assignment of scores for each of the turbines, based on the guidelines established by the abovementioned process along with the weighting factors assigned for the different engines (as was discussed in the previous section) provides a good indication of the engine's overall fit to the Rampressor Turbine 1 Program needs. The sum of the product of the individual engine parameter score and the assigned weighting factor provides each engine with an overall weighted score. The overall score of each of the several engines considered is shown in figure 4.3. From figure 4.3., it is clear that there are a few engines that are clearly better suited for this application than others. The top five candidates are the Solar Spartan, Solar Saturn, Garrett Lycoming T53, Garrett 200 & Sundstrand GTLC engines. Of these five engines, the T53 engine is the only engine with multiple spools. Since dealing with the complexity of a multi spool engine was considered beyond the Rampressor Turbine 1 program requirements, this particular engine was eliminated from consideration for integration with a Rampressor rotor.

4.5 Comparison of the Top Engine Candidates

Based on the weighted scores method, four turbine engines were chosen: Solar Spartan, Solar Saturn, Sundstrand APS2000 and Garrett 36-200. The critical parameters for these four engines are shown in figure 4.4. All of these engines operate at about a pressure ratio of four, except the Saturn engine. The mass flow rates are vastly different, which directly impacts the bleed system requirement. As expected, the size of the bleed system requirement for each of these different engines is quite different. For most of these engines, the starter motor that is currently being used at Ramgen for Rampressor 1 can be made use of except for the Saturn engine. Among the four engines, a consultant for the Garrett engine is the toughest to find and clearly there are more suppliers for the Saturn and the Spartan engines. The Saturn engine is much bigger than the remaining engines and the Garret engine is really small. The centerline Mach number of the Saturn engine is much higher than the other engines. The Rampressor rig that is currently in operation at Ramgen operates at a centerline mach number of 1.6, which is consistent with all engines other than the Saturn engine. A table showing the pros & cons of each of the four designs is discussed below.

Since the top four engine candidates have their own advantages and disadvantages, further in-depth analysis was required to choose one final engine configuration for the Rampressor turbine 1 program. In order to do this, the Rampressor rotor design, which is described in the following section, was laid out with the four turbine engines.

Table 4.17 Pros & Cons of the four engines

Spartan		Saturn		Sundstrand APS 2000		Garrett 36-200	
Pros	Cons	Pros	Cons	Pros	Cons	Pros	Cons
Mean line design point relative Mach Number comparable to Rampressor 1 design	Potential overall efficiency improvements by having a Rampressor in the front end are modest	Consultants available to help Ramgen design a compressor	Pressure ratio much higher than the Rampressor 1 design	Pressure ratio comparable to the Rampressor 1 design	Minimally available in the secondary market	Pressure ratio comparable to the Rampressor 1 design	Impeller design for the design point does not meet established design criteria.
Design point mass flow rate/ pressure ratio comparable to the Rampressor 1 design		Widely available in the secondary market	Design point mass flow rate much higher than the Rampressor 1 design	Mean line design point relative Mach Number comparable to Rampressor 1 design	Design point mass flow rate more than twice that of the Rampressor 1 design	Design point mass flow rate comparable to the Rampressor 1 design	Relatively less number of consultants with expertise on this engine available to help Ramgen
Consultants available to help Ramgen design a compressor		An acceptable front end impeller design, if required, is available.	Requirements on test cells much more onerous than the other 3 engines		Relatively less number of consultants with expertise on this engine available to help Ramgen	Requirements on test cells similar not very burdensome.	
Widely available in the secondary market			Mean line design point relative Mach Number much higher than Rampressor 1 design		Potential overall efficiency improvements by having a Rampressor in the front end are modest	Mean line design point relative Mach Number comparable to Rampressor 1 design	Potential overall efficiency improvements by having a Rampressor in the front end are modest

4.6 Rampressor Rotor Layout Process

For laying out the design of the Rampressor rotor, the information that was required was the engine rpm, the overall compressor pressure ratio, the engine mass flow rate. Once this information was provided, the designer uses the usual design tools to layout the Rampressor rotor design. For all of the designs a variety of inlet conditions were tried out and only the design pertaining to an inflow total pressure of nearly 1 atmosphere and an inlet temperature of 59 F and 80 F are reported. The design layout process is by itself an iterative process starting with the incorporation of the lessons learned from the Rampressor 1 design process. The design process consisted of three steps

1. The Mean line radius is adjusted to get the rotor Mrel (relative Mach Number) at the gas turbine operating RPM.
2. The capture area is adjusted for the mass flow rate
3. If the tip speed is too high, the pre-swirl nozzle Mach number was increased along with the pre-swirl nozzle stage pressure ratio.

The rotor capture area and radius is scaled from the Rampressor 1 design to achieve the desired mass flow and the contraction ratio is adjusted to achieve a 1.3 Mach for the normal shock. The desired pressure ratio and inlet absolute mach number is checked to see if they are matched for highest performance and the process is repeated until all the design requirements are met. The parameters for the four turbines described earlier are captured in Figure 4.4.

From the above information, it is clear that the Saturn turbine engine design carries a slightly higher risk than any of the other engines, strictly from a Rampressor rotor design point of view. This is because of the higher Mrel for Saturn turbine than for other engines. However, the other factors discussed in the ranking and weighting section, make Saturn a highly viable candidate.

One of the principal components for the Rampressor Turbine engine is the impeller in front. This is currently shown in the design because it is assumed that the Rampressor in its current design state cannot self-aspirate. Depending on the data being collected with the Rampressor 1 design, this decision needs to be revisited. An early design analysis for the four engines for the impeller was carried out through a consultant and from his work, the only two turbines for which an impeller could be laid out for were the Solar Spartan and the Solar Saturn turbines. For the other two turbine engines, the impeller rotor designs became highly risky (meaning that design guidelines had to be violated to come up with reasonable impeller rotor designs). This led Ramgen with only two viable candidates namely Solar Saturn and the Solar Spartan gas turbine.

One more important consideration for designing the Rampressor Turbine is the availability of test data for the Rampressor part of the engine. Since Rampressor 1 testing has been completed, it is advantageous to design a system that has a rotor which is similar to the Rampressor 1 rotor. The Solar Spartan gas turbine Rampressor layout is very similar while the Solar Saturn turbine engine Rampressor layout is vastly different, in their operating characteristics, to that of the Rampressor rotor. All these important factors, in addition to the resource, cost and schedule, make the Spartan gas turbine, the turbine engine of choice for the Rampressor turbine 1 program. The next few sections deal with the layout of the Spartan Rampressor Engine.

4.7 Aero-Mechanical Design of Spartan Based Rampressor Turbine

The layout of the Spartan gas turbine based Rampressor Turbine is shown in figure 4.5. The components that are within the dashed line box are the components that exist in the Spartan engine and components outside of the same are what need to be designed by Ramgen for an overall Rampressor Turbine engine. The part that Ramgen needs to concentrate and design to fit up with a Spartan gas turbine is shown in figure 4.6. As can be seen, the principal components include the : Impeller rotor, de-swirl vane, pre-swirl nozzle, Rampressor rotor, a diffuser, a de-swirl vane and the duct that takes the flow from the deswirler to the combustor section of the Spartan engine. The details of some of the individual components are discussed in the next few sections.

4.8 Impeller Design

The impeller layout is shown in figure 4.7. It has a 2.94 inch tip radius and spins at approximately 950 ft/s and needs to be designed for at least a 91% efficiency. The constraints with which this design has been evolved is the engine rpm of 37059 and a mass flow rate 5 lbm/s.

4.9 Rampressor Rotor Design

The Rampressor rotor for the Spartan engine based Rampressor turbine has the following preliminary details:

- Rotor size
- Tip Speed
- Relative Mach Number
- Pressure Ratio
- Outflow Mach Number
- Pre-Swirl Mach Number
    - Angle

4.10 Rampressor Turbine Stationary Diffuser

The current Spartan compressor discharge flow has no swirl component and is mostly axial flow discharging at a low mach number of 0.1. The Rampressor rotor design conditions for the Rampressor turbine engine has flow exhausting at a high swirl angle and a high mach number. These are design estimates at an early stage and will be verified and modified according to the test data generated from Rampressor 1 test data, which is currently operational at Boeing. Assuming that the estimates are correct, there is significant diffusion and turning required in the flow exhausting out of the Rampressor rotor. In order to assist in that, a tandem vane cascade with a potential for a hybrid "Pre-Diffuser" volute section is shown in the layout shown in figure 4.8.

4.11 Potential Design Point Performance gains

A preliminary estimate of the efficiency of the individual components of the Spartan gas turbine based Rampressor Turbine was made based on certain assumptions. This section discusses those performance estimates. The impeller has 1.1 pressure ratio and is considered to be 91% efficient and the preswirl nozzles are expected to have a 2% pressure loss at design point. The Rampressor rotor is assumed to have a 92% efficiency without taking into account the tip clearance system loss and the mechanical losses. The existing Spartan compressor efficiency is approximately 75%. The de-swirl vanes and the diffusers are assumed to have a 4% pressure loss and the existing performance estimates for the combustor and the turbine are used for estimating the overall cycle efficiency. These component efficiencies cause an 18% overall simple cycle thermal efficiency which is 3-4% increase from the existing Spartan simple cycle efficiency.

This section discusses some of the off-design and starting/un-starting issues that the Spartan based Rampressor Turbine might face. Since the mean line Mach number is very similar to the Rampressor 1 hardware, the starting issues are expected to be very similar to Rampressor 1. So, a good understanding of this issue will be available after the completion of the Rampressor 1 testing. Then the detail design of the Rampressor turbine is ready to be carried out. Also, a better understanding of the unstart./surge characteristics of the Rampressor rotor will be available (from the test data of the Rampressor 1 rotor) before different components are matched to the Rampressor rotor.

The significant issue with the starting of the Rampressor turbine is the matching of various components during the startup process. There might be a need to bleed the flow between the impeller and the Rampressor rotor as well as bleed the flow between the Rampressor rotor and the combustor for starting purposes. More detailed information regarding this will be available during the detail design phase of this project. One of the ways that this particular issue can be better understood and resolved is by de-coupling the compressor part from the combustor and turbine. This intermediary step might be necessarily required to better understand the characteristics of different components before a final coupled Rampressor turbine is operated. Ramgen is seriously considering proceeding with such a design in the above mentioned fashion to give us the best chance of successful demonstration of the Rampressor turbine engine.

The starter motor required for the Rampressor turbine is estimated to be able to deliver atmost 448 hp at 37000 rpm. This is estimated based on assuming that the starter motor is required to take the compressor to full speed and full pressure ratio, before it can be dropped off from the starting sequence. A more realistic case would be where the power generated from the turbine is greater that that required by the compressor, which is expected to happen at around 18500 rpm and that which requires 112 horse power. The drive motor that is currently available with Ramgen can support worst case scenario requirement, but its availability at the time of requirement is in question. Mechanically, the two significant issue are the tip speed of the Rampressor rotor and the rotor dynamics of the system.

4.12 Test Rig Cost

The components and the requirements identified, helped in estimating the costs for the Spartan Engine based Rampressor turbine test rig. The details of this are attached in the table captured in Figure 4.9. The table indicates that the initial cost estimate for the rig is $706,000. This cost estimate has been arrived at based on Ramgen's prior experience with building the Rampressor 1 test rig. Since the size of the Rampressor part of the Rampressor turbine test rig is similar to the Rampressor 1 test rig, the cost estimates should be similar. The overhauled Spartan engine package has been estimated to be about $40,000 and the drive, if a new one is required for this test rig, is expected to cost around $50,000. These two component costs have the highest uncertainty in their estimates because of the availability factor. Ramgen has used the best available information, to date, to estimate these costs.

4.13 Test Cell Cost

The other part of the cost structure is the estimate for test cell cost. In order to obtain this, a number of test cells were approached with a set of initial requirements. The list of initial requirements that were specified for the test cells were

i. A test cell large enough to accommodate our test rig with an approximate size of 150 inches long, 60 inches high and 40 inches wide.
ii. Availability of liquid fuel like diesel or kerosene, as well as natural gas.
iii. Test cell capable of dealing with approximately 6 lbm/s of exhaust air at 1200 F.
iv. A test cell capable of handling a rig weighing approximately 5000 lbm.
v. A vacuum system capable of bleeding approximately 1.5 lbm/s @ 5psia at 200F.
vi. Secondary air requirement of approximately 6 lbm/s at 100 psig at 280 F for the drive turbine.
vii. Tertiary air requirement of approximately 3.0 lbm/s at 100 psig at 70 f for secondary flow.
viii. Water cooling for oil cooling purposes.
ix. An oil system capable of delivering 8gpm at 65 psia that conforms to MIL-G-6529 Type III Spec.
x. Facility should have appropriate inlet ducting to feed the air to the drive turbine.
xi. Exhaust ducting to dump hot air at conditions mentioned before.
xii. Load banks capable of using up to 200kW of power generated by the Rampressor turbine or a dynamometer of that size, for that same power requirements.
xiii. A video taping of test data.

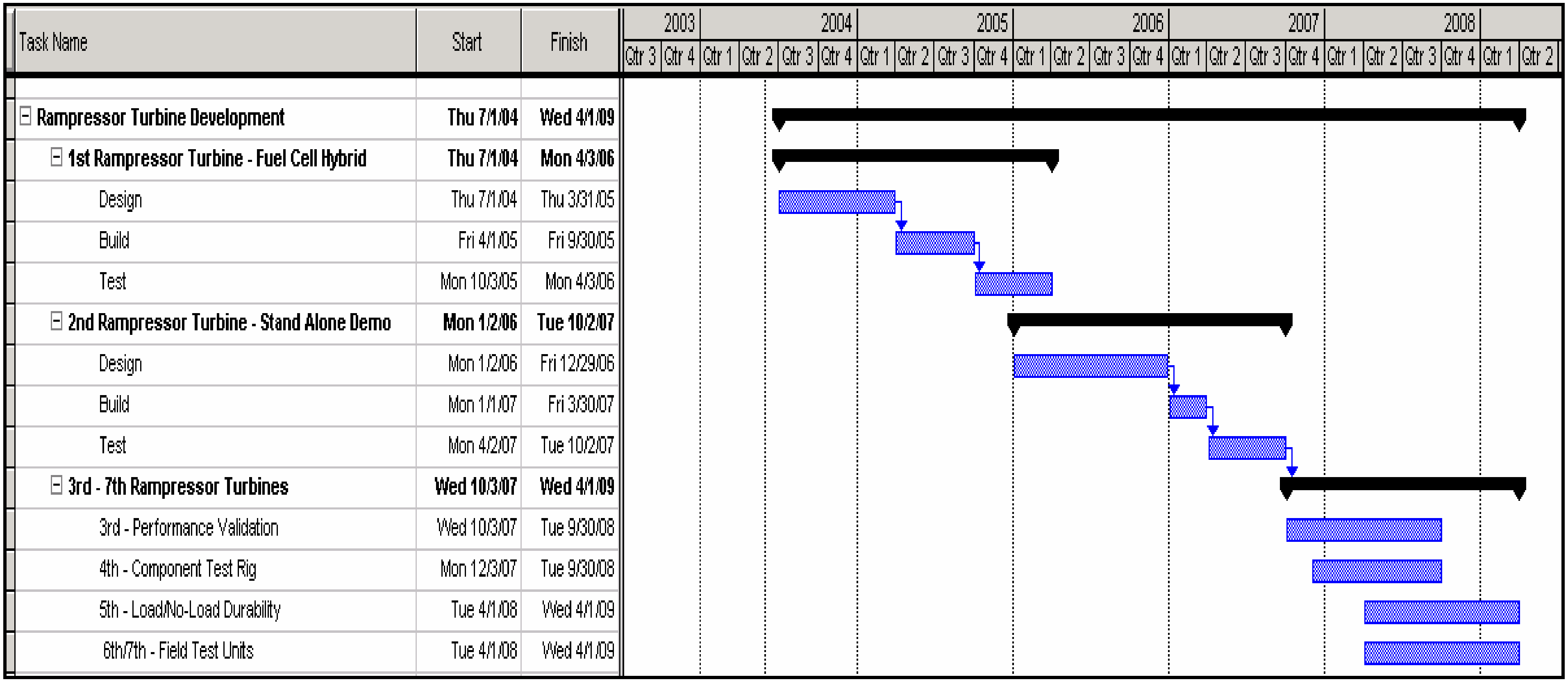
xiv. Data Acquisition details regarding the pressure, temperature and mass flow rate measurements.
xv. A build up area for assembling the engine together.
xvi. Test cell availability from Jan 1, 2005 for 8 months including two months of build up time and 6 months of testing.

Based on the above mentioned requirements, the cost estimates provided by different test cells are shown in table of Figure 4.10. The test cell costs range from $500,000 to $2,000,000. As can be seen, the Boeing Test Cell at Seattle provides the most cost efficient choice amongst all the test cells.

Finally, the different test rig configurations based on availability of funds for this program was considered. There is interest from DOD on a fuel cell application of the Rampressor Turbine. Depending on what becomes available, it was decided that the Rampressor Turbine will be designed in a way so as to be easily adaptable to a hybrid fuel cell application, if possible. Such an application requires an external combustor to be integrated to the Rampressor based Spartan turbine, and not directly coupled with the engine as was previously shown in the figure 4.5.

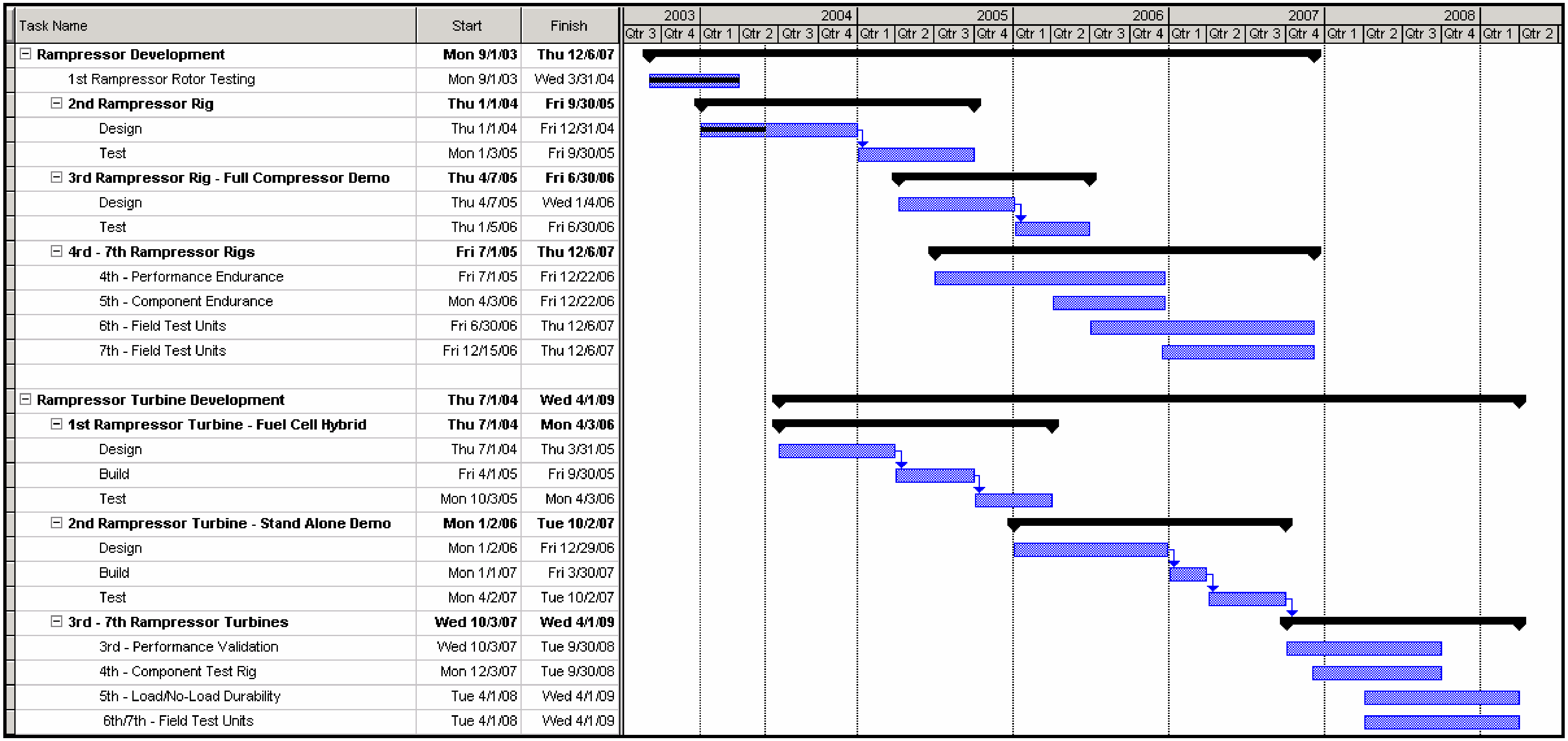
4.0 Conclusion

The early stage design layout of the Spartan Engine based Rampressor Turbine is complete. From a pool of 22 different engines, the Spartan gas turbine was chosen as the most appropriate design for integrating the Rampressor to an industrial gas turbine. The reasons for this selection and the advantages of such a selection were discussed. The advantages of testing a de-coupled design of the same were also discussed and during the 2004-05 fiscal year, the final design of this design is expected to be complete.



Task Name	Start	Finish
⊟ **Rampressor Turbine Development**	**Thu 7/1/04**	**Wed 4/1/09**
⊟ **1st Rampressor Turbine - Fuel Cell Hybrid**	**Thu 7/1/04**	**Mon 4/3/06**
Design	Thu 7/1/04	Thu 3/31/05
Build	Fri 4/1/05	Fri 9/30/05
Test	Mon 10/3/05	Mon 4/3/06
⊟ **2nd Rampressor Turbine - Stand Alone Demo**	**Mon 1/2/06**	**Tue 10/2/07**
Design	Mon 1/2/06	Fri 12/29/06
Build	Mon 1/1/07	Fri 3/30/07
Test	Mon 4/2/07	Tue 10/2/07
⊟ **3rd - 7th Rampressor Turbines**	**Wed 10/3/07**	**Wed 4/1/09**
3rd - Performance Validation	Wed 10/3/07	Tue 9/30/08
4th - Component Test Rig	Mon 12/3/07	Tue 9/30/08
5th - Load/No-Load Durability	Tue 4/1/08	Wed 4/1/09
6th/7th - Field Test Units	Tue 4/1/08	Wed 4/1/09

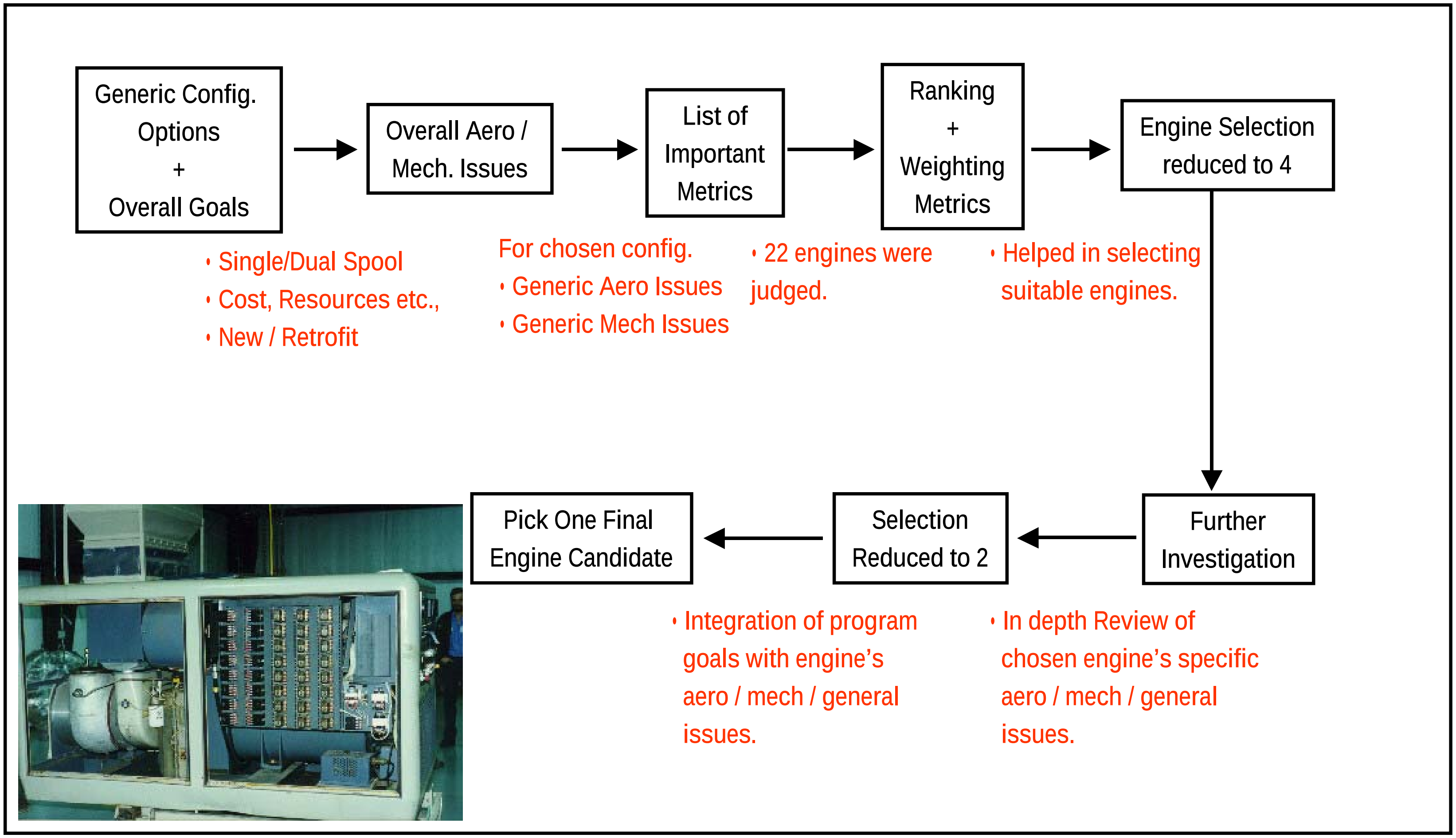
Figure 3.5. Ramgen's Rampressor Turbine Development Plan



Task Name	Start	Finish
⊟ **Rampressor Development**	**Mon 9/1/03**	**Thu 12/6/07**
1st Rampressor Rotor Testing	Mon 9/1/03	Wed 3/31/04
⊟ **2nd Rampressor Rig**	**Thu 1/1/04**	**Fri 9/30/05**
Design	Thu 1/1/04	Fri 12/31/04
Test	Mon 1/3/05	Fri 9/30/05
⊟ **3rd Rampressor Rig - Full Compressor Demo**	**Thu 4/7/05**	**Fri 6/30/06**
Design	Thu 4/7/05	Wed 1/4/06
Test	Thu 1/5/06	Fri 6/30/06
⊟ **4rd - 7th Rampressor Rigs**	**Fri 7/1/05**	**Thu 12/6/07**
4th - Performance Endurance	Fri 7/1/05	Fri 12/22/06
5th - Component Endurance	Mon 4/3/06	Fri 12/22/06
6th - Field Test Units	Fri 6/30/06	Thu 12/6/07
7th - Field Test Units	Fri 12/15/06	Thu 12/6/07
⊟ **Rampressor Turbine Development**	**Thu 7/1/04**	**Wed 4/1/09**
⊟ **1st Rampressor Turbine - Fuel Cell Hybrid**	**Thu 7/1/04**	**Mon 4/3/06**
Design	Thu 7/1/04	Thu 3/31/05
Build	Fri 4/1/05	Fri 9/30/05
Test	Mon 10/3/05	Mon 4/3/06
⊟ **2nd Rampressor Turbine - Stand Alone Demo**	**Mon 1/2/06**	**Tue 10/2/07**
Design	Mon 1/2/06	Fri 12/29/06
Build	Mon 1/1/07	Fri 3/30/07
Test	Mon 4/2/07	Tue 10/2/07
⊟ **3rd - 7th Rampressor Turbines**	**Wed 10/3/07**	**Wed 4/1/09**
3rd - Performance Validation	Wed 10/3/07	Tue 9/30/08
4th - Component Test Rig	Mon 12/3/07	Tue 9/30/08
5th - Load/No-Load Durability	Tue 4/1/08	Wed 4/1/09
6th/7th - Field Test Units	Tue 4/1/08	Wed 4/1/09

Figure 4.1. Ramgen's Technology Development Plan

Methodology



Generic Config. Options + Overall Goals

- Single/Dual Spool
- Cost, Resources etc.,
- New / Retrofit

Overall Aero / Mech. Issues

For chosen config.
- Generic Aero Issues
- Generic Mech Issues

List of Important Metrics

- 22 engines were judged.

Ranking + Weighting Metrics

- Helped in selecting suitable engines.

Engine Selection reduced to 4

Further Investigation

- In depth Review of chosen engine’s specific aero / mech / general issues.

Selection Reduced to 2

- Integration of program goals with engine’s aero / mech / general issues.

Pick One Final Engine Candidate

Figure 4.2. Engine Selection Process Flow Chart

Results of Engine Selection Process

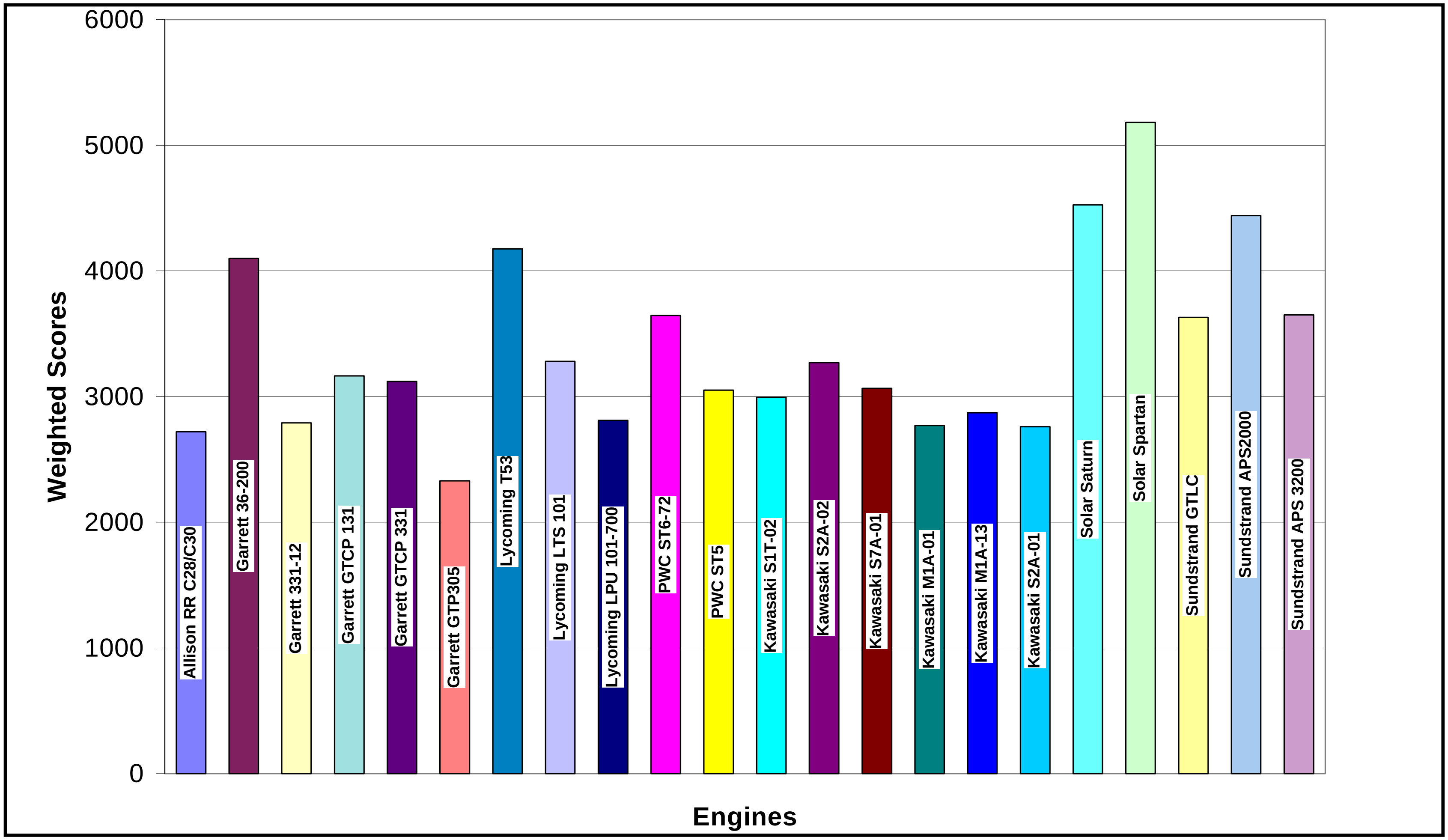


Figure 4.3. Engine Selection Process Scoring

Engine Layout Details

Engine	Engine RPM	Required Pressure Ratio	Mass Flow (lbm/s)	Tip Speed (ft/s)	Impeller PR	PSN Exit Mach No.	Rampressor Tip Radius (inches)	Rampressor Centerline Radius (inches)	Rotor relative Mach number	DeSwirl Vane Inlet Mach	DeSwirl Vane Inlet Angle (deg)
Garrett 36-200	62400	4.2	2.80	1774	1.2	0.39	3.26	2.92	1.54	0.7	-80
Solar Saturn	22516	6.27	13.45	1785	1.1	0.56	9.08	8.35	1.92	0.68	-83
Solar Spartan	37059	4.2	5.00	1756	1.1	0.33	5.43	4.96	1.56	0.71	-82
Sundstrand APS2000	45000	4.3	7.00	1795	1.2	0.46	4.57	4.03	1.58	0.7	-79

Figure 4.4. Critical Parameters for Four Engines

Rampressor- Turbine 1 X-Section

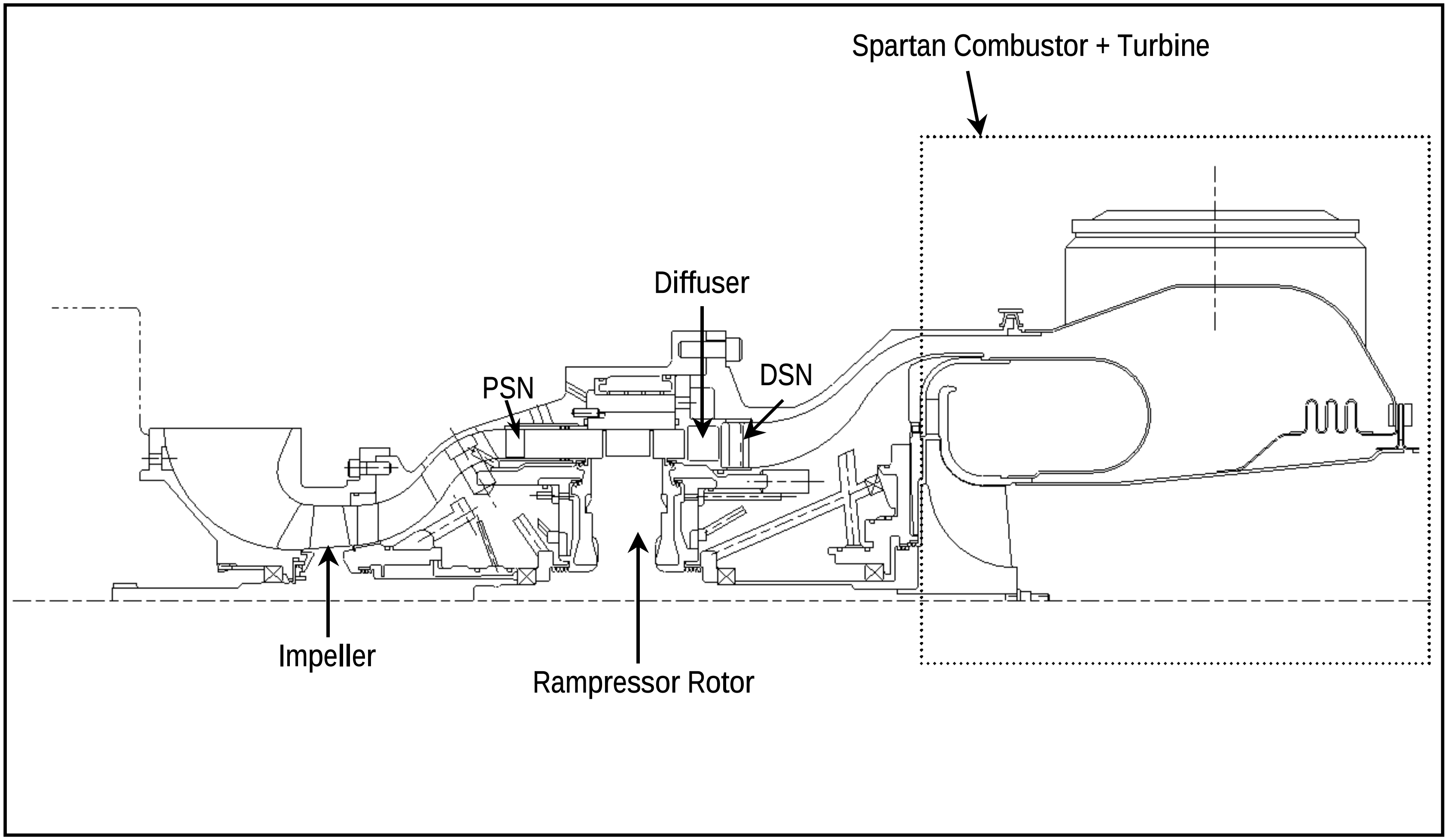


Figure 4.5. Rampressor Turbine 1 Layout

Spartan Aero Components

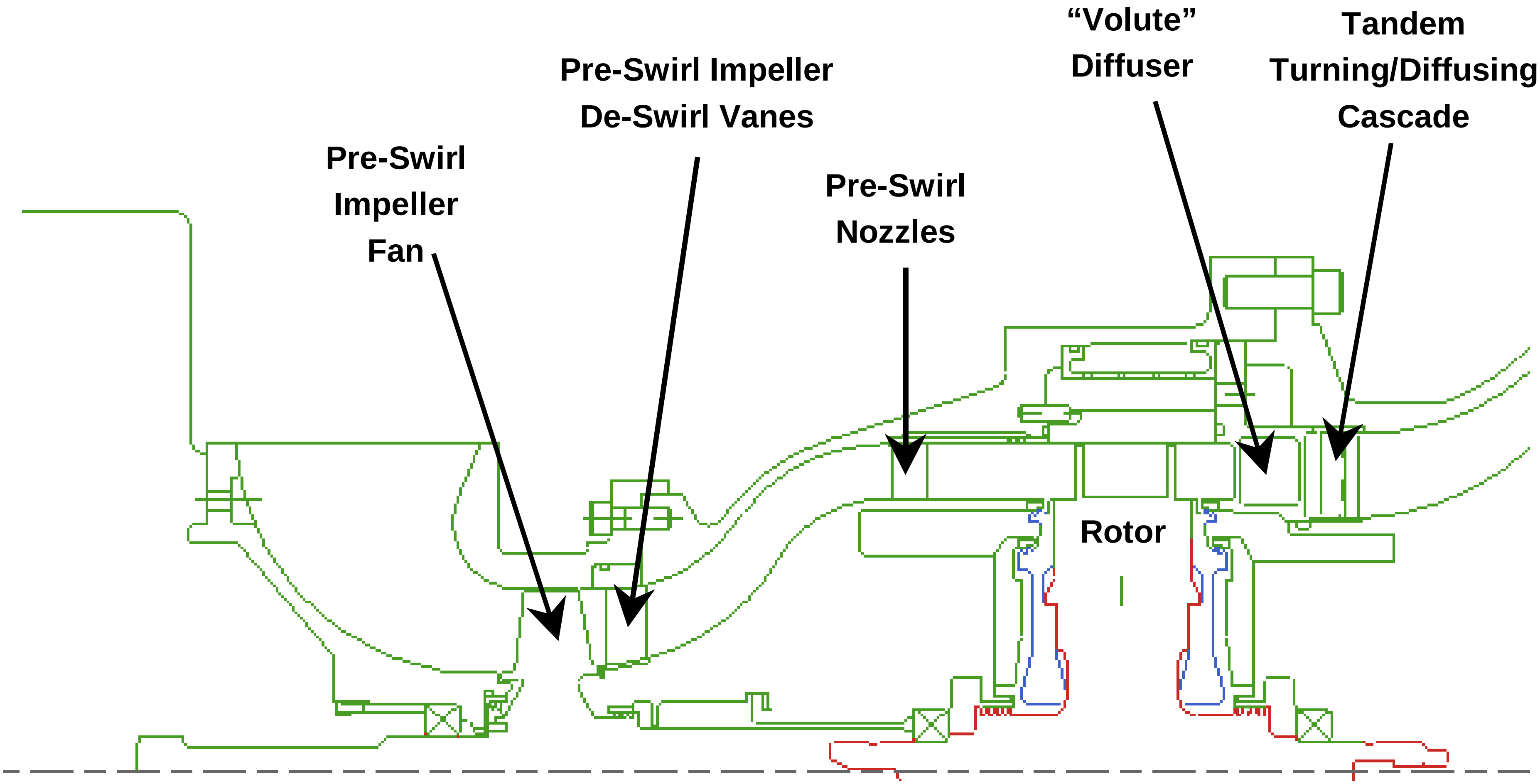
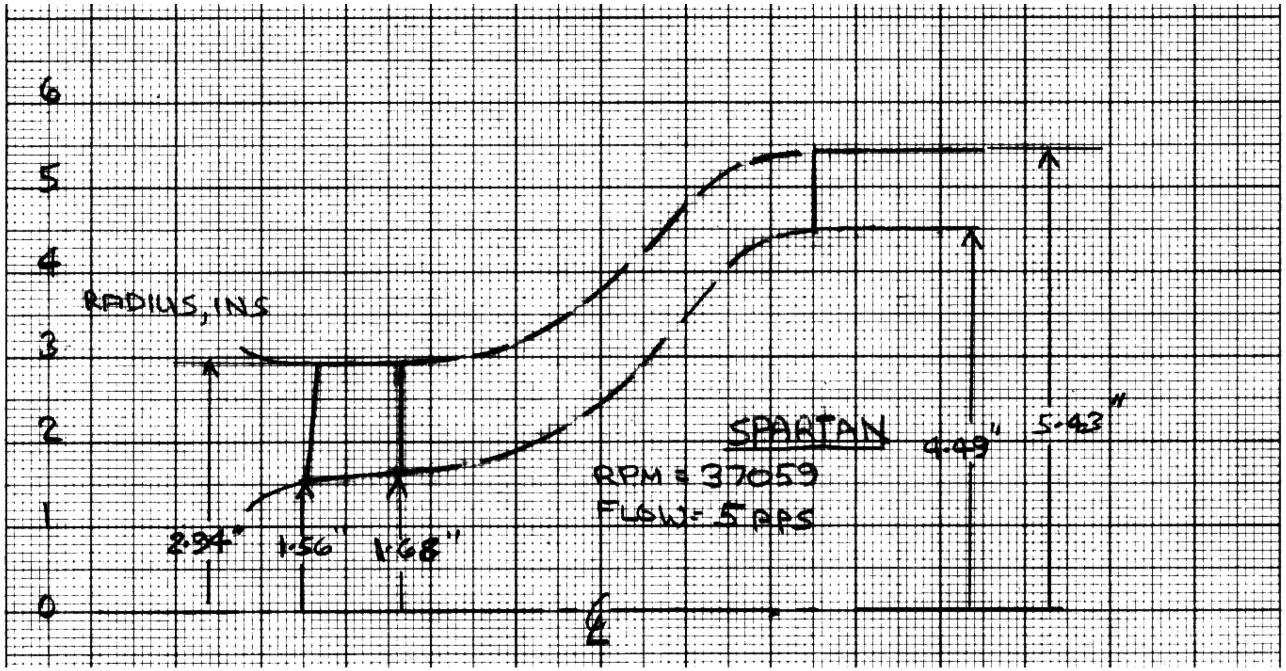


Figure 4.6. Spartan Rampressor Turbine Aero Components

Impeller Design

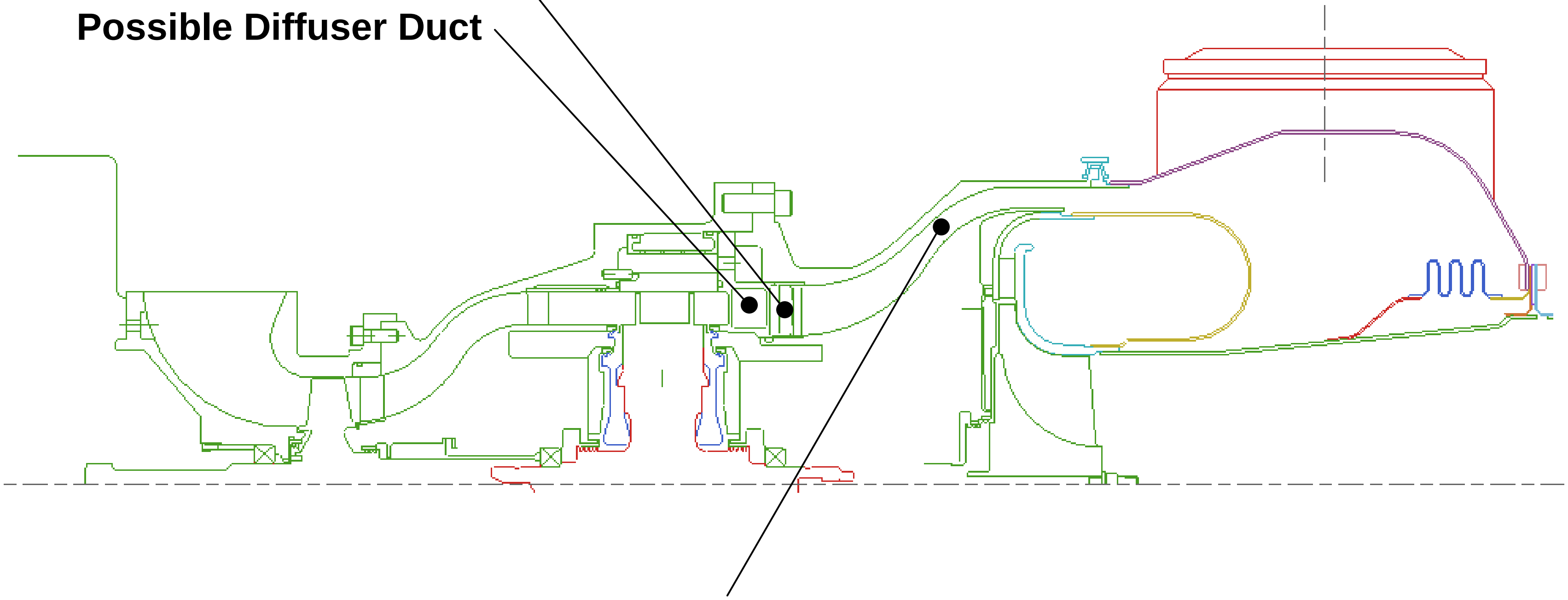


- 1.1 PR Design by A. Stone
    - – 2.94” Tip Radius
    - – 950 ft/sec tip speed (550 ft/sec outflow) -> Needs to be de-swirled?
    - – Want ~91% efficiency

Figure 4.7. Impeller Design for a Spartan Rampressor Turbine

Rampressor Turbine Diffuser Design

Current Conceptual Layout



Tandem De-Swirl Cascade

Possible Diffuser Duct

Duct Height Must Be Managed with Conservation of Angular Momentum to Avoid Increasing Swirl with Duct Radius

Figure 4.8. Rampressor Turbine Diffuser Design

Estimated Test Rig Cost Summary

Component	Description	Estimated cost	Estimated Cost Basis
Peripheral Equipment			
Drive	Electric Direct Drive	$50,000	Probably use Bsi Drive again
Lube	Hydraulic components	$4,000	Only needed for Rampressor Bearings
Controls		$15,000	Upgrade/Modification to existing
Instrumentation		$75,000	Puts total Instrumentation/Controls at ~$100K
Rig Table	Mounting Stand	$5,000	Engineering estimate
Containment		$1,000	Engineering estimate
Peripheral Equipment		$35,000	Load banks/gearbox
Analog to Digital Equipment		$10,000	Engineering estimate
Misc.	Nut, Bolts, O-rings, Tubes, etc.	$25,000	Engineering estimate
Impellor Rotor		$15,000	Engineering estimate
Test Unit			
Rotor			Engineering estimate
Forgings	Mcwilliams	$30,000	
Rotor machining	Sermatec	$20,000	
Rotor Segments	3 sets of flow paths	$168,000	
Unit (less Rotor)			Engineering estimate
Static Hardware		$150,000	
Pre Swirl (2 sets)		$16,000	
De-swirl (2 sets)		$32,000	
Snail-shell Diffuser		$10,000	
Bearings		$5,000	
Turbine and Combustor	Commerical unit for purchase	$40,000	Online quotes
Total Turbine Rig		**$706,000**	

Figure 4.9. Estimated Test Rig Cost for a Spartan Rampressor Turbine

Rampressor- Turbine Test Facility Costs

Test Cells	Boeing (WA)	Wyle Labs (LA, CA)	Alturdyne (SD, CA))	NRC (ON)	Standard Aero (Winnipeg)	MTSI (OH)	Woodgroup (LA)	Aero Systems Eng (MN)	China Lake (CA)	NASA Glenn
Setup Costs	$114,000			$115,000	$500,000	$480,000	$485,000	$522,000		$1,200,000
Cell Mods	$10,000									
Exhaust Duct	$5,000									
LN2 system	$7,000									
Load Banks	$2,000									
Facility Usage										
DAS	$0									
Testing (6 months)	$300,000			$450,000	$490,000	$322,500	$244,000	$244,000		$1,000,000
Fuel Costs (6 months)	$30,000			$30,000	$30,000					
Travel		$80,000	$80,000	$80,000	$80,000	$80,000	$80,000	$80,000	$80,000	$80,000
Total Cell Cost	$468,000	$80,000	$80,000	$675,000	$1,100,000	$882,500	$809,000	$846,000	$80,000	$2,280,000

- Preliminary testing costs range from $500,000 to $2,000,000.
- Boeing is the preferred location.

Figure 4.10. Estimated Test Facility Costs for testing a Spartan Rampressor Turbine