Meeting Report

April, 2002

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Technical Report

Abstract

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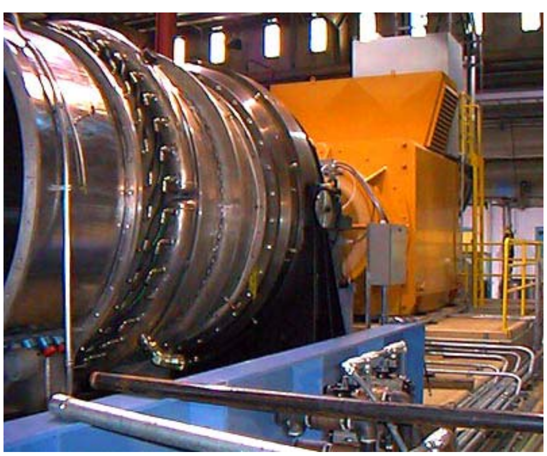

Ramgen Prototype Engine

RAMGEN Design Review Workshop

The RAMGEN generator is a new way to make shaft power to drive an electric generator or other driven equipment. The novel engine concept uses a high rotational-speed rotor to induce supersonic flow to ramjet modules in the wheel perimeter, making the unit mechanically simple, and avoiding many of the moving airfoils that exist in gas turbines. The RAMGEN process is efficient with little pollution, attractive cost, and features that will make it a significant competitor that can compete with today's gas turbine engines when development is complete.

Ohio Aerospace Institute, Cleveland, Ohio

On April 9-10, 2002, RAMGEN assembled a Government review team to evaluate the RAMGEN engine technology. The RAMGEN staff introduced and reviewed the status of the technology and the next generation engine design to members of the design review committee. Recognizing the talent that exists in the government, the group was used to critique the current design approach, suggest ways of improving the design, and helped find areas where the government had particular expertise to contribute to its development.

The Design Review process documented here includes:

- Discussions on the general orientation, technology evolution and milestone achievements of the RAMGEN engine.
- Assessments on the group's views about RAMGEN's 2.8 MW engine design and Technology Readiness Level.

Executive Summary

On April 9th and 10th 2002, RAMGEN, under the direction of NETL U.S. Department of Energy ("DOE" Morgantown) assembled a team of approximately 20 senior engineers and scientists representing various branches of the federal government (NASA, Army, USAF, DOE/NETL) to review and evaluate the RAMGEN engine technology at the Ohio Aerospace Institute Cleveland.

This team was well qualified to technically critique the RAMGEN engine technology, based on their individual expertise, and their considerable collective experiences in relation to flight propulsion, mechanical drive, and power generation systems. RAMGEN experts presented the technology with assistance from several industry consultants.

To ensure transparency of process, the evaluation of the RAMGEN engine technology was approached from a "workshop style" perspective and facilitated by a technically competent, independent DOE selected contractor ("Parsons Infrastructure and Technology"). Throughout the evaluation there was ample time for reviewers to "cross examine" RAMGEN's experts in open forum, and to probe deeper into any specific areas of technical interest or concern during several highly detailed "technology breakout" sessions.

The evaluation and summary conclusions of government reviewers (which can be found in this report) were organized by the use of a federal based Technology Readiness Level ("TRL") approach as applied to four distinct aspects of the RAMGEN engine technology, namely:

- The overall technical concept
- Engineering and design
- Manufacturing
- Integration and test

The reviewers did not identify any technology challenges that would prevent the development of the RAMGEN engine technology to meet projected commercial performance targets. Independently, the reviewers confirmed RAMGEN's internal evaluation of technology issues requiring additional development and of the Company's plan to reach successful commercialization.

There was agreement that in successfully resolving the remaining technological issues the scientific resources of the federal agencies are essential. Two cited examples of this were the knowledge and experience in federal agencies of advanced materials and the access by RAMGEN to engine component test facilities at federal sites.

NETL is committed to repeating this design review in the future; and, to the maximum degree possible, with government experts in turbo-machinery technologies. It was recommended that NETL (DOE) ensure that maximum federal technical review and support be provided for the development of this technology. Rigorous design review of the RAMGEN technology is critical as it has serious promise for making a significant contribution to meeting the nation's energy needs.

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The RAMGEN engine is a new approach to generate power. A RAMGEN engine can drive an electric generator or supply power to other driven equipment. Initial testing of the RAMGEN engine concept is complete and the refinement of its next generation design and development is proceeding. When development is complete, the engine's simplicity will provide a system with competitive low cost and ease of maintenance. This and the other attractive operational features of the RAMGEN engine will give this new technology an effective competitive edge that will challenge and displace the present 2 to 20 MW stationary power generation machines.

RAMGEN Design Review and Workshop

In April, 2002 RAMGEN assembled a government review team in a workshop to evaluate the RAMGEN engine technology. RAMGEN introduced and reviewed the status of the technology, described the first test device and how that has led to the next test engine design. After a thorough review of the technology, design methods, and program status to the members of the design review team, a dialog was initiated to better understand how to improve the device, and the development process. The group critiqued the current design approach, suggested ways of improving the design, and helped find areas where the government had particular expertise to contribute to the development of this new type of engine.

Ohio Aerospace Institute Conference Room

The government panel represented at the workshop was well versed in the many fields of technology needed to understand and develop engine designs. The panel included engineers and scientists with backgrounds that spanned: inlet design assessment and test professionals, thermal and combustion research facilities, fluid dynamics and computational fluid dynamics, system analysis, gas turbines, turbomachinery, aerodynamics, propulsion, turbine cooling, combustion, and power plant design. These professionals came from diverse backgrounds that included: the Air Force and Air Force Research Laboratory, the Army, the Department of Energy, NASA, and Oak Ridge National Laboratory.

Design Review

The RAMGEN engine is an entirely new engine concept, just beginning its development, not unlike the situation that existed in 1929 when Sir Frank Whittle pioneered the development of the very first gas turbine intended for aircraft propulsion that led to Hans von Ohain's design that made possible the first gas turbine propelled flight on August 27th 1939.

At the workshop, the novel features and operation of the RAMGEN engine were introduced to the diverse group of technical experts. The testing of the first prototype in Tacoma, Washington was reviewed. The status of the present test program was presented and what was learned from the earlier tests. The group discussed how these test lessons have led to an improved prototype design. Finally, a preview was given of the new design and the planned continuation of the research and development program that will further refine the development of the RAMGEN engine.

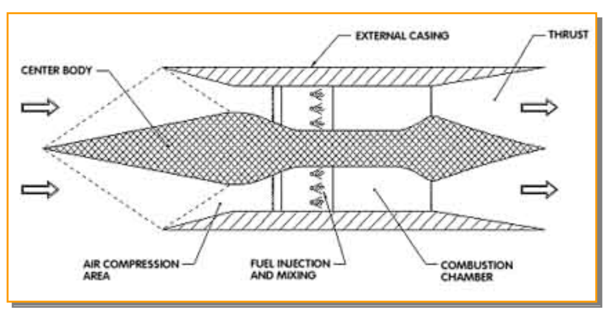
How the RAMGEN Engine Works

The novel engine concept uses multiple ramjets wrapped into the rim of a rotor to develop power in a gas turbine-like (Brayton) combustion power cycle. Engines, like gas turbines, ramjets, or the RAMGEN concept operate by supplying some power to compress air, using that pressurized air to burn fuel and increase temperature, and then pass the high temperature air either through gas turbine blades to spin a shaft, or through a high velocity exhaust jet to create thrust in a jet engine, ramjet or the RAMGEN engine

Shawn Lawlor, Ramgen Power Systems

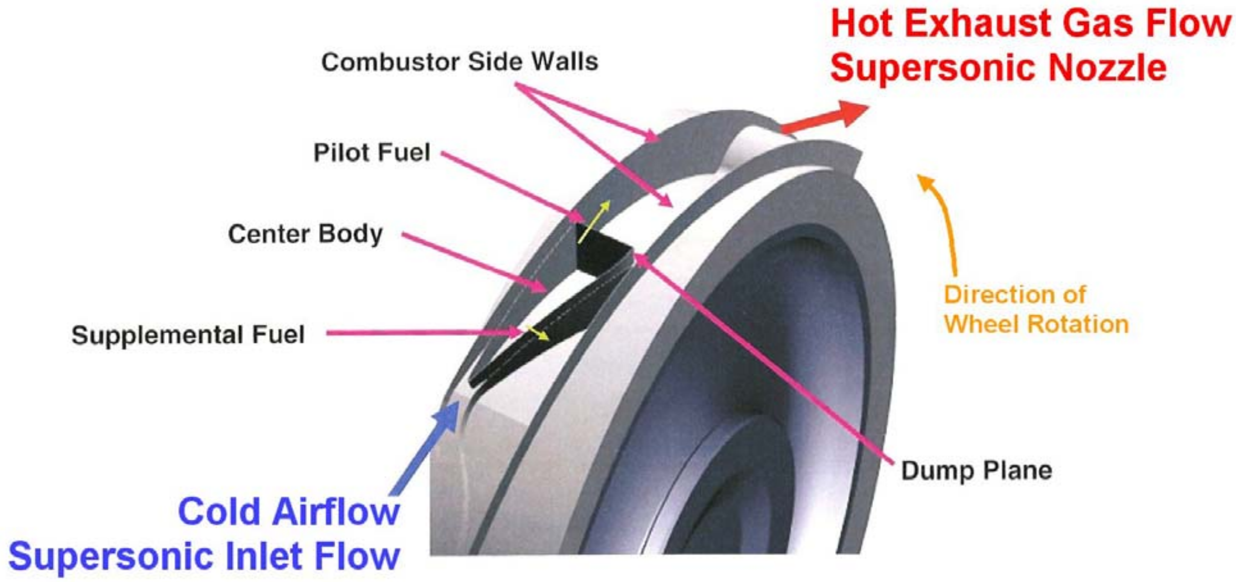
The RAMGEN engine design is based upon two earlier successful 'grandfather' technologies. One is the gas turbine engine, the other is the ramjet. Gas turbine engine technology supplies the high-strength, high-temperature materials and cooling methods adapted by the RAMGEN engine. The ramjet supplies the compression, combustion, and jet expansion technology adapted by the RAMGEN engine.

A ramjet is a type of high-speed propulsion device that takes advantage of the unique way supersonic shock waves compress air. When air moves at high Mach number supersonic speeds where the air moves faster than the speed of sound, a shock wave occurs when the air encounters a stationary part. Shock waves increase the pressure. When a carefully



Ramjet Flow Path

designed inlet is used, the shock waves can be captured by the inlet, and compression can be very efficient. The pressurized air is burned, and then expands in a converging-diverging nozzle that converts the heat in the gases to a supersonic high-velocity exhaust which produces thrust.



Ramgen Engine Flow Path

A RAMGEN engine wraps several uniquely-designed ramjets into the rim of a heavy wheel, as shown in the illustration above. These flow-paths wrap to form a helix or auger. The rotor is spun at high speed so that the outer edge produces Mach 2.6 supersonic airflow to the inlet. The ramjet inlet is carefully designed to efficiently convert the velocity into pressure rise. The compressed air and fuel burn in the ramjet's rotating combustor which is effective in mixing the fuel and air to keep NOx production low. These gases then pass through the exhaust-jet nozzle, a passage contoured into the rotating wheel rim. These jets generate the thrust that spins the rotor, making power.

While this is a sophisticated high-technology design, in implementation, a RAMGEN engine is a mechanically simple device whose few moving parts avoids the need for multiple highly stressed, row-upon-row of high precision compressor blades and cooled rotating turbine airfoils that are needed in gas turbines. Instead, the RAMGEN engine is a much more compact helical open passageway with very precisely machined geometry for efficient operation. Some of the design problems are similar to those in gas turbines, others are unique to this device. The high-strength rim of the rotor for example, has the same type of strength requirements as a gas turbine. However, its effect on the gases is much different. The high RAMGEN wheel speeds chosen induce a tremendous g-loading to the combustion gases, subjecting them to over 50,000 g's. As a consequence, the combustor design takes unique advantage of the stratification that occurs as combustion gasses change density during the combustion process to produce lower emissions and higher efficiences.

RAMGEN is in the midst of the development of this unique approach to power generation. The elegance of the RAMGEN engine is its simple but sophisticated approach to efficient operation, high energy efficiency, and low pollution.

The First Prototype Tests: The Tacoma Design. The first-of-a kind prototype RAMGEN engine was run in Tacoma, Washington. While the test durations were fairly short, the tests did prove that the technology works, and that the computational tools for projecting performance to the latest design are adequate. A tremendous amount was learned from the Tacoma prototype, and all of this valuable test experience is now being used for the new design, despite the rotational speed limit of Mach 1.1. This is at the threshold of positive thrust.

The New 2.8 MW Prototype Design.

The new engine, is presently in the design phase. This second RAMGEN engine prototype will produce 2.8 MW output. In the 2.8 MW engine inlet design, an oblique shock structure rotating on the disk will provide an apparent Mach 2.6 flow. The inlet is designed to capture the airflow, moving the air through a series of oblique shocks to a final normal shock in the throat of the inlet.

Design features of the 2.8 MW engine design include the following:

Mark Novaresi, Ramgen Power Systems

- The ramjet rotating parts comprise the inlet, burner, and planar supersonic nozzle. It uses an un-shrouded design, so from the relative viewpoint of the rotating onboard air and combustion products, these gases see three ‘stationary’ (to the gases) rotor walls and one ‘moving’ casing wall, very much different than other combustors. Of course that is the view relative to the combustion gases; of course the casing is fixed, and the rotor is in fact moving the gases and rotor walls at high rim speed.
- To control hoop stresses we are using a design with 52 unique cooled segments per ramjet; there can be two or three ramjets equally spaced around the perimeter of the rim.
- Conservative limits are used on materials well-established in the gas turbine industry for the construction of the 2.8 MW engine components. These are kept well within the temperature and stress limitations of the materials.

- Tip leakage control is critical. The design areas of focus are the engine body design, active tip clearance control, and out-of-round situations. The amount of leakage over the strake tips is critical. First, the goal is to minimize leakage at steady state. However, during transients, the time constant mismatch between case and seal is what matters. It is important that the seals do not rub during the transients, yet are in position to be tight at steady-state.
- The combustion occurs at very high g-loading levels. The problem is dealing with combustion stabilization and stratification in a high g-force environment. We're using the difference in density of the hot/cold products under the high g-loading to enhance mixing. Since combustion will occur 50,000 g's in the 2.8 MW engine we expect to learn a lot during test, as this is an operating regime that has not been seen before. The rotating natural-gas-fueled burners are reliably ignited by propane-air mix, lit by a spark at low rotor speed as proven in the Tacoma engine.
- Flow is choked at the supersonic converging-diverging exhaust nozzle. At the exhaust throat, the exhaust gas is at Mach 1, then is expanded supersonically to develop tangential thrust at the wheel rim, providing the torque. Unlike a flight convergent-divergent nozzle where weight is a premium, here you can afford the length of expansion surface to provide a near isentropic expansion profile for the exhaust gases, improving the nozzle thrust.

Feedback and Comments:

At the conclusion of the group technical reviews, three separate break-out sessions were conducted. These break-outs were run in parallel sessions to provide each of the three groups with additional detail about the RAMGEN design, while allowing for a smaller group setting to solicit feedback and comments about the readiness of the design from the assembled government experts.

 **Break-Out A: Mechanical / Materials / Manufacturing**	 **Break-Out B: Combustion / Heat Transfer**	 **Break-Out C: Aerodynamics / Engine Integration / Performance**

The evaluation and summary conclusions of the panel of government scientists and engineers were organized by the use of a federal based Technology Readiness Level ("TRL") approach to four distinct aspects of the RAMGEN engine technology:

- The overall technical concept

- Engineering and design
- Manufacturing
- Integration and test

The opinions of the participants were measured by taking rankings and expressing them in technical risk level (TRL) numbers was accomplished by weighting the risk levels as:

- TRL= 1-3 low readiness, higher risk; Basic principles, technology concepts, scientific feasibility demonstrated.
- TRL= 4-6 medium readiness, medium risk; Technology development and demonstration.
- TRL= 7-9 high readiness, low risk; complete system demonstrated under actual conditions and loading.

The overall results of these sessions are summarized as follows: <u>RAMGEN's conservative approach to engineering design was respected by the reviewers The reviewers did not identify any technology challenges that would prevent the development of the RAMGEN engine technology.</u>

However, there was consensus that continued development and testing is needed. The reviewers independently confirmed RAMGEN's own internal assessment of key development challenges, such as tip clearance, flame stabilization under high gravity loading, reducing air for cooling, etc. The group was very direct and open in its review and critique of the design. Their opinions are described in great detail in this report. Some of the major points raised include:

The need for better understanding of the sensitivity of leakage effects for the inlet, combustion chamber, and its effect on nozzle performance and cycle efficiency. Controlling tip leakage and leakage over the strakes was viewed a significant design issue.

In general, the group was comfortable that the materials existed, and design solutions existed to produce the engine. Design oriented comments were summarized in the format of TRL's as presented below. <u>The overall average TRL was 4.8 for the complete engine under the five categories shown below. The voting categorizes the technology as "medium risk".</u>

In general, the panel members felt that manufacturing and integration / testing development of the RAMGEN engine did not have the same level of risk as that associated with engineering and design.

	Technical Readiness Level			
Issue	**Technology**	**Engineering Design**	**Manufacturing**	**Integration and Test**
Tip Leakage / Strakes	3.7	2.3	4.7	3.7
Material-Rotor	6.0	4.7	5.0	6.0
Material-Segments	5.0	4.3	5.3	6.3
Slinger Design	4.7	3.3	3.3	4.7
Casing Concentricity`	6.0	4.7	6.0	6.7

Mechanical Design Priorities

Additional high priority technology issues that were emphasized by the other breakout groups, and were already recognized by the RAMGEN staff, are listed below.

- Need for proof of concept test big enough to produce and measure net positive torque.
- Inlet performance needs to be understood better, good computation models are needed, and confirmed by test.
- Flame stabilization is a design concern that needs to be established by test.
- Reduced air cooling should be a priority.
- Fuel/air mixing needs to be confirmed.
- High-g combustion needs to be better understood.
- Testing is needed to understand and calibrate the computational flow dynamics models for operating in this unique regime.

A TRL range of 2 to 4 was identified for the advancement of the inlet aerodynamics and the combustor optimization.

The expectation is that there is still a need for substantial investment in testing and development. A projected 4 to 5 year engine program will take RAMGEN to the point of development which will yield a TRL of 9 and an accumulation of sufficient hours of operation to give confidence in the technology.

The Future

- By the end of this year with sufficient funding, the 2.8 MW design will be finished.
- If all funding were in place, RAMGEN could manufacture the core engine for the proof of concept by 4th quarter of 2003 for cold-flow testing.
- Hot core testing is anticipated to follow in 2004.

What You Will Find Here

This report gives a comprehensive review of what happened in the Workshop. The sections that follow describe the following:

- **Tuesday April 9 Group Session**: This section documents the RAMGEN design, approach to testing, performance predictions, and plans.

- **Tuesday April 9 Break-Out Sessions**: This section introduces how the three break-out sessions were conducted.

- **Wednesday April 10 Group Session**: This section begins with a summary of the results from the three break out sessions:
- Break-Out Session A: which concentrated on mechanical, materials and manufacturing issues,
- Break-Out Session B: which focused on combustion / heat transfer issues, and
- Break-Out Session C: which focused on aerodynamics / engine integration / performance

Later, in the Appendices A,B,C of this report, the full verbatim discussion of issues in each of these break-out sessions is detailed.

Once the break-out sessions comments were summarized, a general discussion follows in the text, where the RAMGEN design team sat as a panel. This discussion summarizes the dialog of the audience and comments of the design team.

- **Appendices**: The report concludes with three appendices that give the verbatim scribe's notes detailing the comments from the three breakout sessions:
- Break-Out Session A: Mechanical / Materials / Manufacturing
- Break-Out Session B: Combustion / Heat Transfer
- Break-Out Session C: Aerodynamics / Engine Integration / Performance

- ****Workshop Handouts***********

RAMGEN Workshop Panel

Glenn Smith   Shawn Lawlor   Mark Novaresi   Donald Kendrick   Rob Steele

Acknowledgements

RAMGEN appreciated the interaction, and contributions of the group. RAMGEN also recognizes the assistance of Parsons Corporation for their help in preparing this report. Particular thanks to:

Harvey N. Goldstein

Richard E. Weinstein

William M. McMahon, Jr.

General Session Notes

Tuesday April 9 Group Session (a.m.)

Scribe: Richard E. Weinstein

Ohio Aerospace Institute Conference Room

Tom George, NETL

Opening Remarks - Tom George, NETL

Tom George, NETL program manager, opened the meeting by acknowledging the technical expertise that exists in the various government agencies and soliciting the participation of the attendees in developing this new device. He introduced the NASA Technical Readiness Level (TRL) system, and reminded the audience that the RAMGEN concepts were proprietary information which the audience was familiar with handling.

Glenn Smith, COO, RAMGEN

In addition to the RAMGEN power unit, the company is now also developing a spin-off technology, a new product, "RamComp" now undergoing patent, that is a ram compressor design variant of the base engine. RamComp drops the burner and nozzle, using the ram concept as a stand-alone high efficiency compression device.

Glenn Smith, Ramgen Power Systems

Introduction to the Technology – Dr. Robert Steele, RAMGEN

Technology Introduction by Rob Steele, Ramgen Power Systems, Vice President of Engineering

The prototype RAMGEN engine run in Tacoma Washington was discussed, and a video of the engine assembly was shown. There were limitations in the disk that kept the system from running at full speed. In the Tacoma test, tip speed was at M=1.1. Just at the threshold of positive thrust.

RAMGEN is a 'disruptive' technology. It could displace current gas turbine technology, at least in the size range from 2 to 20 MWe.

Ram accelerators have been able to accelerate a projectile to several 1000 fps. RAMGEN has some similarities to this technology.

Q: Did the rotor in the video have a center body?

A: No that configuration did not have a center body

Design challenges at RAMGEN:

- Maintain acceptable metal temperatures on rotor assembly
- Develop tip clearance system
- Manage supersonic wheelspace drag and heating
- Utilize slinger technology
- Develop lean pre-mix (LPM) combustor at high g-loads and supersonic boundary conditions (non moving wall, so there is supersonic shear. Will high g-loading stratify combustion products?)

Description of the Pre-Prototype Test Engine – Dr. Donald Kendrick, RAMGEN

- 800 HP starter motor
- Rotor 2 disks sandwiched together, dovetailed, slotted into the rotor 120 segments
- Fuel enters inside rotor
- Laser-drilled cooling holes

Q: where is the cooling drawn from?

A: external cooling pump

- Instrumentation description

Dr. Donald Kendrick, Ramgen Power Systems

Q: Couldn't help notice a lack of a torque measurement; torque measurement is necessary for the baseline performance measurements of the engine.

A: We don't have one, couldn't find one for our specs, we need one.

Q: How fast do the IR instruments respond?

A: 10 kHz sampling at 800 rpm

Q: Do they respond that quick?

A: Yes, absolutely.

- IR information comes from a stationary probe in the case, since we have a known orientation, we can index the measurements to the rotor position.
- The ignition system simultaneously ignites both combustors at 800 rpm, after a pulse of pilot fuel. The ignitors are in the casing, perpendicular to the rotor.
- The rotating burners are ignited by propane-air mix. After the spark ignites the propane, the ignitor expels flame at the appropriate time during the rotation to inject the flame just as the step of the flame-holder moves beneath it. This establishes ignition in the rotating burner.
- To hold the flame, we used a bluff-body step, vortex generators, and a pylon device with fuel slots, and this dramatically increases motion intensity.
- Once ignited, you need to hold the flame, stabilize it, then bring the unit up to speed. This involves a delicate balance of fuel and air-cooling schedule.
- This is a delicate strategy, with fuel scheduling and air-film-cooling scheduling; each has a carefully scheduled rate. You walk a fine line between too rich and too lean, so it is precisely controlled.

Q: If you change fuel, would the range change?

A: absolutely

Q: If you change fuel, you start, restart?

A: After stabilization at full speed, 4300 rpm.

- We have "orange-trace" 90-degree combustor temperature and "blue-trace" 45-degree combustion temperature IR detectors. The 90-degree detectors sense combustion chamber temperature, the 45-degree detectors get part of the side-wall.
- We ran at a number of steady state test cases, with steady-state held for 50 seconds duration.
- At steady state, looked at a variety of sensitivities.
- Found hot spots, needing a change in cooling hole patterns in the combustor wall.

Q: Do you have a solution for the problems?

A: More a diffusion mix of the fuel- type burner.

- We use PSR modeling, breaking the model into packets, and use just that to predict using simplified reactor modeling techniques. This has proven an acceptable way of understanding the kinetics of the combustion modeling.
- The combustion occurs at very high g-loading levels, much higher than reported in the literature. In the Tacoma RAMGEN, the level of the g-

fields is about 15,000 g's. The problem is dealing with combustion stabilization, stratification at high g. Will this all work at 50,000 g's in the scaled-up engine? It is naïve to expect we'd know without test.

Q: What was the strake clearance for the Tacoma engine?

A: approximately 20 mils.

Q: Question on the inlet: am I correct you have a partial admission as you come in from annulus to augur? I'd like to see an efficient partial admission inlet, I've never seen a successful one, and thus suspect yours has a high pressure drop.

A: Don't know off the top of my head. Have the data to find out.

Mechanical Design of the 2.8 MW Engine – Mark Novaresi, RAMGEN

Mark Novaresi, Ramgen Power Systems

- There are 52 unique segments per ramjet; there can be two or three ramjets equally spaced around the perimeter of the rim.

Q: Why a segmented design?

A: Because of the hoop stresses, if it were solid you'd develop cracks, and it would segment itself, it's the same reason you have segments in a gas turbine design.

- Cooling air comes down the center of the aft shaft and up through the aft slinger. The fuel comes in through the forward shaft and slinger.
- We alternate fuel and air in the dovetails, and these are sealed off by the slinger.
- Right now design is focusing on geometry definition and on stress analysis.
- We're working on the engine body design, working very carefully on tip clearance control.
- We're also establishing rotor dynamics and bearing design.

Q: What type of bearings?

A: Hydrodynamic tilt-pad bearings

Q: Critical speeds?

A: We will be free of critical speeds in the operating range.

Q: Do you plan a burst test in a pit?

A: No. We're relying on very stringent quality control and inspection. Right now we have no plans to burst a disk.

- Materials Mar-M246 for the segments and IN718 for the disk.

Q: What is the operating temperature?

A: 1200ºF maximum metal temperature for the floor of the combustor. We have fairly conservative cooling assumptions, so we believe we can attain that.

Q: Each segment is all one piece?

A: Yes, one piece.

Q: Is the combustor segment an air-cooled component?

A: Yes, air cooled.

Q: Are these at high stress?

A: 120 ksi is the allowable stress.

- Disk analysis: highly stressed, but within material limits.

Q: Are you using equivalent stress theories?

A: Yes, we use the worst case for sizing.

- There is 3D assembly stress analysis.
- Tip leakage control is critical. The amount of leakage over the strake tips is critical. First, we minimize gap at steady state. However, during transients, the time constant mismatch between case and seal is what matters. It is important that the strake tips don't rub during the transients, yet are in position to be tight at steady-state.
- If you don't get proper cooling distribution on case, you'll get out-of-round, another source of leakage if roundness isn't controlled.

Q: Have you thought of going to a shrouded design?

A: Yes, but even if we found the material, it would creep. We could cool it, but remember, we have a huge centrifugal load. We have other ideas that I won't go into now.

- We're moving toward an active tip-clearance scheme. Here, when we start the engine, we'd heat the case, moving the seals out of the way until the engine is heated, while the engine is moving through its thermal growth trajectories. Once the engine is at steady state, we'd then turn off the heating, to get the seals back to their final tight clearance position.

Q: What is the source of heat?

A: Could be anything. Right now, we're thinking of electric heating, but there are drawbacks. We're looking at other choices.

- We're going out to industry experts for ideas.
- Passive clearance control systems typically hold clearances of 0.015 to 0.030 inch.
- Aero engines with active tip clearance control have attained 0.005 to 0.015 inch clearance, this is the clearance we're looking at.
- We have analytically looked at squealer tips to reduce leakage at the strake tips
- We've considered an aerodynamic curtain, that is, put the cooling right up there to block the leakage flow.

Mr. Novaresi then gave a review of looking ahead on the design. He continued:

- We'd activate the case locally to avoid out-of-round ovalization and consequent seal leakage.
- We're also looking to a regenerative adaptive system, a seal system that would restore itself after an inadvertent rub.
- In order to achieve higher tip speeds, and therefore better efficiencies, we have started investigations into the use of gamma titanium, which is castable, and available in forgings. Machining however is difficult. Cost of this high strength material is high. Gamma titanium is much more help to a RAMGEN type design than it would be for the gas turbine designers. For a RAMGEN design the superior properties of gamma titanium is worth the two-times cost premium over the alternatives.

NASA COMMENT: We have a good contact at NASA on gamma titanium.

Q: A question about seal clearance: is there a safety issue for fuel leaking over into the strake?

A: Yes that is a concern, we worry about combustibles leaking over the strake.

Q: How do you seal the segments?

A: There is a feather seal between them.

Flowpath Definition of 2.8 MW Engine – Shawn Lawlor / Donald Kendrick, RAMGEN

Shawn Lawlor, Ramgen Power Systems

Shawn Lawlor

- We use a precompression impeller to add a delta pressure to precharge the air entering the ramjet inlet.
- A subsonic cascade adds swirl, moving the air from the stationary to the rotating parts.
- The ramjet rotating parts comprise the inlet, burner, and planar supersonic nozzle
- After leaving the supersonic nozzle the exhaust gas has a significant amount of swirl. We recover this high degree of residual swirl in a downstream cascaded supersonic diffuser. There we stagnate the flow and subsequently impart the proper rotation for the radial outflow turbine that recovers the kinetic energy of the ramjet exhaust. This downstream expander adds torque.
- The radial turbine expander is designed by a contracted expert in radial expander design.

Q: Do you have or will you have a figure showing the shock structure and the principal surfaces, and where the positive or negative torques are developed?

A: Yes, absolutely; I will be discussing that in the Session C break-out this afternoon.

- The combination of disk rotation and pre-swirl creates an inlet inflow of M=2.6.
- High velocity exhaust gas leaves the reference frame of the rotor and is injected as appropriate onto the radial outflow turbine.
- This design uses a center-body that both defines the bifurcated subsonic diffuser and the flame stabilizer, and stabilizes a normal shock at the inlet throat.
- The inlet is designed to capture an oblique shock, with a normal shock in the inlet.
- Combustion efficiencies are assumed high, 99.5%
- Flow is choked at the supersonic converging-diverging exhaust nozzle. At the throat the exhaust gas is at M=1, then expanded supersonically to develop thrust and shaft torque. Unlike a flight convergent-divergent nozzle where weight is a premium, here you can afford the expansion surface to provide a near isentropic expansion profile for the exhaust gases, improving the nozzle thrust.
- Some of the major loss mechanisms:
- Static pressure drop on walls
- Nozzle gross thrust factor
- Tip leakage loss of propellant

Dr. Donald Kendrick

Dr. Donald Kendrick, Ramgen Power Systems

- We want to run the liner walls as hot as possible for best possible combustion efficiency.
- The constraints of a RAMGEN engine mean you have to live with a long narrow burner, thus, you don't have capability to add swirlers, so our design uses other approaches.
- There are three moving walls and one stationary wall, very much different than other combustors.
- We're trying to use the difference in density of the hot/cold products under the high g-loading to enhance mixing.
- Emission limit goals at full load design conditions at 15% O_2 are the following:

- NOx - 10 ppm

- CO - 10 ppm
- UHC - 10 ppm
- We've established combustor acoustic limits Pcomb'/Pcomb <2% to avoid upsetting other systems.
- Cold flow modeling support is underway.
- Turndown and flame stability are part of the testing plan.
- The combustion test rig is a half-scale burner, but with same pressures, temperatures, and acoustic conditions expected of the full-scale engine. The rig includes upstream and downstream orifices that match the Mach numbers and temperature conditions.

Q: Perhaps you need a shrouded design?

A: Well, mechanically it's a problem, but yes potentially we'd consider it.

Q: Have you established the temperatures in the flow field?

A: Yes, absolutely, I'll go over that <explains with charts> there's a CO knee at lower equivalence ratio.

Q: Did you measure NOx in your tests?

A: Yes.

Q: What were the results?

A: The Tacoma rig was built with a diffusion burner. The Tacoma burner was not run at design conditions, and had inadequate length, and is not prototypical of the current design status. Burning occurred in the eshaust nozzle, which should not occur when properly operated. The Tacoma NOx was thus very high, hundreds of ppm. We learned a lot from the Tacoma tests, and thanks to the tests, the new design avoids these problems.

Shawn reviewed the performance expected of the RAMGEN engine.

Tuesday April 9 Break-Out Sessions

Three separate break-out sessions were conducted in parallel sessions held Tuesday afternoon. The group members were allowed to join whichever session most interested them.

		
Break-Out A **Mechanical / Materials / Manufacturing** summary........................page 28 detail..............................page 43	**Break-Out B** **Combustion / Heat Transfer** summary....................... page 29 detail .... page 51	**Break-Out C** **Aerodynamics / Engine Integration / Performance** summary....................... page 31 detail .... page 67

The general conclusions from these sessions are summarized later in the section titled:," that begin on page 27. In addition, there were detailed notes taken during each of the three sessions. These detailed notes are included verbatim in the Appendix at the back of this report, beginning on page 42.

Wednesday April 10 Group Session

Scribe: Richard E. Weinstein

Wednesday morning discussions were broken into three areas:

- An overview of the results from the three break-out sessions,
- A panel discussion with the RAMGEN personnel addressing the major concerns from each break-out session, and
- A general discussion.

After these were complete, a tour of the NASA facilities in Cleveland was provided.

Break-Out Session Review Summaries

The introduction to the break-out sessions was addressed by Harvey Goldstein. A more complete explanation of the TRL evaluation approach can be found in each break-out session and in the Appendix at the end of the report. Harvey noted that there was a need for further understanding of the principles of operation of the RAMGEN engine. Later, the group would be used to help discuss these. The observations of the three break-out groups were summarized by their respective facilitators:

- Breakout A Summary: Mechanical / Materials / Manufacturing. Summary begins on page 28. If you need more information, you should also see the detailed notes in the Appendix: "Appendix A - Break-Out Session A: Mechanical / Materials / Manufacturing," beginning on page 43.
- Breakout B Summary: Combustion / Heat Transfer Summary begins on page 29. If you need more information, you should also see the detailed notes in the Appendix: "Appendix B - Break-Out Session B: Combustion / Heat Transfer," beginning on page 51.
- Breakout C Summary: Aerodynamics / Engine Integration / Performance Summary begins on page 31. If you need more information, you should also see the detailed notes in the Appendix: "Appendix C - Break-Out Session C: Aerodynamics / Engine Integration / Performance," beginning on page 67.

Breakout A Summary: Mechanical / Materials / Manufacturing

Taking rankings and expressing them in technical risk level (TRL) numbers was accomplished by weighting the risk levels (high as 2, Med as 5 and Low as 8) by the number of votes in that risk level and dividing the sum by 9 (number of voters). The results give an approximation of the session member's views of the readiness levels, which are as follows.

Issue	Technology	Eng. Design	Manufacturing	Integration and Test
Tip Leakage / Strakes	3.7	2.3	4.7	3.7
Material-Rotor	6.0	4.7	5.0	6.0
Material-Segments	5.0	4.3	5.3	6.3
Slinger Design	4.7	3.3	3.3	4.7
Casing Concentricity`	6.0	4.7	6.0	6.7

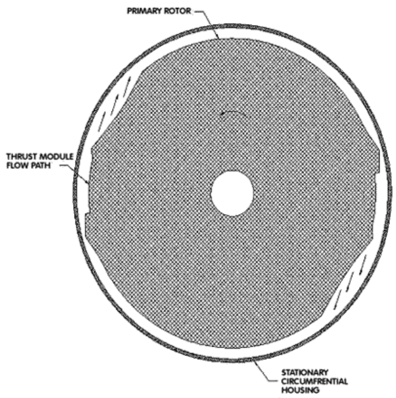
The results show that by far the greatest risk and the lowest TRL in the opinion of the members was for the engineering and design to prevent leakage at the tips and strakes at 2.3.

The second greatest risk was in the engineering and design of the Slinger assembly at 3.3. From a TRL standpoint, the members rated this second in priority.

In general, the members felt that manufacturing and Integration/testing development of the Ramgen engine was not as risky as Engineering and Design.

Breakout B Summary: Combustion / Heat Transfer

RAMGEN Design Review Workshop



Breakout Group B
Combustion / Heat Transfer

Tuesday, April 9, 2002

Harvey N. Goldstein, P.E. facilitator

Ramgen Design Review Workshop - 2002-04-RG-1

Make-Up of Breakout Group B

Don Kendrick	Ramgen
Jenna Jepperson	Scribe-Area Temps
Pete Meitner	US Army
Dale Shouse	USAF
Doug Straub	DOE/NETL
Lee Noble	Allied Aerospace
Jarad Daniels	DOE
Rolf Sondergaard	USAF
Mike Foley	Ramgen

Ramgen Design Review Workshop - 2002-04-RG

Combustion/Heat Transfer -Principal Findings

• Flame Stabilization	19
• Reduced Air Cooling	15
• Tip Sealing	14
• Fuel/Air Mixing	12
• High g Combustion	10

RAMGEN POWER SYSTEMS

Ramgen Design Review Workshop - 2002-04-RG

Combustion/Heat Transfer -Principal Findings

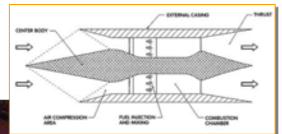
• Emissions Issues	10
• Cooling Effectiveness	8
• Fuel/Air Sealing	8
• Ignition	5
• Long Term Durability	4

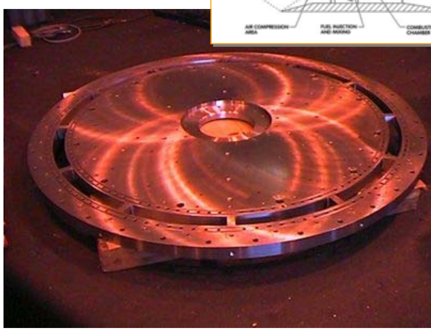
RAMGEN POWER SYSTEMS

Ramgen Design Review Workshop - 2002-04-RG

Breakout C Summary: Aerodynamics / Engine Integration / Performance

RAMGEN Design Review Workshop





Breakout Group C
Aerodynamics / Engine Integration / Performance

Tuesday, April 9, 2002
Shawn Lawlor

RAMGEN

Richard E. Weinstein, P.E. facilitator

Ramgen Design Review Workshop - 2002-04-RG-10

Make-Up of Breakout Group C

The makeup of the group included people with technical specialties in the following:

- Inlets (several)
- Inlet design assessment & test
- Research facilities (thermal and combustion)
- Fluid dynamics / CFD
- System analysis / Gas turbine modeling
- Turbomachinery
- Aero / Propulsion
- Turbine cooling and combustion
- Power plant conceptual design

RAMGEN

Ramgen Design Review Workshop - 2002-04-RG-

Observations About the Group Make-Up

- The group included many inlet and aerodynamic experts, so the observations and discussions were weighted toward subjects in that area

Ramgen Design Review Workshop - 2002-04-RG-

Other Observations

- The group included needed more explanation on the operation of the RAMGEN device
- A 3D 'hands-on' scale model would help understand the device and its operation

- Four areas of higher priority were highlighted
- Ten additional areas were a focus of discussion by the group
- Judgment of technical readiness level (TRL) in all areas hovered between 2 and 3

Ramgen Design Review Workshop - 2002-04-RG-

Need for proof of concept test big enough to produce and measure net positive torque

- 21 votes, most important area
- Need for proof-of concept test that will produce and measure net positive torque
- Technical readiness level (TRL) 2 is definitely achieved, need to work toward a 3
- If the Tacoma test had succeeded, would have been a 3

Technology Concept /Application Formulated TRL=2	Proof of Concept TRL=3

RAMGEN

Inlet performance – 3D Flow Issues

- Second-ranked issue· receiving 15 votes
- Inlet performance flow path analysis (complex; uses research codes, but in new regimes)

Technology Concept /Application Formulated TRL=2	Proof of Concept TRL=3

RAMGEN

Need for Good Inlet Testing to Accurately Represent the System

- Received 14 votes
- Testing and calibration of the models important

Technology Concept /Application Formulated TRL=2	Proof of Concept TRL=3
■■■■■	■■

RAMGEN

Ramgen Design Review Workshop - 2002-04-RG-

Sensitivity of Leakage Effects

- Received 11 votes
- Sensitivity of leakage effects for the inlet, combustion chamber, the effect on nozzle performance and on cycle of efficiency need to be better understood

Technology Concept /Application Formulated TRL=2	Proof of Concept TRL=3
■■■■■	

RAMGEN

Ramgen Design Review Workshop - 2002-04-RG-

Other Issues

- 9 Power of compression for film coolant with off-board compressor.
- 9 Estimate performance using CFD 3D methods, identify what data must be collected, and calibration vs test
- 8 Nozzle testing needed with simulation of leakage
- 7 Cross-bleed across strake tip
- 7 Pre-swirl performance, or impact of pre-swirler on inlet performance
- 5 Do present flow models adequately model in high-g high boundary layer? Are the tools up to snuff?
- 5 Demonstration of part load performance
- 3 Controlling strake tip leakage is a key issue as a source of propellant loss.
- 2 Bleed recycle is a major issue.
- 1 Torque measurement is needed

RAMGEN

Ramgen Design Review Workshop - 2002-04-RG-

General Discussions

Tom George: Last Minute Issues:

If there are any Government discussion areas, Tom will address them. Tom asked if the group would like to raise any issues not raised in the break-out sessions. Suggestions included the following:

- What was the Tacoma test really out to do, if it was to be the proof-of-concept, why didn't it accomplish that?
- The teams are raising things that can be worked at the component rig at Tacoma, rather than trying again
- What is a proof-of-concept device?
- Government issue: where is DOE program taking this now?
- Ramjets ordinarily don't work in a noisy operating environment, while the RAMGEN device is behind noisy impeller inflow interactions, which potentially could move the inlet shocks all over the place.
- The 2.8 MW engine: will that be an engine for sale if everything goes right? You're still trying to understand how RAMGEN operates, do you need to go to the 2.8 MW full implementation, if all that you're trying to do is to describe the physics as a production item.
- Would an axial turbine do the same job of verifying the physics?

RAMGEN Panel Discussion:

Don Kendrick, Shawn Lawlor, and Mark Novaresi sat as Panel, Harvey Goldstein (Parsons) acted as moderator.

Sensitivity to leaks across strakes:

- What is the performance sensitivity to leakage? RAMGEN has performed sensitivity assessments on leakage.
- Loss of propellant, loss of charge across strake.
- What if we lose this much flow from the cycle, other studies show that even small flows leaking in the wrong place can have dramatic changes in the main flow streams. Flows like 1.5 percent in gas turbines have resulted in significant divergence from the planned flow.
- RAMGEN needs to look at the effects of secondary flow fields, and on shock interactions.
- You need to worry about these changes.
- RAMGEN noted that the Tacoma primary rotor disks were not manufactured to specification; 4300 rpm and M=1.1 limits were the result of out-of-spec disks. RAMGEN came to the conclusion that subscale tests would better address the issues than trying to rebuild, reorder this expensive component.
- A follow-up presentation on the state of the program might have value.

- A test bed would be valuable for the slinger performance to compare to empirical predictions, bearing loads and cooling, etc. The rig is not being wasted, it is addressing many of these issues. RAMGEN is looking at the use of the facility for those issues its best equipped to handle.

Need for proof-of-concept test to measure positive torque:

- The next generation of RAMGEN would be up to a 5 MW engine.
- Core engine program is the next phase, would design the rotor, but not radial inflow turbine; why build the whole thing when the interim scale might do it.
- Concentrating on the RAMGEN rotor and tip seals, and the major issues become understandable.
- Precharged concepts could turbocharge the 2.8 MW rotor inlet to 5 MW, *IF* the combustor can handle the increase in pressure.
- Core engine program \$30 - \$40 million over 36 months.
- Demonstrator engine phase next, 15 months, add pre-compressor and radial turbine; then at a commercial point where you could probably capitalize the company. Begin thinking of commercial sales.
- The precharge, pre-swirl has the capability to take 2.8 to 5 MW.
- Inflow and leakage issues, the core engine demonstrator would be the experimental platform to understand inflow quality, strake-tip leakage, secondary flow, etc.
- RAMGEN wants to do subscale testing, and there are a number of discussions underway about what might happen.
- Probably a 4-5 year program to take it all the way to the end to develop with sufficient number of duration hours to give confidence to investors and underwriters.

Instrumentation and Controls:

- Phase I is cold phase flow of the inlet, slinger performance, and how the inlet plenum works. The system would have full instrumentation, center case, pressure ratio, optical ports, exhaust for modular capable, variable IGVs, instrumentation and control to look at performance under varying conditions.
- Phase II would be the hot version of that same testing.
- Incremental strategy to avoid the risk of trying to accomplish all that at once.
- Want to put in as much instrumentation as you possibly can.
- When do you reach a point where the instrumentation affects the flow path? We're using non-intrusive flush-mounted probes; the high Mach numbers in this device couldn't tolerate intrusive probes.
- There's a synergy with the static non-rotating tests.
- The fidelity of the analytical tools needs to be developed, and calibrated to the actual performance of the inlet system.

- Static instrumentation for the rotating path might be possible, and is under consideration.
- Is it possible to run the rotor without all the inlet paraphernalia, with a straight annular tube to sight in? Not possible with the rotating helix for that to happen. An annular tube coming in straight could develop high-g data, but with controlled inlet conditions.
- RAMGEN wants to validate the CFD (computational fluid dynamics) codes.

Effectiveness of air cooling and air management:

- The chargeable vs. non-chargeable air is 36% of the total airflow, 26% is actually going through the burner and generating thrust
- Very conservative in first go-around in cooling; as experience is developed, plan to reduce the cooling.
- If get all segments to interact properly you could significantly reduce the cooling.
- For best chance of success, they've segmented cooling to assure that failure in one will not fail another, important in first-of-a-kind learning, that with experience, hopefully would no longer be needed.

Materials for Rotors and Segments

- Got votes not because of the materials, which are proven gas turbine materials with a lot of experience, but rather their operation and implementation in the unique environment of a RAMGEN engine.

High-G-Force Combustion

- High g-force stratifies the combustion gases, so RAMGEN has the added challenge of understanding high-g combustion. There are two papers in the literature. There is the potential for greater turbulence intensity, and hence RAMGEN wants to exploit this as an advantage, a potential negative turned positive.
- It would be wise to not describe the current plans for the high-g stabilizer, as its in the proprietary invention phase.
- Liquid droplet form fuel is NOT part of the present design, now using only gaseous fuels.

What assumptions are made in the predictions of high energy efficiency?

- There's a big list, 36 percent coolant, 5 mil average tip gap, effective discharge coefficient of 0.7, inlet total pressure recovery just below 90%, ramjet combustor efficiency of 95%, radial inflow turbine 85%, static pressure loss in burner 4%, etc. For the assumptions RAMGEN used outside experts, and exercised due-diligence; the choices have been scrutinized by a number of outside people. This is a high-fidelity prediction. Worst case: net LHV energy efficiency 34%, the floor; we really expect to greatly improve over that.

- Outside people were used to fully validate the process.
- This is an area RAMGEN feels they've very thoroughly covered with high fidelity and credibility.

What are the targets for Wear and Deteoriation?

- How will the performance degrade?
- Don't know yet, oxidation of strake tips, other wear will occur for sure.

What Government Resources Agencies Can Be Used to Assist RAMGEN

The group was asked which areas might help RAMGEN. Either Tom George or Rob Steele would be contacted with suggestions.

Typical Army Issues

(IMPORTANT NOTE: none of these positions represent official Army position, rather these issues and concerns are typical concerns often heard)

- Army – There will be only one fuel on the battlefield: either diesel, or Jet fuel. If it works, and you can burn diesel fuel, then and only then will the military step in.
- 80 percent of the tonnange hauled in by the Army is fuel.
- Unless you can burn well on diesel, you will get no military support.
- If we could burn diesel, would there be interest? The army would be interested in battle-field generation.
- Would have big diameter, prefer small so that a helicopter could deliver.
- Battle tanks need rapid response, 2 sec to max power, so RAMGEN might not be conducive as a candidate for tank propulsion.
- Would army help with diesel fuel spec? Ft. Monroe people might have that… could we have a cleaner fuel.
- Unofficial: in battle, the Army wants any fuel they can get their hands on, so the spec is low because you need to take what you can get. If you can burn poor quality fuel it would be a great advantage.
- Could RAMGEN make a story to ARMY for battefield generation; is there someone to talk to?
- Yes, can get contacts and phone numbers to discuss.

- The Army is very dissatisified with their present diesel generators, they gunk-up at part load. Anyone who comes up with a broad speed range, power range unit that avoids these problems would be welcomed.

NASA

- NASA has a lot of wind tunnel capability.
- Anything with high spin capability, tips would be very useful.
- Variety of compressor/component rigs that might, however concern there won't be enough diameter.
- Trying to match Mach number.
- Tour might show some of this capability.
- Rotating rig you already have at Tacoma – it looks like RAMGEN already has what they need for rig-test.
- NASA has some high speed capabilities to match the high Mach needs, but have a lot of restrictions because restrictions from other work.
- NASA has lots of CFD tools that might prove of use.
- Thermal kinetics codes might also be of some use.

Materials

- Bob Miller, NASA Glenn would be a great resource, a guru, who most certainly if he doesn't himself know, would know WHO knows.
- Very high strength single-crystal, nickel aluminide was a very high strength alloy, but you might want to consider its use for RAMGEN, it wasn't popular because it wasn't good at high temperature, it was dropped; it seems it might be a choice here though.
- C.T. Lew (sp?) at Oak Ridge would be a starting point.
- Structural intermetallics might hold promise.
- Pick their minds: here's our requirements, and see what percolates up.
- Rich Walters of Albany Research Center should be contacted.
- Pat Martin of AFRL would be a great materials contact.

Where will RAMGEN be in 6 Months?

- By the end of this year, the design will be finished.
- Testing at GASL or other sub-component facilities will go to the middle of next year.
- If all were in place, could manufacture the core engine for the proof of concept by 4th quarter of 2003 for cold-flow testing.
- What is a sensible point for a follow-up? Perhaps after the design phase conclusion.

- A lot of points raised have been really valuable – no 'oops' or 'gotchas' have come up in these two days of meetings– but perhaps the issues here will cause RAMGEN to tighten their focus in the right areas.
- Hot core engine testing in 2004.
- Limitations of Tacoma facility might suggest considering testing in a facility that has better precharging pressure capability, multiple shifts of support. RAMGEN is looking to see if another facility has better capability.
- The cold system needs another rig. Could later add hot section parts, use the same rotor for hot tests, perhaps at another facility.
- Some discussion of the various rigs available at government facilities.

Final Remarks – Tom George

- Thanks to RAMGEN and facilitators.
- Next..RAMGEN will prepare proceedings, and these will be shared with the group.
- Tom reminded the group that the information revealed in this meeting is sensitive, often proprietary information.
- What's next, if there's more you'd like to see, let Tom know.
- If there are Government things that are needed, let Tom know.
- Education tools would help.
- Overall, pleased with meeting, some things we could do better.
- Very pleased Rob Steele was able to put this together on such very short notice.

RAMGEN and the DOE appreciated the interaction, and contributions of the group.

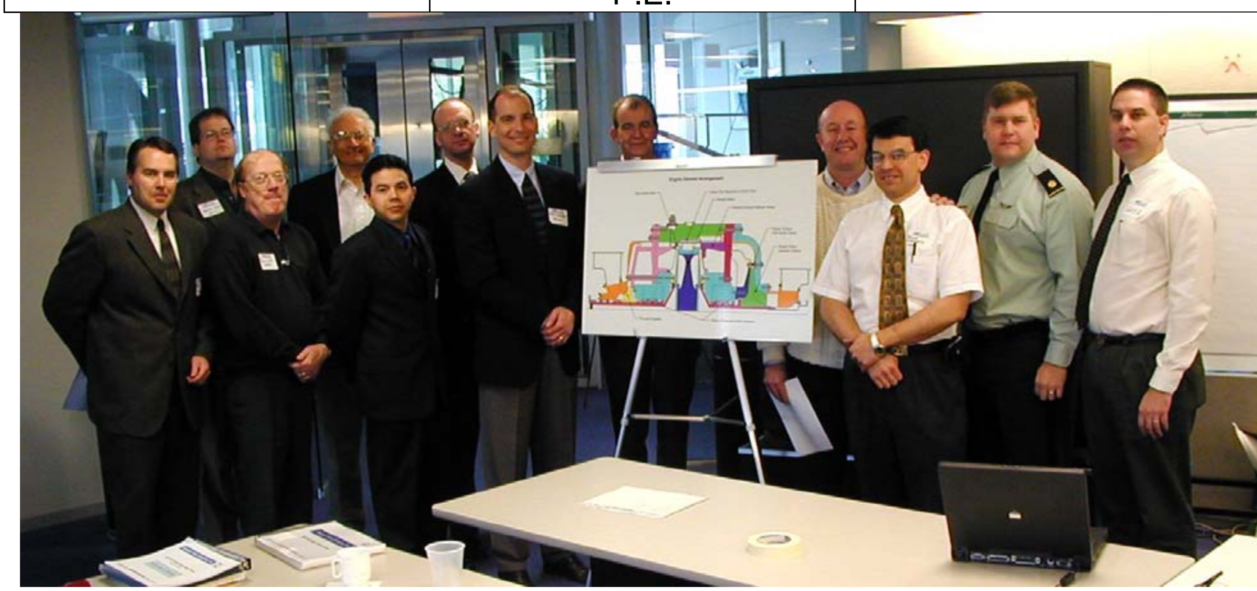
Appendices:
Verbatim Scribe's Notes from Breakout Sessions & Handouts

- Appendix A, beginning on page 43
  Breakout Group A
  Mechanical / Materials / Manufacturing
- Appendix B, beginning on page 51
  Breakout Group B
  Combustion / Heat Transfer
- Appendix C, beginning on page 67
  Breakout Group C
  Aerodynamics / Engine Integration / Performance
- Appendix D, beginning on page 78
  Handout Materials at Design Review

Detailed Break-Out Session Notes

Appendix A - Break-Out Session A: Mechanical / Materials / Manufacturing

		
RAMGEN Discussion Leader: Mark A. Novaresi	**Facilitator**: William M. McMahon, Jr. P.E.	**Scribe**: Mary Ann DeAngelo



Technical Group A. Mechanical / Materials / Manufacturing

This breakout section began at approximately 1:30 PM and concerned matters discussed by Mr. Mark Novaresi of Ramgen Power Systems earlier in the morning.

Mr. William M. McMahon Jr. of Parsons Corporation was the facilitator for the afternoon breakout session. Mr. Mark Novaresi of Ramgen was present to address specific matters when raised by the group. Mary Ann DeAngelo acted as the scribe to record key thoughts raised.

The following nine members of the group contributed to the discussions and subsequent evaluations.

- Bruce Steinetz - NASA
- Bruce Pint – Oak Ridge Nat'l Labs
- Al Kascak – Army
- Mark Valco - Army
- Lewis Rasado - USAF
- Udaya Rau – DOE
- Rob Barrie - Army
- Greg Bloch - AFRL
- Bruce Lyon – Allied Aerospace

The afternoon program was organized in five distinct phases as follows:

1. General areas of concern without discussion. ½ hour.

2. Detailed discussions on the items raised in the first phase. 1-1/2 hours

3. Voting by the members on the items that were of most importance to successful development. ¼ hour.

4. Assessing the risks or the Technological Readiness Levels of the most important areas of concern. ½ hour.

5. Review of the day and any after-thoughts of the members. ½ hour.

Phase 1. General Areas of Concern.

Thirteen items were raised without regard for importance or further discussions. These are discussed in more detail below.

Phase 2. Detailed discussions in the order in which they were first raised.

Please note that the following thoughts represent our best effort to capture the key thoughts from a spirited and often brisk rate of conversation. Specific thoughts have not been attributed to specific people.

Issue 1. Three Jets on the Rotor

Concern was raised about the effect of three burners on the rotor. Would this cause unbalancing, harmonics, warping or bending to occur? The thought was that the frequencies might triple from normal. Could bend shaft to critical limit. Is this more difficult to balance? What happens when one burner does not operate at the same force as the other two? There would be a shift in pressures and temperatures. After some discussion, the members agreed that this would not occur.

Issue 2. Tip Leakage at the Strakes.

Tip leakage is important in many ways. First it has a big impact on efficiency. This is an area of great research in the industry. A new engine, the GE90 is planning on only a 5-mil gap. How real is this and how is RAMGEN proposing to achieve a low level of losses? One member suggested the investigation of brush seals that is being considered as state of the art in the industry. This may be difficult because of the helix nature of the burners and strakes. The current bristles work well but are currently being run at a lower tip speed and temperature than the RAMGEN engine. Creep of metals at these extreme conditions is a concern. It is felt that ½% creep may be experienced at temperatures in the 1200 to 1400 Degrees. F range. How about shrouds around the burner area? This would solve the leakage of combustion losses. The G forces are large or 50,000 g's and the metals would be deformed and not work properly. Too much bending is expected. Not on the present design. Maybe later.

Issue 3. Fuel Mix Leakage at the Tips.

Not only would air leak but fuel too if the gap is too large at the strakes. This is an economical and environmental matter too. Is there any possibility of fuel combusting after it is lost with leakage? It was agreed that this is practically the same issue as 2. above.

Issue 4. Tip Clearances on the Inlet Compressor and the Exit Turbine.

Having a single shaft with two different locations of tip clearances will be a problem. This is especially true with startup and different operating conditions of the engines. It was noted that tip clearance control on the radial impeller was not critical due to it's low pressure ratio, whereas tip clearance control on the radial turbine was essential. Therefore, the thrust bearing will need to be located near the radial turbine for better tip clearance control.

Issue 5A. Materials for Rotors.

The disk is made out of 718 inconel. It is 7-1/2 inches thick and made of one piece. If they are properly heat treated, the grain size can be checked as they are in the detectable range. The diameters are 34" to the tips. The overall weight is between 1500 and 2200 lbs. Titanium was considered but not now. Maybe in 2005 to 2007 time frame. One of the requirements for the disk material is high specific strength. Titanium alloys, with half the density as 718 inconel, have specific strength but require quenching during heat treatment, and lack fracture toughness at the current state of development. Stainless steel was also considered but there are concerns of stress corrosion cracking. It was mentioned that the Tacoma rotor was the limiting factor for the prior tests – that improper heat-treating limited the speed of that engine. There was a general consensus that RAMGEN has chosen the correct material at this time.

Issue 5B. Materials for Segments.

Ramgen has chosen to use Mar M 246 for the segment material, which is a nickel alloy. The segments are castings and it is important to keep the temperatures as low as possible to overcome creep. Other materials were considered but the matrix of considerations favored the Mar-M 246. Were TBCs (Thermal Barrier Coatings?) considered? The overriding consideration of the materials was strength versus density. What about other fuels – black liquor? Only the present fuel – methane or natural gas is necessary for this engine. What about Ceramics for the future? Perhaps, but not now. The group agreed with the overall choice of the material.

Issue 6. The Effect of High RPMs on Bearing Temperatures.

What are the bearing selected? They are tilt pad bearings – 4.5" in diameter. How about magnetic bearings? No they were not considered. Good hydraulic bearings have small clearances of 3 to 4 mils and when pumped up will do a good job of centering the shaft. Speeds are well within the normal operating RPMs and temperatures for this application. Not a problem at low or no speeds and should not affect the gaps at the segment tips.

Issue 7. Rotor Dynamics.

Are there any concerns over gyroscopics of the rotor assembly? With the high RPMs of the machine will any stress be created on the bearings or the rotor assembly itself? This will not be totally known until actual tests are conducted but it is should not be an important issue at this time. This too relates to the bearing issue just discussed. The group agreed.

Issue 8. Contour Tip Grinding.

This issue is closely associated to Issue 2 above. It is currently in the industry, a means of setting the tip clearances of the segments and the strakes. An abrasive material is applied to the outer casing and when the machine speeds up, the tips of the rotor are ground to the exact length. It may also lead to some cutting into the outer casing. What if the abrasive was put on the tip of the strakes and the casing was machined to tight tolerance. The gaps will depend on the exact roundness of the casing. The group felt that the roundness was technically feasible.

Issue 9. Cost.

Some members questioned the potential high costs of materials and machining associated with this unique engine. The materials are more exotic than conventional machines and the close tolerance, while possible to build, will be expensive. Others brought up the possibility of high insurance costs considering the high speeds and new concepts involved. On the other hand, the engine is quite simple, has a lot fewer parts than conventional gas turbines, and when produced for commercial production, the overall costs should not be too high. In fact one of the best ways to keep costs down, is to build the units with good materials so that they are reliable and need less replacement. The total eventual cost of $300 per kilowatt seems reasonable.

Issue 10. Maintainability – Split Case versus Vertical (One-Piece) Assembly.

The group felt that the engine would be easier to maintain if the outer casing was of the split case design. This benefit is offset by the ability to achieve closer tip clearances for the single case design. The discussion then centered on whether we as a group should be concerned for the development engine or the commercial engine that will follow. We concluded that the development engine was more of a concern at this time. The discussion covered the machining of split cases and their accuracy, forces on the split case, bolting, and ultimate performance over time.

Issue 11. Slinger Design.

Mark Novaresi, at the request of the group, gave a more detailed explanation of the design concepts considered for the development engine. There are a great many unknowns with this concept. The slinger is the part of the machine attached to each side of the rotor whose function is to deliver fuel and cooling air to the outer segments. Each slinger would have 156 small passages from the shaft to the segments. How will the slinger act when at full rotation? How hard is this to manufacture? How will the slinger be attached to the rotor? How is the fuel rate controlled under these high centrifugal forces? Someone asked about liquid fuels. They were reminded that we are only considering gaseous fuels at this stage of development. It was not possible to answer all of the concerns at this point but most of the issues are clearly understood by RAMGEN and they are working on them.

Issue 12. Torque Measurement.

It was understood that the Tacoma model did not have a torque measurement device when it was tested recently. The group feels that this is most important and it appears that Ramgen is planning to add such a device at the next phase of development – the 2.8 MW engine in three or four years. This brought up a further discussion of tip clearance measurement and overall instrumentation. There were many opinions given on specific types of devices. At the end it was concluded that RAMGEN is certainly aware of the importance of all of these matters, that they are being studied, and will be addressed at the appropriate time. Maintenance of sensors was also discussed but was inconclusive until a specific design is proposed. RAMGEN's most recent experiments were quite impressive on pressures and temperatures in the combustion zone. Much more will be done.

Issue 13. Casing Concentricity.

It was agreed that we had essentially covered this item in Issue 10. No further discussion was needed.

Phase 3. Voting on Most Important Issues.

Each of the members were given 15 colored stickers to use as votes for their opinion of the most important issues among those raised above. They could vote with all of their stickers for one issue, many stickers for one issue and none for others, or vote evenly as they pleased. There were nine voters plus one member who abstained from voting as a biased and somewhat inside participant with Ramgen. Votes indicated the importance of the issue to be successfully resolved before the Ramgen engine can become a success. The results of the voting are shown below in order of greatest number of votes by issue.

- Tip leakage/strakes: .... 29 Votes
- Material for segments .... 15 Votes
- Slinger .... 14 Votes
- Casing concentricity... 10 Votes
- Fuel mix leakage .... 8 Votes
- Torque measurement .... 6 Votes
- Cost .... 6 Votes
- RPM – bearings temperatures .... 5 Votes

- Rotor dynamics .... 5 Votes
- 3 jets/rev:.. 4 Votes
- Tip clearance -inlet compressor/ exhaust turbine .... 4 Votes
- Maintainability – split case vs. vertical assembly .... 4 Votes
- Contour tip grind .... 3 Votes

The voting clearly showed a strong feeling by the members on the top five issues from a mechanical, materials and manufacturing standpoint. It also showed that some of the issues which were raised earlier in the discussion, became less important to the members.

Phase 4. Assessing Risks of Five Most Important Issues.

The members were asked to further evaluate the five most important issues raised above for their risks from this point of development to commercial production of engines. There were four distinct levels that could be considered for evaluation. These are listed below:

Level 1. Technology. How does the RAMGEN engine concept seem to be understood and evaluated compared to other similar technologies?

Level 2. Engineering and Design. What risks will be encountered during this phase of the project?

Level 3. Manufacturing. What risks are expected during the fabrication of the components?

Level 4. Integration & Testing. What risks can be anticipated in startup and testing?

Estimating the degree of risk for new products is always a difficult step. However, it was decided to evaluate the RAMGEN risks according to a simplified system set by NASA and other governmental agencies. This overall system is called Technology Readiness Levels (TRLs) and consists of nine steps that normally occur in bringing along a new space system from concept to reality. A paper describing the various levels was mailed to the members before the conference and an additional copy was handed out at the session and is included in the Appendix. A further simplification of the TRL methodology was further given as follows:

- High Risk – normally associated with the earliest stages of project development or TRL 1 thru TRL3.
- Medium Risk – normally associated with the middle stages of project development or TRL 4 thru TRL6.
- Low Risk – normally associated with the latest stages of project development or TRL 7 thru TRL, 9.

The members were again asked to evaluate the five most important mechanical, materials and manufacturing issues discussed above using a handout sheet prepared for this purpose. The results of this last evaluation are presented below:

Issue	Technology	Eng. Design	Manufacturing	Interg&Test
Risk (TRL)	High-Med-Low	High-Med-Low	High-Med-Low	High-Med-Low
Tip Leakage/Strakes	4 - 5 - 0	8 - 1 - 0	1 - 8 - 0	4 - 5 - 0
Material-Rotor	0 - 6 - 3	1 - 8 - 0	1 - 7 - 1	0 - 6 - 3
Material-Segments	1 - 7 - 1	3 - 5 - 1	1 - 6 - 2	0 - 5 - 4
Slinger Design	3 - 4 - 2	5 - 4 - 0	6 - 2 - 1	4 - 2 - 3
Casing Concentricity`	2 - 4 - 3	1 - 8 - 0	2 - 4 - 3	0 - 4 - 5

Mechanical Design Evaluations Using TRL

Taking the above rankings and expressing them in TRL numbers was accomplished by weighting the risk levels (high as 2, Med as 5 and L as 8) by the number of votes in that risk level and dividing the sum by 9 (number of voters). The results are as follows.

Issue	Technology	Eng. Design	Manufacturing	Interg&Test
Tip Leakage / Strakes	3.7	2.3	4.7	3.7
Material-Rotor	6.0	4.7	5.0	6.0
Material-Segments	5.0	4.3	5.3	6.3
Slinger Design	4.7	3.3	3.3	4.7
Casing Concentricity`	6.0	4.7	6.0	6.7

Results of the TRL Approach

The results show that by far the greatest risk and the lowest TRL in the opinion of the members was for the engineering and design to prevent leakage at the tips and strakes at 2.3.

The second greatest risk was in the engineering and design of the Slinger assembly at 3.3. From a TRL standpoint, the members rated this second in priority.

In general, the members felt that manufacturing and Integration/testing development of the Ramgen engine was not as risky as Engineering & Design.

Phase 5. Review of the Day and Afterthoughts.

The group fully appreciated the excellent work performed by the Ramgen staff and their willingness to expose themselves to questioning and challenge.

The group knew that there was much more information that the Ramgen staff could present but was limited by the time schedule that morning. There may have been an opportunity to get much deeper into specific issues if more information was presented ahead of time. As a suggestion, if this type of review occurs again, the morning session should be expanded into an all day presentation.

There was a lot of interest in the Tacoma tests and the results. It was felt that many of the issues of the test were glossed over either from proprietary reasons, failure to meet all the technical goals, or time constraints. There was a sense of much to learn from those tests that would have been useful in the discussions.

The members were anxious to have test data available to show the merits or problems of much of the technical issues raised. Of course that information will not be available for some time until the next demonstration engine is built and tested – a few years away.

Overall, the RAMGEN staff was able to respond to almost every issue with either answers or that they were aware of the matter. It appears that RAMGEN is going in the right direction.

The discussion continued informally after the main session.

Detailed Break-Out Session Notes

Appendix B - Break-Out Session B: Combustion / Heat Transfer

		
RAMGEN Discussion Leader: Dr. Donald W. Kendrick, Ph.D	**Facilitator**: Harvey N. Goldstein, P.E.	**Scribe**: Jenna Jeppersen

Break-Out Session B Participants:

- Doug Straub – US Department of Energy/NETL
- Lee Noble – Allied Aerospace
- Rolf Sondergard – US Air Force
- Dale Shouse – US Air Force
- Harvey Goldstein – Parsons Corporation (facilitator)
- Donald Kendrick – RAMGEN
- Mike Foley - RAMGEN
- Jarad Daniels – US Department of Energy
- Pete Meitner – US Army
- Jenna Jeppersen – Area Temps (scribe)

Heat Transfer

Understanding this technology requires several iterations. The audience requested that Don Kendrick explain, graphically, the air, fuel flow paths.

Frame work of past, present and future – audience requested clarification of past, present, and future work. A lot of people were confused and a lot of information to digest. Make sure to go point by point with what you're discussing and where you're going with it.

Proof –of-Concept Engine

Tacoma Engine – This is the engine that was developed in 1999, 10 MW engine, fuel admitted through jets cross flow to the air flow.

Inlet airflow was not forced. Engine was equipped with an inlet fan; engine ran with fan on/fan off.

Primary Fuel Injection – talk of running engine on premix, auto ignition and studies like that. How were the Tacoma tests run. Studies 90-95% Fueling through the slinger. Premix – all the fuel isn't going to burn, premix is along put at this stage, longer than a put.

Fuel-methane natural gas.

- A lot of the DOE funding today seems more available and more focused on clean coal technology. These applications will be dealing with syn-gases and hydrogen.

Fueling

- Fuel delivery was 99-95% using a fuel slinger for the initial combustion tests – centrifugal pump with radial channels
- Studies investigate slinger performance and wheel space aerodynamics.
- Fuel injection stress, through the slingers themselves

Ingestion of fuel in the wheel space. Some results, some better results; safety became an issue.

Q: Did the fuel leak out?

A: Fuel comes up through the slingers, interface. Labyrinth seal, Circulation patterns develop in the wheel space, causing ingestion. This is why we didn't do testing on other fueling strategies.

Purge cavity – purge to cool it. Define amount of air for cooling . Pressure for wheel space is very low.

Pre-charging – purge the air at a higher pressure.

Space heating rate, do you have any requirements. Volume flux through the rig, label on it or target. Need the premix.

For low efficiency for the premix to work. Look at this need to fuel in their , cause a loss in the overall system. Leads to slide. Don't really want to fund flammable premixing. That could be easily ingested. Off the center body, supplement.

Run with a flammable premix.

66 kilowatts for one side.

Need to cool it and provide purge flow, clear potential flammables.

Ideally want the wheel space under a vacuum, to keep the air out of there.

Maintaining the clearance, quantifying and minimizing it.

Did you get positive thrust?

- Able to get some degree of mixing.
- Combustion Stabilization
- Fuel and Cooling Air deliver/injection strategies
- Reliable Ignition System
- Air film cooling

- Supply/ Exhaust removal
- Controls/Instrumentation
- Integration/ Mechanics

In-sufficient thrust from starting motor.

Efficiency was poor,

High combustion efficiency was obtained,

Water cooling on the inner casing was used;

Q: Why did you need to cool on the inside?

A: Thought would be needed, but wasn't needed.

Back engine cooling?

- Strategies shown
- What was concern with thermal barrier coating?
- A little bit of thermal barrier coating (TBC) flaking off, there are certain challenges. When TBC flakes off, this causes serious unbalancing of the rotor? We did not experience rotor balance problems during operation.

Sensitivity Studies

Test in Tacoma CFD, AFD want some experimental validation. Lower cooling temperatures.

Combination of Impingement/Diffusion + Impingement + Diffusion comparison shown in a slide.

1200ºF metal temperatures in the new engine? Yes, on the combustor floor.

What temperature at the surface? 50 to 200 degree F cooling drop.

Higher than in a modern gas turbine.

Surface area is that much larger?

- Make the combustors bigger, problematic in case, more width to fuel path and requires a thicker rotor, causes to degrade the rotor of the engine, limitation mechanically. Mark and Donald need to think about. That is why cooling rates are higher.
- T4 using a lot of cooling air, what pressure to supply the cooling area. 50 psig inlet pressure to the hub, 50 psi absolute, a 4 or 5 % pressure drop.

Fuel as cooling? Using a heat pipe? Layer of water around the walls and letting it evaporate?

- Cool the surface, thin layer of water on the surface and bring down as you do the slingers and water will be forced to the outside and the water will cool.

Water in the slinger? Maybe, it's just like a heat pipe.

- Thought of water in the slinger. Are moving the heat inside and will have to replenish it.
- Need at a high enough pressure to condense on the inside.

Performance prediction on a hot day/ cold day?

So many challenges did some of that work, stuff to worry about down the road. It's not something forgotten.

New 2.8 MW Engine

Engine wanting to build – 2.8 megawatt prototype engine.

Three sections

- Inlet
- Rotor cartridge
- Exhaust

Well defined aerodynamic conditions – very slick way to preserve Mach number

Exhaust – Flow coming off rotor has swirl; problem is that it's going the wrong direction. Diffuse and deswirl to go through radial inflow turbine stage.

Rotor – Several issues, including:

- Cooling air coming in through the slingers. Thin plates on either side of the rotor.
- What is reason for 3 ramjets vs. 2? Sensitivity studies,
- Certain length and then put on rotor, and certain length of the rotor. A lot of give and take
- Balance- single thrust pod, counterbalance, a long enough combustor.
- Roof the fourth wall, the shroud, reduce the diameter of the rotor, you can put a roof on the combustor, enclose and alleviate all the leakage. No sizeable thrust.
- Instead of using remaining kinetic energy, totally separate shaft. Use the energy to drive the compressor that you have off line. Which would spin in the other direction. You can include 700 kilowatts to use for the compressed air.

Aerodynamic Flow Path

- The flow angled in to the rotor. Then the flow was processed by the inlet process.
- The flow entering the supersonic nozzle. Studies bleeding off the rim and side wall for sufficient uniformity. Mixed compression inlet- series of internal and external compressions.
- What does curved cowl do to the inlet flow? Flow is deflected off and re-ingested by the ramjet inlet, shock structure is set up. Re-ingested, not wasted.
- After the normal shock, subsonic diffusion process takes the static pressure up to 275 psi.
- Nozzle is the key – need to design the nozzle, the length restrictions of the flow path, minimum length planner nozzle. Method characteristics inhibit shock reflections.
- What % of energy is converted to thrust?
- Where is the thrust being produced? Is the inlet contributing to thrust?
- Causing a higher straight angle is going to change the vector, if you tilt it you get more potential thrust?

What are Issues and Concerns?

Following are verbatim evaluation sheets filled out by the group members.

Item	Description of the Issues	Technology	Design & Engineering	Manufacturing	Integration & Test	Other
Cooling Air Quantity	Cost and internal compression of the cooling air Low Power Density Attachment of TBC	EFF Bonding Cooling				Cost Cost
Combustion Noise	Ability to deal with and eliminate noise if it occurs					
Slingers	How practical? How durable? Cost		X X			Cost
Fuel-Air Mixing Homogeneity	High Nox due to locally High Flame temperatures	X				Emission Performance

Item	Description of the Issues	Technology	Design & Engineering	Manufacturing	Integration & Test	Other
Tip Clearance Control	Tip Clearance Control Containment of Combustion Is .005" leakage okay?	H	H	M	M	H
Sealing	Slinger & Segment., Fuel Air Seals Temperature Considerations	H	M	L	L	M
Rotor Stress	Eccentric Loading From Adjacent Heavy Light Segments.	M	M	L	L	M

Item	Description of the Issues	Technology	Design & Engineering	Manufacturing	Integration & Test	Other
Tip Seals	Tip Losses (Efficiency Hit) Hot gas ? (efficiency hit) Tip erosion (durability hit)	High	Med			
Flame Stab/ Mixing	How to obtain stable efficient flame in the sub-optimal geometry. High "G" in bad direction.	High	Med			

Item	Description of the Issues	Technology	Design & Engineering	Manufacturing	Integration & Test	Other
Flame Stabilization Margin	Maintaining Sufficient Flame space for good mixing and even temperature distribution	Med	High	Low	Low	
Material for hot section	Providing cooling scheme to allow for higher heat loads	Med	Low	High		
	Better relight (avoid relight) Turn down ratio.	Same as above				
G Loading	High "G" combustor loading effect understanding to utilize for benefits.	H	M	L		

Item	Description of the Issues	Technology	Design & Engineering	Manufacturing	Integration & Test	Other
High G Combustor	Stabilization of flame in the 75,000 G environment – hostile? Possible hot/cold gas stratisfication	H				
Super Sonic Combustor Boundary Condition	With Stationary wall will destabilize combustion zone if no mitigating factors employed.	H				
Tip	Leakage of any gas (combustion products, inlet flow) over strake tip out of aerodynamic flow path.	H	H			
Rotational Performance of Aero Sub Components	Unproven performance of inlet, diffuser, combustor, nozzle, cooling strategies, (all aero sub components) with rotation effects.	H				

Item	Description of the Issues	Technology	Design & Engineering	Manufacturing	Integration & Test	Other
Cooling Flows	There are very large surface areas associated with this concept. A very large amount of cooling flow is repaired, the use of which must be judiciously allocated.		X			
Combustor	The whole combustion process at high G loads does not seem to be well understood. Basic information still needs to be generated.	X				

Item	Description of the Issues	Technology	Design & Engineering	Manufacturing	Integration & Test	Other
Tip Seals Clearance	Optimize Design of Tip Seals		X			
General System Optimization	EG: look @ separate compressor using exhaust energy to charge input air, vs. trying to redirect gas path to use only one shaft.		X			
PREMIX	Need to look @ emissions issues associated with not premixing fuel; find ways to optimize system.					
Design issues for alternative fuel	How does operation on syngas affect design , residence times, furl delivery systems.					

Item	Description of the Issues	Technology	Design & Engineering	Manufacturing	Integration & Test	Other
	Reduce Req'ts for air cooling		H			
	Improve Combustion Efficiency/And Flame Holding	H				
	Minimize leakage Fuel/ Air sealing Tip (Strake) Clearances		M			
	Identify Durability Issues				H	

Summary of Issues. Ranked by number of votes and risk consensus.

Issues	Risk
Flame Stabilization	H 19
Tip Sealing	H 14
Fuel/ Air Seals (Segment)	M 8
Reduced Requirements for Air Cooling (excessive secondary air)	H 15
Whole Combustion Process / Do not understand the Basic physics behind the whole process	
Emissions Issues/ Fuel well mixed if not premixed	M
Metal Temp. – Cooling Effectiveness	8
Understanding High-G Combustion	10
Emission Issues	M 10
Fuel Air Mixing (Homogenous)	12
Long Term Durability	4
Firing Syngas or Hydrogen	0
Ignition	5
Overall/Component Performance with Rotation (vs. State)	

Discussion of Issues

Issues	Discussion
Flame Stabilization	
Tip Sealing	
Fuel/ Air Seals (Segment)	
Reduced Requirements for Air Cooling (excessive secondary air)	
Whole Combustion Process Do not understand the Basic physics behind the whole process	
Emissions Issues Fuel well mixed if not premixed	
Understanding High-g Combustion	50,000 g's X 9.1 cm/sec^2
Metal Temperature – Cooling Effectiveness Mike Foley	What are you looking for the management of cooling strategies. Way of further increasing by treating surfaces. Stuck on Straight walls Choose prudent strategies without "what-ifs." Stick with known true tried things Silicon nitrate hoops Partial premixing up-stream Combustion noise is treated with fuel placement. How much effort did you put into your

Rolf S	slingers? Didn't look like much was put into it. Design injectors properly, can get cooling temperatures way down, and fuel pressure way up.
Fuel Air Mixing	Donald – Didn't find any degradation
Long Term Durability Harvey	Flame speed of hydrogen is greater than methane Syngas – flame temperatures are low Firing syngas in gas turbines Westinghouse doesn't want to talk about the G, and GE didn't want to talk about getting the H frame ready for syngas. Still a lot of issues now, going to G and H technology they made a leap and years before talking about syngas. Development time the same or faster
Firing Syngas or Hydrogen	Will try and leverage help Conventional turbines? Donald – no answer to question Gas Turbines – problems are combustor, combustion zone of your engine. Donald – makeup of syngas different densities, there could be some different secondary effects happening. Is it a matter of replacing the cartridge? Donald – no answer of the question. Donald – Fuel injection will have to be revisited. Flame stabilization because of variations in chemical composition. Shock system wouldn't be affected from fuel coming

	in from the inlet. With zero clearance, can you contain the combustion? Don: leaking hot products, not going to have flame, because of cooling air being squirted out. Will try to minimize it. Will there be more than cooling air coming? CFD to look at the edges of the tip. Labyrinth seal. Looking at strategies mechanically, aerodynamically. It's a performance hit. Full combustion pressure on one side and atmospheric on the other side. A lot of potential flow leaking. It's a big job solving it.
Ignition	Flame stability concept Better flame stability will alleviate flame out. Not running at those kinds of mach #'s Turbine has fuel scheduling to get up to idling. Would have to do scheduling. Modulating the fuel flow. Modulating the cooling flow. Done passively in a gas turbine. Equivalent of turbine inlet temp. High cycle in this engine. 2900ºF standard gas turbine How can you get low NOx? Don: Flame temperature Mixing formula and dump plant Operating flame temperature 2950ºF or below, so not to approach the seal.

	Competitive NOx levels. Harvey: Any thought given to catalyst to reduce NOx levels? Don: Don't have experience and they have reliability issues. They don't have the track record for the outset. Catalyst surface is sitting on rotating combustor with a lot of g-loads. Don: Forget about running syngas with those things. Harvey: This is one of the issues that came up in Reston that was raised by the manufacturers. The politicians should come up with a number; set the bar and not move it. Many areas it's hard to get a permit, even with low NOx levels. Emissions are always a big thing. Cartridge performance sensitivity studies. Take nominal 6 megawatt and double it. No other engine can do that. Other attributes that are good things, that make the whole package highly desirable.
Overall/ component performance with rotation (vs. static)	
Outside wall temperature Mike Foley	1250 F metal temperature on the combustor floor and 1400F at the tip of the strakes How does it affect the compression? D. Have thought of it. TBC allowed another 100-deg. F in the cooling strategies. Will help the combustor but not the inlet. What are the boundaries?

	It would require to let it bleed a little bit more. D. Good point will get back to it.
Harvey	What is the temp of the air? Datalogger imbedded in the hub, rotating with the shaft, radial increase of temperature. Cooling flow comes off initial stage? D. Comes from off-board compressor. Why couldn't you cool it down to lower temps to make more effective? More heat you throw away, will have to run hotter. D. will run studies D. measure slinger and temp. Trying to validate this stuff. If you are able to bring cooling air without throwing it away, cavity regiments. Considered an external burden. 34% burden, reduce to 22% burden. Now you have a separate device. Drop the availability. Dale. Rotation on the exhaust side. Rotation was going the wrong direction. What would you do if it was going the right direction? D. It really comes into the normal shock loss. Gearing? Impulse turbine. Seemed slicker than the gearing. Gearing has associated problems. De-swirl and dump the fuel in anther direction.

Detailed Break-Out Session Notes

Appendix C - Break-Out Session C:
Aerodynamics / Engine Integration / Performance

 **RAMGEN Discussion Leader**: Shawn Lawlor	 **Facilitator**: Richard E. Weinstein, P.E.	 **Scribe**: Diana Gurley

Break-Out Session C Participants:

Name		Affiliation	Specialty	Telephone Number
Dave	Arend	NASA	Inlet design assessment and test	216 433 2387
Kaz	Civinskas	NASA	Turbomachinery	216 433 5890
Ruben	Del Rosario	NASA	Research facilities (thermal and combustion)	216 433 5679
Bill	Engblom	NASA	Fluid dynamics / CFD	216 433 5542
Diana	Gurley	(scribe)		
Shawn	Lawlor	RAMGEN (technical lead))	Aero / Propulsion	425 828 4919
Patrick H.	Le	NETL	System analysis / Gas turbine modeling	412 386 5727
John	Rohde	NASA	Turbine cooling and combustion	216 433 3949
Bobby	Sanders	Techland (consultant)	Inlets	440 716 9077
Richard E.	Weinstein	Parsons Corporation (facilitator)	Power plant conceptual design	484 338 2293
Lois	Weir	Techland (consultant)	Inlets	440 716 9077

Purpose

RAMGEN is seeking the group's thoughts on the design to help and advise on developing the product. In our discussion area, Aerodynamics / Engine Integration / Performance, we hope that the group can identify the status of the RAMGEN program using NASA technical readiness levels (TRL). Response range:

- TRL= 1-3 low readiness;
- TRL= 4-6 medium readiness;
- TRL= 7-9 Some confidence that the technology is actually working, high, ready to roll

What are the issues in our focus area? We hope the group will focus on areas necessary for product development. Later, we will use the "Fluorescent Dots" to identify and prioritize areas deserving the most attention.

Shawn Lawlor: Gave an overview with increased details after the morning meeting remarks on performance and flow path.

- Request from the group that Shawn go through charts missed in the morning.

Technical Readiness Levels:

Before beginning the discussion, the session leaders began by laying out the background of the NASA Technical Readiness Levels. The group began with a discussion of the technical readiness level (TRL) ranking system: It was noted that Rob Steele copied the framework from a NASA paper. Review and examples.

(There were discrepancies in the interpretation of the grid level of risk and readiness.

Comment: We don't think in the way you've interpreted it. RAMGEN needs to define its interest).

Shawn Lawlor: RAMGEN wants to know your perception of the readiness of each category. RAMGEN wants to identify risk areas and readiness areas.

TRL=9: Engine is in commercial service.

TRL=6: When hot engine tests are run in NASA, it is usually considered TRL=6. This usually means a core engine test is on the ground.

TRL=5: Rig test at relevant conditions.

TRL=4: High speed rig test. In components facility, then TRL=4. As an example, the "Ultra Efficient Engine Program:" This technical program is working toward flight, right now, in the rigs, it is at TRL=4 working toward TRL=5.

TRL=3: Somewhat reduced conditions test.

TRL=2: A cascade test is about a TRL=2

TRL=1: Conceptual idea and "straw-man" of the direction of the design effort.

Review of the Background of Group C Participants:

Before discussions began, the group was asked to summarize their background, so that everyone would understand where their comments arose. The group responded as follows:

- Rich Weinstein: Conceptual performance evaluation and planning on emerging electric power generation plant technology and systems.
- Ruben Del Rosario: Was in experimental testing for NASA.
- John Rohde Low emission combustors for alter/ engine technology. High speed / hydrocarbon ramjets.
- Dave Arend: Researcher design test, overall propulsion system.
- Bob Sanders: Worked inlets all his life
- Lois Weir: Inlet researcher
- Patrick Le: Simulation looks at efficiency of performance

- Bill Engblom: Contractor in aerospace, nozzle branch
- Shawn Lawlor: Boeing hypersonic tests, wind tunnel, flight propulsion. Rocketdyne. Early 80s, flow-path definition studies. Then started this company, RAMGEN power systems.

Group Request for information on the Basic Configuration of the RAMGEN System

Before the group was ready to begin discussion of technical readiness levels for the RAMGEN system, they needed much more detail on the operation of the RAMGEN system than was given in the morning reviews. Shawn Lawlor continued with a detailed briefing. This discussion took nearly an hour, and covered the operation of the RAMGEN engine in considerably more detail than in the morning session. The range of discussion and the questions that arose included the following:

How much thrust does a ramjet generate? Bookkeeping of … turning into shaft torque… calculate system losses.

What puzzles me is orientation of the surfaces that translate into tangential force. Don't see enough surface area except on the hub of your flow-path. What surfaces are providing us with…

With an inlet system, may be a little harder to see. Look at the system built and tested in Tacoma to see where stream thrust ?? act in that configuration.

Thrust is the difference between stream thrust at inlet and nozzle discharge.

Q: Are the strake surfaces doing anything for you in terms of generating thrust?

A: No.

Q: So when you convert an inlet nozzle to this geometry, aren't you losing a lot of area?

A: No.

Going from thrust to torque. If the side in walls are not contributing anything, you're losing area.

Thrust of this system is the change in stream thrust/ difference in a 2-dimensional system from in/out. Internal pressure fields are simplified between inflow and outflow

What changes the pressure is the change in momentum.

The effect of curvature along the flow path is not sufficient to get you away from the 2d approximation?

What's the difference in the level of torque generated?

This is such a small part of the overall machine, it's hard to see what it does.

You don't have a torque cell, but the starter motor functions as the torque cell and the power input to the system was calculated very precisely.

TORQUE MEASUREMENT NEEDED. UNDERSTANDING OF PRESSURE REACTION AREA TO PRODUCE TORQUE.

There are different fuel flows. Matching achieved over the power range is both in the inlet and the power nozzle.

Compares our inlet with NASA inlet, slide on screen.

As you decrease heat release by decreasing fuel, the normal shock starts to move further back in the diffuser, increase in pressure loss. That maintains continuity in the flow. If you decrease burner pressure, force goes down. Component efficiency vs load characteristic.

OFF DESIGN, NORMAL SHOCK MOVES BACK NOZZLE GOES OFF DESIGN OVEREXPANDED BUT DOESN'T SEPARATE.

Any thought to counteracting vortices?

3D CFD modeling should illustrate that.

Multi-domain modeling capabilities at RAMGEN are limited. Simulating imbedded flows, haven't attempted to evaluate it in the burner.

CHALLENGES MODELING RECIRCULATION.

Was ever intended to be a torque producing motion. Strake is only a fence.

Easier for SL to see on … [slide Inlet Design "G" Integration.]

As long as you match the level of attack

Totally confused about the direction. Which way is oblique side?

RAMGEN F3 Inlet and NASA inlet slide. Top inlet is the configuration …

Point at 0/0 on graph. Is at the beginning of the compressive ramp. Top is leading edge of both the cowl and one of the strakes. Turned 90 degrees.

3D PHYSICAL MODEL WOULD HELP DEVELOP CONCEPT UNDERSTANDING.

Slide on Inlet Design Goals.

Inlet capable of self-starting using passive bleeds only. Design of the bleed system of the inlet recycled the fraction of fuel so it is not dumped overboard. Total pressure recovery goal of 86% -- which should be readily achievable in this Mach level range. Transient response. At full power, shock at normal position, imagine… With the F3 configuration, it's an oversimplification to say there's no contribution from the thrust reaction. For these jmixed compression inlets, we set a cowl drag level at 5% or less. Targeted a bleed flow at < 10%.

There might be a little compromise to design a self-starting inlet.

Could you change this? Not easily. Variable inflow pressure concepts could be used in that way, to get the mechanism to start.

There are ways to look at that, but first you need a set of data. Are you about to show them?

Within spitting distance of those goals being achievable.

Four types of inlets investigated, two were selected for full-scale testing, F3 and G2.

All external compression (like arrow spike inlets, shock structure forward of the cowl). Leads to prohibitively high cowl drag levels.

Bobby and Lois familiarized them with 70/30 mixed compression (Inlet F2) hybrid, F3 design. High total pressure ratio levels, low cowl drag levels.

Inlet G2 has potential for no drag, but getting this inlet to self-start requires high amt of bleed. The throat would be about ¼ " X 5" Concern about normal shock stability in this long, thin throat. Higher risk candidate.

Slide 2D Inlet tested at NASA Lewis.

Slide Inlet "G" Spill path during startup.

Multiplicatively bad effect. But it comes up to speed, willing to take this problem in exchange for starting the engine.

Slide RAMGEN Planar Diffuser Configuration. Don't think flash is an issue here. Bifurcated diffuser path.

Important feature: inlet bleed/recycle approach/ Slide illustration to show where you would bleed off boundary layer to retrieve some momentum of bleed flow. Supersonic inlet tests underway now, using F3 and G2 at three Mach numbers up to 2.6.

By rotating 90 degrees, does it change the overall performance? It's a lot shorter height-wise, but longer distance fore-body shock compression system. In D2 you have a foreshortened pressure ramp, but have to go to the same… … Works out about the same. Elimination of cowl drag about compensates for the lower total pressure ratio. Shock that is reflected off main engine case is stronger.

Have carried forward with testing two inlet candidates at full scale Mach number. Compromised on static pressure.

EFFICIENCY OF COMPRESSION PROCESS IS CRITICAL. FULL SCALE 3.8 X 3.5"

CAPTIVE AREA 0.75" RADIAL 3.5" AXIAL.

Do you look at the bleeding of the premix? Yes. Major issue. When bled, it is cycled through the rim segment interior. Then route it out through the inlets through a separate compartment for reintroduction.

What creates the total flow field in that direction?

Bleed consistent with most supersonic inlet systems

Is that compression system area close to a compression area where flow might leak?

The exhaust side has hot gas in it, don't want to leak fuel into exhaust flow path.

Fuel exhaust is not near the combustion area. Getting dumped out on the side surface of the rim segment into a secondary duct. Then recycled. Not a wake flowing into the next ramjet.

Basically taking part of the airflow bringing in out of the existing fuel, then bringing it right back in again.

Part of the compression process. Entropy. If you balanced it, you'd see a slight increase in the gas properties, but not a major disruptive element.

Adequate turbulence for good mixing? Yes.

Potential for hot gas leaking back into the compression system, does the design change a lot if you have 1-2% going back into that area? ¾" ht with a (something) gap.

There's a region in the flow path where it is leaking. Main passage. Right through the compression area, in the primary flow path. Over the strake from the different flow path.

This is leakage.

It is not flow in, it's flow out. It would not be bleed. Bleeding the corners is good for performance, maybe not so good for cycle. The leakage mass flow is modeled. Effect of secondary flow fields … a jet of gas out through the left gap, causing recirculation as it grows along the intersection until it shows up for the next inlet. There's an offset between strake Y strake wall, to bleed off any secondary flow. Is it big enough? Uncertain. Maybe only resolved with actual rotating tests.

As you progressively go through this inlet, the pressures increase. Watch you don't have some leak downstream that's now Really high, then goes down and blows in the front. If you have leakage all along the surface, you have to make sure you take it out, so you don't blow the front of that inlet.

IF THERE ARE LEAKS, THE LEAK DISPOSAL MUST BE TAKEN AWAY FROM THE INLET SO IT DOESN'T DISTURB INLET.

System integration/ Slide, Cooling air and fuel flow feed.

Review of the balance of the system.

SOME PRECOMPRESSION OF PILOT FUEL AND COOLING TO GET TO BURNER.

Can you get a strake rub that produces sparks? Haven't in tests in Tacoma. Reingesting. Flashback and pre-ignition are a major issue.

Do you have igniter on continuously? No. Cycles until both are lit, then stops.

So there's enough combustion material left in the chamber…?

No. We wait until the chamber is completely filled with premix. It's not continuous combustion. Pulsed. Burners run continuously after igniters are off.

FLASHBACK, PRE-IGNITION, STRAKE-RUB-SPARK ARE CONCERNS.

IGNITOR ONLY USED TO START. CYCLED INTERMITTENTLY. BURNERS RUN CONTINUOUSLY.

What are your controls issues?

Generally, we had entire gamut of controls you'd expect to see. …

1 infrared thermometer ?? Haven't fully developed a control system. We've got a prototype for Tacoma, but there's a world of difference between that and an automated control package.

PROOF-OF-CONCEPT CONTROL, BUT NOT FULLY AUTOMATED.

GOAL IS TO DEVELOPE A REMOTE OPERATION AUTOMATED CONTROL.

Comment earlier: Why is this a better system? Chart was static pressure loss in the burner. 4% number. We're modeling based on proven ideal bell nozzle thrust performance characteristics. Ideal nozzle contour. In the design of a typical nozzle for a flight system, the determination of the length of the nozzle is a process of trading off the extra thrust gained by the final bit of flow expansion against the viscous drag of that extra nozzle wall. In the case of the ramjet nozzle in RAMGEN's engine, the nozzle wall is incorporated directly into the rim of the rotor and therefore it is possible to completely utilize the ideal nozzle contour without having to trade-off viscous drag against pressure thrust.

Our nozzle surface is integrated directly into the rim of the ramjet wheel.

So this makes it a better nozzle?

Classic tradeoff between efficiency and cost.

In a conventional rocket nozzle, there's no radial velocity profile.

FUEL BURNED LEAN SHOULD BE TOLERANT OF HAVING THE RIGHT NOZZLE DESIGN.

RAMGEN engine process slide b/w is not an adequate drawing of current state of the model. Chart is 4 yrs old.

Had a nozzle problem and it's already fixed.

Concerns on performance:. Inlet. Compression process efficiency in general. Amount of power required to compress the film coolant. That's a pure loss. If we abandoned the ability of the system to burn uncompressed fuel, we could take the cooling right out of the subsonic diffuser and route it into the burner.

Lower risk is to use the system on pure air. Premix will be next generation design activity, but still a high priority for the company. Pipeline gas option is the primary option right now.

INLET PERFORMANCE

PRESSURE DROP

POWER FOR FILM COOLANT WITH OFF-BOARD COMPRESSOR

UNPRESSURIZED PRE-MIX IS NEXT GENERATION, BUT HIGH PRIORITY.

PIPELINE GAS COMBUSTION FOR FIRST-OF-A-KIND

Next: What are the items of greatest concern? List them here:

Ranking of Concern Areas

Method of Ranking: Each participant was given 15 fluorescent dots to rank the priority of concern for the suggested concern areas mentioned by the group. The Facilitator, RAMGEN technical expert, and Scribe were not allowed to vote.

In the "top four" ranked concern areas, the group was then asked to further evaluate their opinion of the technical readiness level (TRL). They were given one dot per question, and asked to affix the dot to the appropriate TRL for that particular concern area.

Not every member chose to vote in each area.

Highest concern issues of group (11-21 votes)

- **21*** Need for proof of concept test big enough to produce and measure net positive torque.

A. Need for **proof-of concept** test big enough to produce and measure net positive. TRL=2 is done for sure by RAMGEN, still need some work to move fully toward a TRL=3. If RAMGEN had succeeded in Tacoma, they would have been at a TRL=3. **TRL Twos = 4; Threes=2**

- **15*** Inlet performance – 3D flow issues

B. Inlet performance **flow path analysis** (complex; use research codes. Maybe a 2 for tools and methods.) **TRL Twos=3; Threes=3**

- **14*** Need for good inlet testing to accurately represent the system.

C. Need for good **inlet testing** to accurately represent the system. **TRL Twos=5; Threes=2**

- **11*** Sensitivity of leakage effects—inlet, combustion, nozzle performances and cycle of efficiency. .

D. **Sensitivity of leakage**: Inlet, combustion, nozzle performances and cycle efficiency **TRL Twos=5; Threes=0**

Important concern issues of group (7-10 votes)

- **9*** Power of compression for film coolant with off-board compressor. Biggest single parasitic loss from the system. Total coolant load. 35% of coolant load a problem. Not all of that 36% is chargeable. 26% is used. 10% is lost.
- **9*** Estimate performance using CFD 3D methods, ID of what data must be collected, and calibration v test.
- **8*** Nozzle testing needed with simulation of leakage.
- **7*** Cross-bleed across strake tip leakage concern in some inlet configurations.
- **7*** Pre-swirl performance, or impact of pre-swirler on inlet performance.

Lesser issues of concern to group (1-6 votes)

- **5*** Do present flow models adequately model in high-g high boundary layer? Are the tools up to snuff?

- **5*** Demonstration of part load performance
- **3*** Controlling strake tip leakage is a key issue as a source of propellant loss.
- **2*** Bleed recycle is a major issue.
- **1*** (Torque measurement is needed. Subsumed below.)

Other issues (zero votes). Comments or lower priority issues that were noted, but not receiving any priority ranking votes from group

- Bigger issue is need for proof of concept test in a big enough scale to demonstrate the concept; big enough to produce net positive torque.
- Demonstration of part load performance. (If you cut back on the back pressure… Generator is holding at speed but the output of the generator is going down.)
- Estimate performance using CFD 3D methods/computational method. ID of what data must be collected, and calibration versus test. "Insight, not numbers."
- Need good inlet testing that accurately represents the system that is being designed here. With good inlet testing, we can minimize the bleed.
- Flashback, pre-ignition, strake-rub-spark, concern about avoiding flammable mixtures.
- Leakage in the burner and in the nozzle.
- Proof of concept control, but not fully automated control package for remote operation.
- (Coal fuel burned lean should be tolerant of having the right nozzle design. Shift to combustion group for discussion.)
- Unpressurized pre-mix is next generation, but high priority.
- Pipeline gas combustion -- first of a kind
- (Combustion testing is important, however, another breakout group should be considering it, so it won't be further discussed here.

Appendix D – Handout Materials at Design Review:

- Design Review Cover Letter
- Design Review Agenda
- Design Review Attendee List
- Design Review Technical Brief
- Technical Readiness Level White Paper
- Technical Readiness Level Chart A
- Technical Readiness Level Chart B

Cover Letter

11808 Northup Way, Suite W-190
Bellevue, WA 98005
425-828-4919, Fax 425-828-7756
8 March 2002

Re: DOE/NETL Design Review of Ramgen's Engine Technology, April 9-10, 2002, Ohio Aerospace Institute, Cleveland, Ohio.

Dear Colleague:

Our DOE/NETL Project Manager, Mr. Tom J. George, asked me to invite you to participate in a Design Review of the development of the Ramgen engine technology. Tom asked Ramgen to introduce and review the status of the technology and the next generation engine design to members of the design review committee. Recognizing the talent that exists in the government, Tom also has limited review committee participation to government employees. Any government employee with the appropriate talent to contribute to the design review process that is interested in participating, that is not on the attached preliminary list, can contact me.

The US Department of Energy (DOE) has and continues to play a critical role in the development of the technology, from both a funding and technical perspective. As the Ramgen engine progresses from its current early stage of development, it is envisioned that the Ramgen technology could assist in meeting and advancing some of the goals defined by the DOE in its Vision 21 and HEET programs. Your participation in the design review will help anchor the development direction of the technology and justify continued DOE funding support of it.

The Design Review process will:

- Provide general orientation (technology evolution and milestone achievements).
- Assess in detail Ramgen's 2.8 MW engine design.
- Explore cross-cutting applications.

I look forward to your attendance and participation towards a successful design review. If you have any questions, please direct them to me (ext. 288) or to Tom George at DOE/NETL (304-285-4825).

Sincerely,

Dr. Robert Steele
Vice President – Engineering

Ramgen Engine Design Review, Ohio Aerospace Institute, April 9 and 10, 2002

Agenda

DOE NETL Ramgen Power Systems Design Review

Ohio Aerospace Institute, April 9-10, 2002

Tuesday - April 9

Morning Session: **Introduction of the Ramgen Technology**

9:00AM - 9:30AM

Welcome and Opening Remarks	Tom George (NETL) Glenn Smith (Ramgen)

9:30AM - 12:00PM

Introduction of the Technology	Robert Steele (Ramgen)
Description of Pre-Prototype Test Engine	Donald Kendrick (Ramgen)
Mechanical Design of 2.8 MW Engine	Mark Novaresi (Ramgen)
Flowpath Definition of 2.8 MW Engine	Shawn Lawlor/Donald Kendrick (Ramgen)
Performance Predictions	Shawn Lawlor (Ramgen)

Group Lunch: **12:00PM - 1:00PM**

Afternoon Session: **Conduct Design Review**

1:00PM - 1:30PM

Introduce the Design Review Approach	Harvey Goldstein (Parsons)

1:30PM - 4:30PM

Breakout into Technical Groups

Group A	Mechanical / Materials / Manufacturing
Group B	Aerodynamics / Combustion / Heat Transfer
Group C	Engine Integration / Performance

4:30PM - 5:00PM

Return from Groups for Summary Comments	Harvey Goldstein (Parsons)

Reception **6:30PM - 8:30 PM**

Hilton Garden Hotel: Garnet I Room

Wednesday - April 10

Morning Session: **Explore Integration and Application of the Engine Design**

8:30AM - 11:00AM

Reports from Groups A, B, C	Harvey Goldstein & Other Staff (Parsons)

11:00AM - 12:00PM

Final Summary Comments and Action Items	Harvey Goldstein (Parsons) Robert Steele (Ramgen) Tom George (NETL)

Afternoon Session: **Optional Tour of NASA-Glenn Facilities**

1:00PM - 4:00PM

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Technical Brief

Ramgen Engine Technology

Summary

Ramgen Power Systems, Inc. is a privately held company located in Bellevue, Washington engaged in the research, development, and testing of the "Ramgen engine." Ramgen's engine represents a unique application of well-established aerospace ramjet technology to the generation of electric power. The Ramgen engine is projected to be less costly to build, run and maintain, and will do so with lower NOx emissions than other comparable generation alternatives.

In order to satisfy the rapidly expanding worldwide demand for electricity, the power generation industry is currently experiencing fundamental change: deregulation, a move towards diversified generation, increasing environmental regulations, and growing demand for high quality base load and back up power. Ramgen believes that the anticipated evolution of the power generation industry will create a highly attractive commercial opportunity in applying its technology to distributed base load and cogeneration / combined heat and power applications while operating on a wide variety of fuels.

The Ramgen engine may also serve as a means to enable the greater utilization of large US sub-pipeline-quality natural gas reserves thereby reducing reliance on foreign fuel imports, and assisting the current administration's home land security program.

Ramgen projects within five years that its 2.8 to 5MW engines will be performing at simple cycle efficiency levels in the region of 40%, with NOx emission levels of less than 10ppm and capital costs in the order of $300/kW. This means that it will be possible to produce base load power on a consistent basis at less than 7 cents/kWh when operating on pipeline gas at $4/mmBtu.

The US Department of Energy "DOE" has and continues to play a critical role in the development of the technology. As the Ramgen engine progresses from its current early stage of development, the Ramgen technology will assist in meeting and advancing some of the goals defined by the DOE in its Vision 21, HEET, and Agenda 2020 programs.

In particular, the HEET program focuses on clean coal-fired power systems. Ramgen believes that its technology can offer several contributions to the goals of the Clean Coal Effort. As a result of the Ramgen engine's capability to burn low pressure and low Btu gases, it will have the capability to use the dilute methane contained in vent air and gob gas that now escapes into the atmosphere as a result of coal mining. In addition, synthetic gas derived from various gasification techniques will be cost effectively used in the Ramgen engine to produce electricity.

The Ramgen engine is a technology in its infancy. Subsequent generations of Ramgen engines systems will realize cost and performance benefit from a natural maturation process that all new technologies experience. When the Ramgen engine system demonstrates its projected performance targets, it will be disruptive to the existing incumbent technologies in the 2 – 20 MW power output range.

There are a number of fundamental features of the Ramgen system that help focus its future potential and the particular areas where technical advances can be directly translated into improved performance. With subsequent improvements in tip leakage control systems, increased rotor speed supported by improved system cooling and improved rotor materials, and ramjet inflow supercharging, simple cycle efficiencies approaching 50% can be projected.

The basic architecture of the system scales from 2 – 20 MW and in this size range, efficiency levels between 40% and 50% represent unrivaled performance levels. These performance characteristics when coupled with the low emissions signature achievable (using conventional lean premix combustion techniques) and the low system costs that result from decreased part count when compared to conventional gas turbines, the Ramgen engine represents a combustion engine system with unique potential to meet existing and anticipated power generation requirements throughout the world.

In addition, the capability of the Ramgen engine to burn uncompressed dilute fuel streams without significant modification opens the door to a range of niche markets (coal mine vent gas, syn-fuels, land-fill gas, etc…) that have long been completely closed to or uneconomical for conventional engine systems to exploit.

For technical background, the following topics are presented; technical emphasis, engine concept, performance of the engine, pathway to improved performance, scalability, combustion characteristics, and potential configurations under consideration.

Technical Emphasis

In order to optimize the technical expertise that will be available at the Design Review, the Ramgen engineering team will emphasize the specific challenges and areas of focus that are most relevant for the successful development of the Ramgen engine. There are specific elements of the Ramgen engine that are unique, and thus require creative concepts and approaches that will assist the technology in reaching its full potential.

The technical emphasis will be on the following areas of development:

- Design, cooling, and material selection of the rotor assembly.
- Reduction of the supersonic wheel-space drag and heating.
- Development and optimization of fuel and air delivery system (slingers).
- Incorporation of an active tip leakage control system.
- Integration of a rotating inlet, combustor, and nozzle flow-path.

Ramgen Engine Concept

The essential concept of the Ramgen engine is the incorporation of one or more ramjets onto the rim of a rotor such that the thrust from the ramjets acts tangentially, causing it to rotate at supersonic speeds. In this way, the thrust from the ramjets is converted into shaft torque.

Figure 1 is an isometric illustration of the high-speed rotor and the stationary main engine case from the pre-prototype engine (for additional information, visit the company website at www.ramgen.com). The figure illustrates how the two ramjet flow-paths are incorporated into the rim of the high-speed rotor. As shown, the two-dimensional ramjet flow-paths are open on their exterior, or radially outer-most, surface. Closure of the ramjet flow-path is facilitated by the stationary surface of the main engine case. The combination of a ramjet flow-path where one of the ramjet surfaces is moving relative to the other is analogous to the moving projectile and stationary barrel wall of the ram-accelerator concept developed by the Army. The ramjet flow-paths that occupy inter-twined helixes are mounted on the rim of the rotor at an optimized helix angle to ensure sufficient inlet length, combustor velocities, residence times and optimized thrust vectors. The prescribed helix inhibits combustion products from one ramjet from being ingested into its neighbor by a mechanical separation (wall) known as a strake that wraps around the rotor's periphery (Fig. 1). The strake angle required to achieve the intake and exhaust flow separation is an optimization involving the axial length of the engine, rotor diameter, inlet length, diffuser length, and combustor length.

The shallow strake angle has a number of implications. Firstly, despite the supersonic rim speeds, the axial velocity of the inflow premix fuel and air ingested is very low. As a result, the inflow can be delivered to the ramjets with minimal pressure and viscous losses, facilitating a simple atmospheric premixer system. As a consequence, the engine is capable of burning a wide variety of low pressure and sub-quality fuels, including coal-bed methane, low-Btu natural gas (landfill methane), biomass fuels, and hydrogen. Secondly, the "augering" nature of the rotor enables the engine to be self-pumping, drawing in the required flow as determined by the effective flow area of the inlet system.

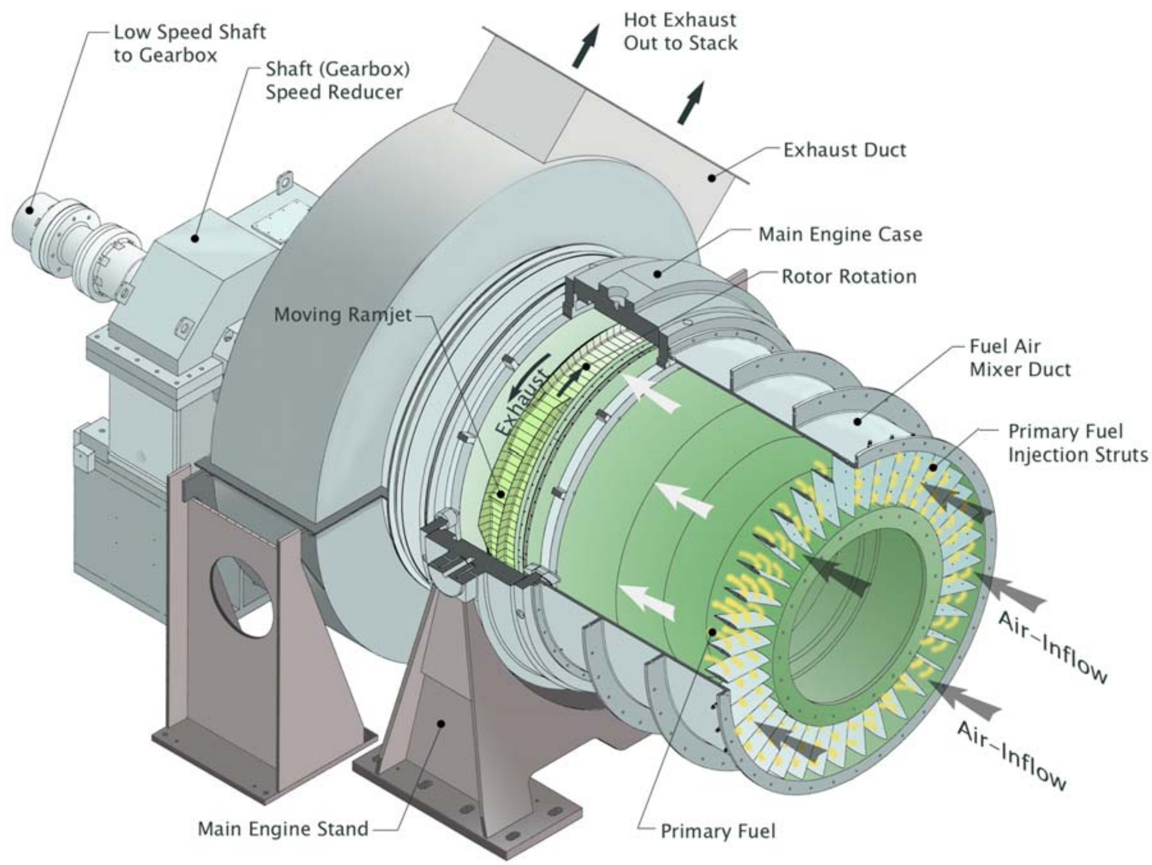

Fig. 1: The Pre-Prototype Ramgen Engine

Figure 2 is a cut-away view depicting the conceptual flow path including the supersonic inlet, diffuser, combustor and exit nozzle for the pre-prototype engine. As shown in the figure, supersonic inflow (Station 0) meets the compression surface comprising the inlet. Through a series of Mach waves and strongly reflected shock (emanating from the stationary casing wall), the required inlet compression is achieved. The gas is then diffused through a two dimensional diffuser whereby the static pressure rises to attain required combustor inflow conditions while ensuring no separation along the diffuser's length. A simple rearward facing step flame-holder is conceptually shown to anchor the combustion activity wherein oxidation ensues. The hot combustion gases are then accelerated to supersonic velocities in the nozzle. Standard diffusion piloting schemes serve to anchor the flame and ensure acceptable combustion efficiency and acoustic levels. The flow continues to expand through the supersonic nozzle until it attains atmospheric conditions – ideal expansion.

Delivery of pilot fuel and cooling air is achieved through incorporation of centrifugal pumps or “slingers” which are attached to the sides of the engine rotor. Air is delivered to the hot side of the rotor while pilot fuel is delivered to the cold or intake side. Each gas is collected in an annular manifold at the rotor’s periphery and then directed to the required segments via internal segment manifolding.

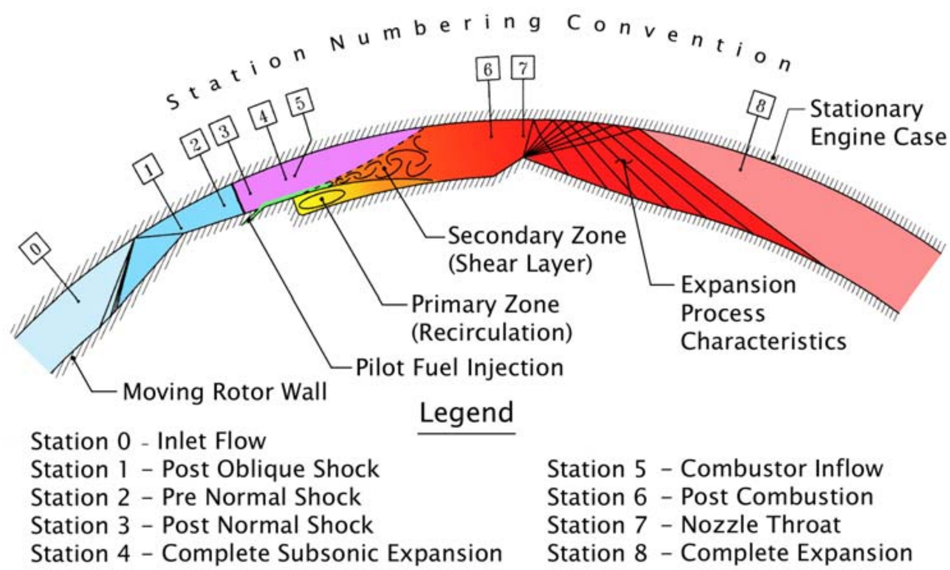

Fig. 2: Ramgen Engine Flow Details

Performance of the Ramgen Engine

As discussed, the Ramgen engine uses the thrust from ramjets integrated into the rim of a high-speed rotor to generate shaft torque and power that can be used to turn an electric generator or other driven machine. In this application, the Ramgen engine competes with other combustion engine systems including gas turbines. Both the ramjet and the gas turbine employ the Brayton thermodynamic cycle in the creation of mechanical power. The Brayton cycle involves the compression, constant pressure heat addition and expansion of a working fluid to generate power.

In an industrial gas turbine the compression, heating and expansion of the working fluid are typically accomplished using a multi-stage axial flow compressor, diffusion or lean pre-mix burner and multi-stage axial flow turbine. In a ramjet, as it would normally be configured for flight propulsion, the compression is accomplished by a series of gas dynamic shock waves that are created by an appropriately shaped aerodynamic duct, typically referred to as an inlet. The heating is accomplished using a solid, liquid or gaseous fuel that is mixed and burned with the air delivered by the inlet. The high pressure, high temperature-working fluid is then expanded back to atmospheric pressure using a supersonic nozzle. Thus in the ramjet embodiment of the Brayton cycle, the supersonic inlet, combustor, and supersonic nozzle replace the axial flow compressor, combustor and axial flow turbine in the gas turbine.

The efficiency of the Brayton cycle can be understood in terms of the compression ratio and the efficiencies of the three processes involved (compression, heating and expansion). For any given level of heat release, the efficiency of the Brayton cycle is only dependant on the compression ratio and the efficiencies of the compression and expansion processes. If the compression and expansion processes are assumed to be ideal (100% isentropic and adiabatic), then a theoretical maximum thermal efficiency can be calculated as a function of compression ratio. Figure 3 shows such a theoretical maximum curve (labeled as Ideal Component Efficiencies) for an assumed maximum Brayton cycle temperature of 2520 R (2060 F). This curve shows the maximum possible thermal efficiency that can be attained for any given compressor pressure ratio. When the effects of actual component efficiencies are included, actual system efficiencies are somewhat lower than the theoretical maximum indicated in Figure 3.

Whether the embodiment of the Brayton cycle is a ramjet or a gas turbine, the overall thermal efficiency of the process, as well as the efficiencies of the compression, heating and expansion processes can be directly compared. In the case of a properly designed supersonic ramjet inlet, high compression process efficiencies can be developed. Similarly, a properly designed, shock free, supersonic nozzle can develop high expansion process efficiencies. Figure 3 includes a shaded band indicating potential Ramgen engine cycle efficiencies that would result from realistic ramjet supersonic inlet compression and nozzle expansion efficiencies over a range of compression ratios.

In the gas turbine, compression and expansion are accomplished by flow acceleration, diffusion, and turning, with compressor and turbine component exit energy losses minimized by reducing component exit swirl and velocity. With typical compressor and turbine components some 50% of the compression and expansion energies are imparted via flow turning, thus pressure losses inherent in flow turning influence the attainable component efficiencies. Figure 3 also shows a range of cycle efficiencies that would result from typical industrial gas turbine component efficiencies ($\eta_c \sim 0.855$, $\eta_t \sim 0.87$) as well as a band that corresponds to the range of cycle efficiencies that would result from the higher component efficiencies typically developed in aero-derivative gas turbines ($\eta_c \sim 0.87$, $\eta_t \sim 0.89$).

The supersonic compression and expansion that are employed in the Ramgen engine, uses virtually no flow turning, with the exception of residual swirl energy recovery in the single stage exhaust turbine that is proposed for the engine. For the same maximum Brayton cycle temperature and pressure ratio, Ramgen engine thermal efficiency is therefore basically dominated by the supersonic compression and expansion processes, which have the potential to be several percentage points more efficient than the conventional gas turbine compressor and turbine efficiencies, thereby producing higher thermal efficiencies.

The curves that appear in Figure 3 illustrate the effect that increased component process (compression and expansion) performance levels can have on overall cycle efficiency.

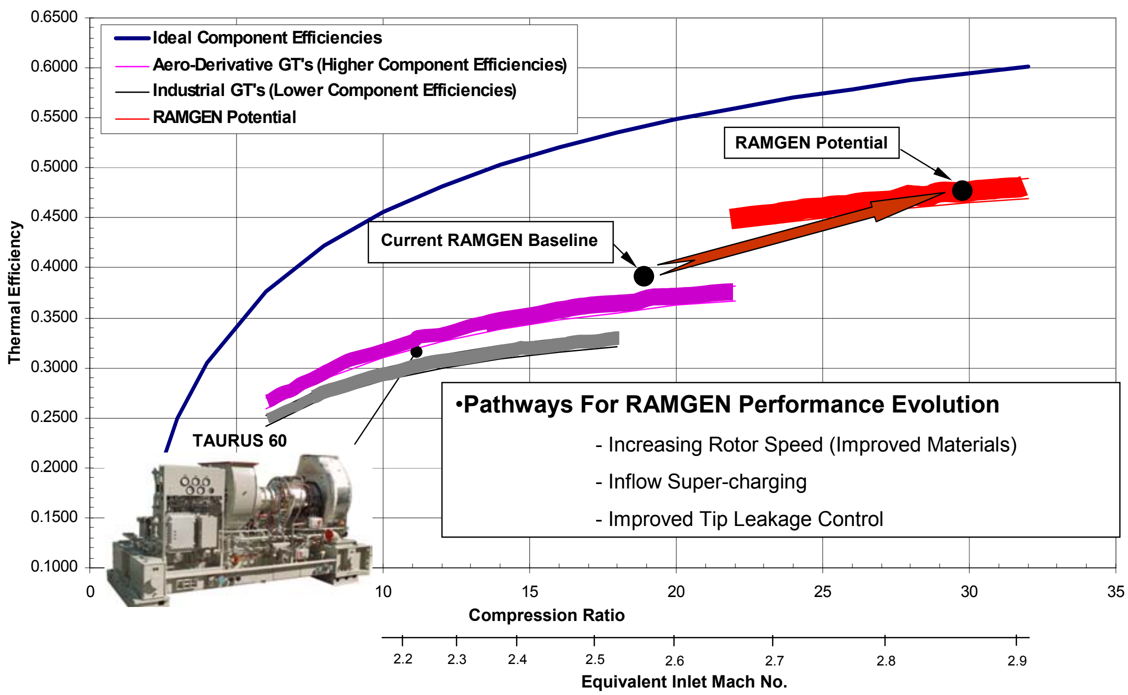

Fig. 3: Effect of Component Efficiencies

Pathways to Improved Performance

The component performance levels that can be achieved in the Ramgen engine make simple cycle efficiencies on the order of 50% theoretically achievable at compression ratios in the range of 30:1. There are a number of system design issues that must be carefully understood and optimized before such performance levels can be achieved. These desirable performance characteristics should be viewed as potentially attainable over a 5-7 year period with the maturation of a limited number of system design features.

Simple cycle efficiency levels on the order of 39% in the 2 – 10 MW size range should be achievable within the next 3 – 5 years given the appropriate levels of support for key subsystem and subcomponent development and test activities.

The ability to decrease the development time between the near term performance capabilities of the Ramgen engine and the long term potential can be supported by the strong potential for advances in four basic areas: tip leakage control, increased rotor speed and preswirl, inflow supercharging, and the approach of providing cooling air to the rotor hot section.

Tip Leakage Control

The compression in the Ramgen engine is achieved across a single helical wall or strake. The gap between the tip of this strake, which is moving at supersonic speeds compared to stationary main engine case, and the case itself forms a source of leakage for the working fluid. Any fluid that leaks out through the gap is not available to do work and consequently results in a decrease in cycle efficiency.

Minimizing this leakage can be accomplished be aerodynamic features on the tips of the strakes that result in decreased discharge coefficients (C_d's) or by minimizing the gap itself. Inter-stage leakage in gas turbine compressor and turbine stages represents a similar loss mechanism and as a result a significant level of research has been directed toward a broad range of leakage control or sealing techniques over the past forty years. Based on this existing body of knowledge, there are a number of techniques that Ramgen will apply to control and minimize the leakage from the ramjet flow path in the Ramgen engine.

Progressing from the early designs and systems that Ramgen has already investigated and developed to a truly optimized tip leakage control strategy will take a number of design iterations over a period of time and will involve a team of industry specialists in this area that have already or will be retained to participate in this process.

Tip leakage control strategies developed in the gas turbine industry are in many cases more easily applied to the Ramgen engine than a gas turbine. This results from the shorter physical length of surface required to be sealed in the Ramgen engine as compared to a gas turbine. In the case of the Ramgen engine the area to be sealed is limited to the relatively small axial extent of the interior surface of the engine case that interacts with the strake tips whereas in the comparable gas turbine the seals must be implemented over many compressor or turbine stages in order to maximize the effect of the system.

Figure 4 shows that there are up to four percentage points of efficiency that could be reclaimed by eliminating tip leakage altogether. While complete elimination of tip leakage does not seem to be a strong possibility, the number of advanced sealing systems currently under consideration within industry and at government labs will almost certainly yield some level of decrease in tip leakage as future designs are developed, tested and optimized.

Increased Rotor Speed & Pre-Swirl

The compression ratio is a critical determinant of Brayton cycle efficiency. In the case of a gas turbine compressor, the compression ratio is determined by the design of the compressor (number of stages, rotor & stator design, etc…). In the case of a supersonic ramjet, the compression ratio is determined by the velocity of the air entering the ramjet inlet. This velocity is typically expressed in terms of the Mach number of the gas entering the inlet. The Mach number of the ramjet inlet inflow is principally determined by two factors in the Ramgen engine – rotor speed and pre-swirl velocity.

The rotation rate and diameter of the rotor determine the tangential velocity of the rim of the rotor and therefore the Mach number of the gas entering the inlet. However, in order to maintain the compression ratio of the Ramgen engine while decreasing the rotor speed

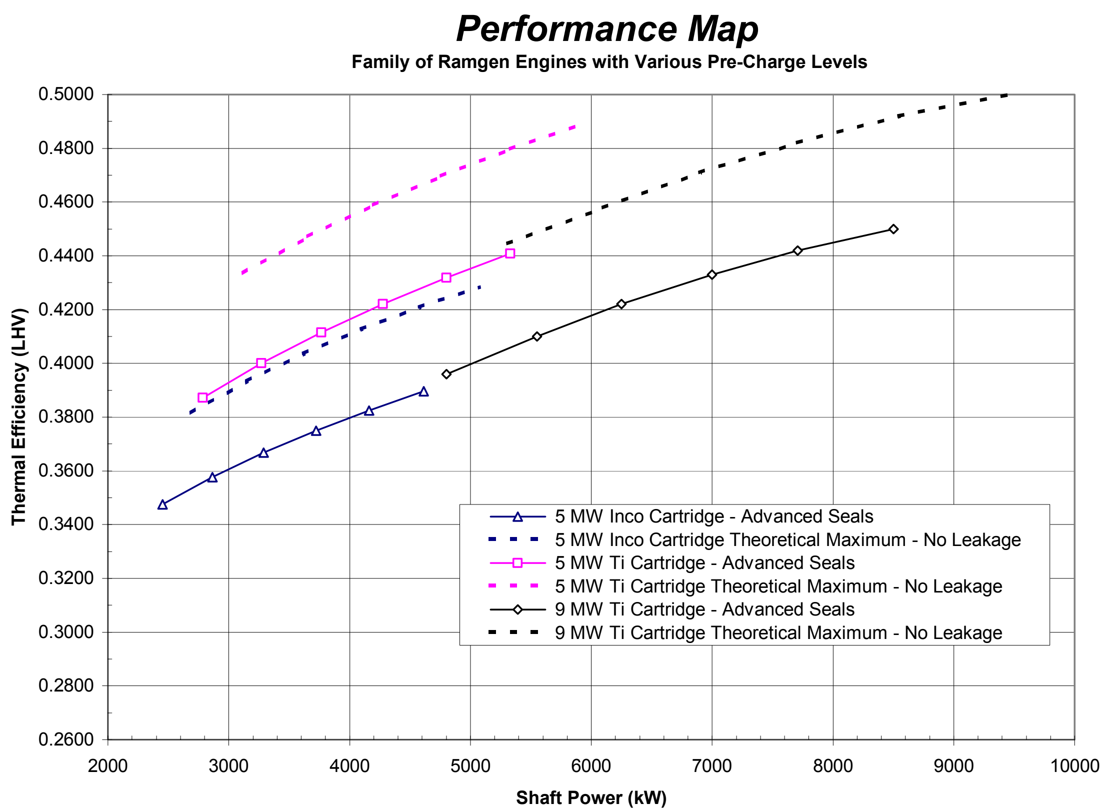

Fig. 4: Effect of Supercharging on Cycle

(which decrease the stresses in the rotating hardware), the Ramgen engine utilizes a small centrifugal impeller mounted on the same shaft with the Ramjet rotor. The pressure created by this compressor is converted back into velocity or "pre-swirl" in the direction opposite to the direction of rotation of the ramjet rotor by an inlet guide vane (IGV) cascade. This increases the apparent Mach number of the gas entering the ramjet inlet to a level above that which would be created by the rotation of the rotor alone. There are limitations on the degree of pre-swirl that can developed in the ramjet inflow field without degrading system efficiency levels. The power required to create the pre-swirl begins to increase disproportionately as the velocity of the pre-swirl approaches Mach = 1.0. The current Ramgen design goal is to keep the pre-swirl velocity below Mach = 0.9.

The allowable stresses in the rotor components are very dependant on the steady state temperatures at which they are operated, the higher the metal temperature the lower the allowable stress. While the preliminary cooling schemes proposed for the Ramgen engine are based on conservative assumptions, the desire to minimize the risk of structural failure has driven the design of early systems to combinations of low rotor speed, high pre-swirl and relatively low cost nickel-based materials. With increasing experience and optimization of the cooling system design as well as the potential for selective use of higher cost material systems, the potential to increase the mechanical speed of the rotor is high.

Any increase in rotor speed can be directly converted into increased compression ratio and cycle efficiency. This trend is reflected in Figure 4, which shows projected cycle efficiency characteristics for a lower speed Inco-718 (curve with open triangles) rotor design as well as a rotor assembly where the slingers and rotor disk have been replaced with Titanium elements (curves with open squares and open diamonds). The resulting increase in allowable rotor speed results in an increase in cycle efficiency of almost four full percentage points.

Inflow Supercharging

In addition to utilizing the centrifugal impeller mounted on the front of the Ramgen rotor cartridge to create pre-swirl at atmospheric pressure (14.7 psia), it is possible to customize the design of the impeller and IGV set to result in a ramjet inlet inflow condition with the same pre-swirl velocity or Mach number but at a super-atmospheric pressure. Since the supersonic ramjet inlet basically multiplies the pressure based on the inflow pressure and Mach number, a small amount of ramjet "supercharging" can result in a significant increase in cycle compression ratio. As previously discussed, increasing the cycle compression ratio can result in an increase in cycle efficiency so long as component efficiencies can be maintained.

Figure 4 shows the effect of supercharging on cycle efficiency. In each of the three configurations shown in Figure 4 the effect of increased ramjet inflow pressure is shown in 2-psi increments. The lower left end of each curve corresponds to no supercharge (atmospheric pressure inlet inflow), the upper right end of each curve shows the effect of 10 psi of inlet supercharge. As the curves progress from lower left to upper right, the symbols correspond to 2 psi increments in supercharge.

Cooling

The current performance model assumes that all the cooling air required by the system is provided by an independent, off-skid compressor. The system power output and therefore cycle efficiency is decremented for the power required to drive this off-skid compression. As the cooling air requirements for the system are optimized through system testing and design improvements, any decreases in cooling air requirements would result in a further increase in cycle efficiency compared to levels shown in Figure 4.

System configurations similar to conventional gas turbines that provide the cooling air to the rotor hot-section from the discharge of the inlet are under consideration. In addition to eliminating the need for any pre-compression of the cooling air, such a configuration would also result in an increase in system efficiency compared to the levels shown in Figure 4 because the efficiency of the compression process in the ramjet inlet is greater than that currently assumed for the off-skid compressor.

Scalability

Based on current understanding of design parameters, systems sized from 2 - 20 MW are feasible with minimum combustor residence time driving the lower end of the scale and rotor disc manufacturing processes determining the maximum possible system size.

Combustion Characteristics

Unlike conventional gas turbine engines, the Ramgen engine's primary fuel is injected at a location where it can be mixed with engine inlet air at near atmospheric pressure, prior to ingestion and processing by the ramjet inlets. This demonstrates an important and unique attribute of the Ramgen engine. Since the fuel is injected into the uncompressed inlet airflow, the fuel pressure requirement is limited to slightly above atmospheric pressure.

The injection strategy allows for near perfect premixing of the gaseous fuel and engine inlet air. The premix has low flammability properties prior to compression in the ramjet inlet on the rotating rotor. The premix must pass through the system of oblique shock waves in the ramjet inlet before it is sufficiently compressed and heated to pre-combustor conditions. The premixing approach allows for exploitation of dry lean premix (LPM) combustion, which will produce single digit NOx emissions. The proper management of cooling techniques and residence times in the combustor will result in the required low CO and UHC emissions.

Ramgen is pursuing the use of the Trapped Vortex Combustor (TVC) concept for the engine. There has been tremendous progress since 1993 at the Air Force Research Laboratories in the development of the TVC. More recently, at the DOE NETL and at GE research, the use of the TVC for natural gas, lean premixed applications is gaining support. Under a government program, GE plans to demonstrate a full-scale land-based TVC engine by 2005. In addition, tests in Morgantown at the combustion facilities are ongoing.

The TVC has proven to exhibit much lower lean blowout limits than conventional systems while maintaining high combustion efficiencies. Other improvements that have been experimentally demonstrated are lower NOx levels, increase in relight capability, lower turndown ratios, and high combustor inlet velocity stability for military applications. In essence, the TVC uses mechanical cavities or flame-holding features to "trap" or lock the position of vortices in the combustor. The control of the aerodynamic features in the flow-path results in a more stable and robust acoustic environment. It is argued that the combination of a TVC concept and the use of the sonic choke points in the Ramgen combustor flow-path will result in a very stable and acoustically quiet, lean premixed system.

The capability of the Ramgen engine to burn uncompressed dilute fuel streams without significant engine modifications has opened the door to a range of potential applications. These include hydrogen by-product, coal mine vent gas, low-pressure gasification fuels from coal, wood products and black liquor, landfill gas, and other sub-quality gases. Therefore, the unique architecture of the Ramgen engine has compelling technical advantages when compared with other technologies that burn non-pipeline gas fuels.

Potential Configurations Under Consideration

The evolutionary process of the Ramgen engine has only begun and there are many optimization, design trade studies and alternative system embodiments to be considered as the Ramgen engine progresses through the same maturation process that all technologies experience over their lives. Already a number of alternative and hybrid systems have been composed for an increasing range of niche market and specific applications. Following is a high level summary of some of the hybrid/alternative systems currently under consideration.

- Premix Ramjet
    - Air Film Cooling (AFC) pre-compression required
    - Premix air/fuel ingested through ramjet inlet
        - Low pressure/dilute fuels easily accommodated
        - Syn-fuels easily accommodated
    - Tip leakage controlled by active case control
    - Low end Nickel alloys used in rotor components

Non-Premix Ramjet

- Pure air ingested by ramjet inlet
- AFC supply taken from inlet discharge
- Eliminates AFC slinger and pre-compression requirement
- Fuel delivered through slingers
- Pre-pressurized fuel required

- Variable Inlet Pressure Ratio Engine (VIPRE)
    - Real time controllable supercharging
    - Pre-swirl impeller bypass to inflow duct
    - Improved NO_x/throttle range characteristics

- Hybrid Systems
    - Ramgen compressor / conventional burner and axial flow turbine
        - Fixed speed gas producer turbine drives supersonic inlet rotor
        - Variable speed power turbine drives variable speed mechanical load

          -or-
        - Fixed speed power turbine drives electric generator
    - Ramgen / Fuel Cell system
        - Ramgen exhaust generates H2 through thermal reformation

Technical Readiness Level White Paper

TECHNOLOGY READINESS LEVELS

A White Paper
April 6, 1995

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Advanced Concepts Office
Office of Space Access and Technology
NASA

Introduction

Technology Readiness Levels (TRLs) are a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology. The TRL approach has been used on-and-off in NASA space technology planning for many years and was recently incorporated in the NASA Management Instruction (NMI 7100) addressing integrated technology planning at NASA. Figure 1 (attached) provides a summary view of the technology maturation process model for NASA space activities for which the TRL's were originally conceived; other process models may be used. However, to be most useful the general model must include: (a) 'basic' research in new technologies and concepts (targeting identified goals, but not necessary specific systems), (b) focused technology development addressing specific technologies for one or more potential identified applications, (c) technology development and demonstration for each specific application before the beginning of full system development of that application, (d) system development (through first unit fabrication), and (e) system 'launch' and operations.

Technology Readiness Levels Summary

TRL 1 Basic principles observed and reported

TRL 2 Technology concept and/or application formulated

TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 4 Component and/or breadboard validation in laboratory environment

TRL 5 Component and/or breadboard validation in relevant environment

TRL 6 System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 7 System prototype demonstration in a space environment

TRL 8 Actual system completed and "flight qualified" through test and demonstration (ground or space)

TRL 9 Actual system "flight proven" through successful mission operations

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Discussion of Each Level

The following paragraphs provide a descriptive discussion of each technology readiness level, including an example of the type of activities that would characterize each TRL.

TRL 1

Basic principles observed and reported

This is the lowest "level" of technology maturation. At this level, scientific research begins to be translated into applied research and development. Examples might include studies of basic properties of materials (e.g., tensile strength as a function of temperature for a new fiber).

Cost to Achieve: Very Low 'Unique' Cost
(investment cost is borne by scientific research programs)

TRL 2

Technology concept and/or application formulated

Once basic physical principles are observed, then at the next level of maturation, practical applications of those characteristics can be 'invented' or identified. For example, following the observation of high critical temperature (Htc) superconductivity, potential applications of the new material for thin film devices (e.g., SIS mixers) and in instrument systems (e.g., telescope sensors) can be defined. At this level, the application is still speculative: there is not experimental proof or detailed analysis to support the conjecture.

Cost to Achieve: Very Low 'Unique' Cost
(investment cost is borne by scientific research programs)

TRL 3

Analytical and experimental critical function and/or characteristic proof-of-concept

At this step in the maturation process, active research and development (R&D) is initiated. This must include both analytical studies to set the technology into an appropriate context and laboratory-based studies to physically validate that the analytical predictions are correct. These studies and experiments should constitute "proof-of-concept" validation of the applications/concepts formulated at TRL 2. For example, a concept for High Energy Density Matter (HEDM) propulsion might depend on slush or super-cooled hydrogen as a propellant: TRL 3 might be attained when the concept-enabling phase/temperature/pressure for the fluid was achieved in a laboratory.

Cost to Achieve: Low 'Unique' Cost
(technology specific)

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TRL 4

Component and/or breadboard validation in laboratory environment

Following successful "proof-of-concept" work, basic technological elements must be integrated to establish that the "pieces" will work together to achieve concept-enabling levels of performance for a component and/or breadboard. This validation must devised to support the concept that was formulated earlier, and should also be consistent with the requirements of potential system applications. The validation is relatively "low-fidelity" compared to the eventual system: it could be composed of ad hoc discrete components in a laboratory. For example, a TRL 4 demonstration of a new 'fuzzy logic' approach to avionics might consist of testing the algorithms in a partially computer-based, partially bench-top component (e.g., fiber optic gyros) demonstration in a controls lab using simulated vehicle inputs.

Cost to Achieve: Low-to-moderate 'Unique' Cost
(investment will be technology specific, but probably
several factors greater than investment required for TRL 3)

TRL 5

Component and/or breadboard validation in relevant environment

At this, the fidelity of the component and/or breadboard being tested has to increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component-level, sub-system level, or system-level) can be tested in a 'simulated' or somewhat realistic environment. From one-to-several new technologies might be involved in the demonstration. For example, a new type of solar photovoltaic material promising higher efficiencies would at this level be used in an actual fabricated solar array 'blanket' that would be integrated with power supplies, supporting structure, etc., and tested in a thermal vacuum chamber with solar simulation capability.

Cost to Achieve: Moderate 'Unique' Cost
(investment cost will be technology dependent, but likely to be several factors
greater that cost to achieve TRL 4)

TRL 6

System/subsystem model or prototype demonstration in a relevant environment (ground or space)

A major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative model or prototype system or system — which would go well beyond ad hoc, 'patch-cord' or discrete component level breadboarding — would be tested in a relevant environment. At this level, if the only 'relevant environment' is the environment of space, then the model/prototype must be demonstrated in space. Of

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course, the demonstration should be successful to represent a true TRL 6. Not all technologies will undergo a TRL 6 demonstration: at this point the maturation step is driven more by assuring management confidence than by R&D requirements. The demonstration might represent an actual system application, or it might only be similar to the planned application, but using the same technologies. At this level, several-to-many new technologies might be integrated into the demonstration. For example, a innovative approach to high temperature/low mass radiators, involving liquid droplets and composite materials, would be demonstrated to TRL 6 by actually flying a working, sub-scale (but scaleable) model of the system on a Space Shuttle or International Space Station 'pallet'. In this example, the reason space is the 'relevant' environment is that microgravity plus vacuum plus thermal environment effects will dictate the success/failure of the system — and the only way to validate the technology is in space.

Cost to Achieve: Technology and demonstration specific; a fraction of TRL 7 if on ground; nearly the same if space is required

TRL 7

System prototype demonstration in a space environment

TRL 7 is a significant step beyond TRL 6, requiring an actual system prototype demonstration in a space environment. It has not always been implemented in the past. In this case, the prototype should be near or at the scale of the planned operational system and the demonstration must take place in space. The driving purposes for achieving this level of maturity are to assure system engineering and development management confidence (more than for purposes of technology R&D). Therefore, the demonstration must be of a prototype of that application. Not all technologies in all systems will go to this level. TRL 7 would normally only be performed in cases where the technology and/or subsystem application is mission critical and relatively high risk. Example: the Mars Pathfinder Rover is a TRL 7 technology demonstration for future Mars micro-rovers based on that system design. Example: X-vehicles are TRL 7, as are the demonstration projects planned in the New Millennium spacecraft program.

Cost to Achieve: Technology and demonstration specific, but a significant fraction of the cost of TRL 8 (investment = "Phase C/D to TFU" for demonstration system)

TRL 8

Actual system completed and "flight qualified" through test and demonstration (ground or space)

By definition, all technologies being applied in actual systems go through TRL 8. In almost all cases, this level is the end of true 'system development' for most technology elements. Example: this would include DDT&E through Theoretical First Unit (TFU) for a new reusable launch vehicle. This might include integration of new technology into an existing system. Example: loading and testing successfully a new control algorithm into the onboard computer on Hubble Space Telescope while in orbit.

Cost to Achieve: Mission specific; typically highest unique cost for a new technology (investment = "Phase C/D to TFU" for actual system)

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TRL 9

Actual system "flight proven" through successful mission operations

By definition, all technologies being applied in actual systems go through TRL 9. In almost all cases, the end of last 'bug fixing' aspects of true 'system development'. For example, small fixes/changes to address problems found following launch (through '30 days' or some related date). This might include integration of new technology into an existing system (such operating a new artificial intelligence tool into operational mission control at JSC). This TRL does <u>not</u> include planned product improvement of ongoing or reusable systems. For example, a new engine for an existing RLV would not start at TRL 9: such 'technology' upgrades would start over at the appropriate level in the TRL system.

Cost to Achieve: Mission Specific; less than cost of TRL 8 (e.g., cost of launch plus 30 days of mission operations)

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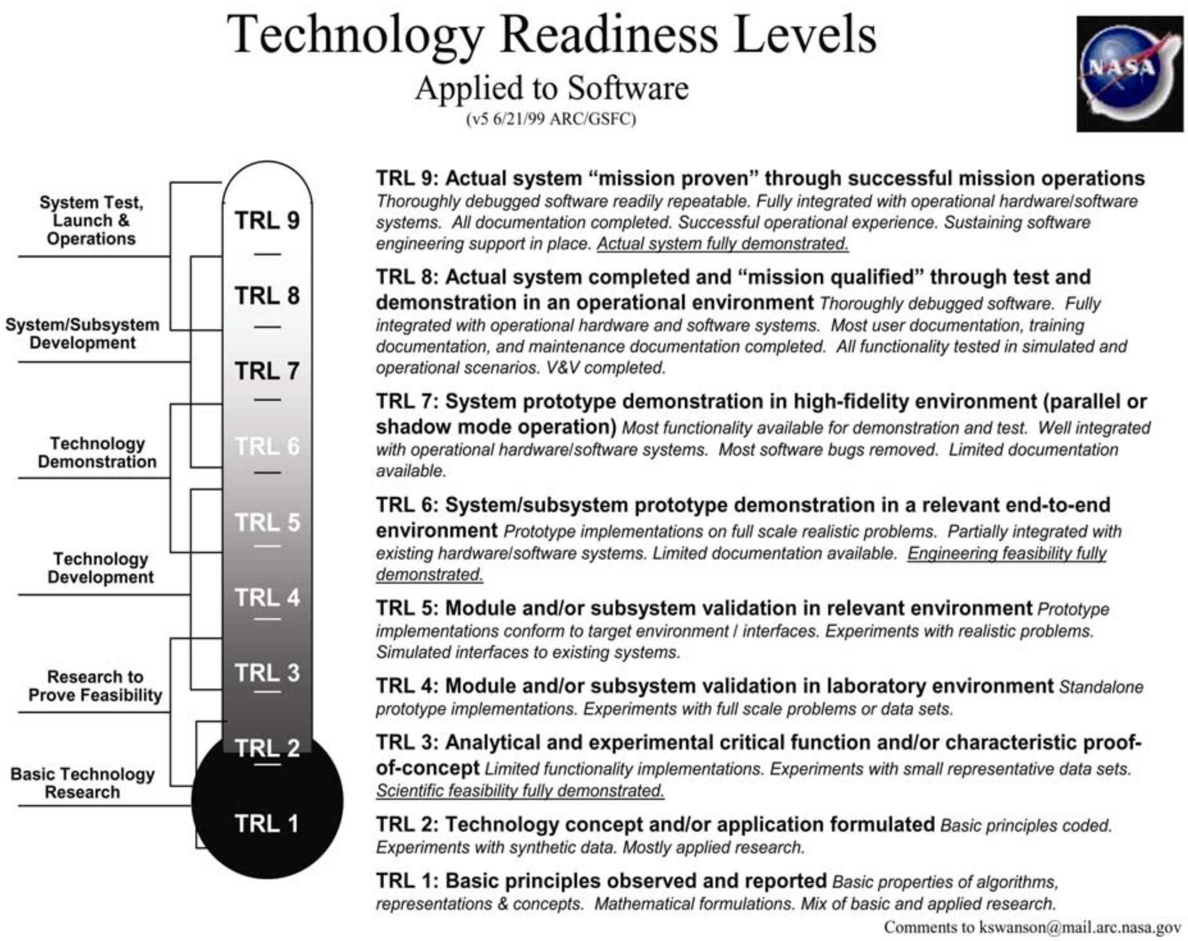
Technical Readiness Charts

Technical Readiness Level Chart A



Technical Readiness Charts

Technical Readiness Level Chart B