Spaceliner 100 Candidate Technology White Paper

Title: Long Life, light weight propulsion materials and structures.

Disclaimer: This disclaimer applies to all technology whitepapers.

When this paper was being reviewed a number of reviewers objected to some statements of benefits with words to the general effect of "when I ask my supplier to do that, he has a hard time and really can not do it". And then they suggested that the benefit being discussed be eliminated or toned down. When they were in turn asked could the supplier probably do it if the money and time were spent to fully develop the technology, the answer generally was "yes" or "probably".

The point of a technology whitepaper is to examine what can be achieved in the future if the time and money is spent to fully develop the particular technology. It is not to examine what can be achieved now with that particular technology. What can be achieved now is the current state of the art and is addressed by assessing the current TRL.

Consequently, this, and most other technology whitepapers, will present benefits as if the technology were fully matured. That is the whole point - to assess the potential gain relative to the potential cost.

Admittedly, since the future course of a technology's development, particularly when the current TRL is low, can not be perfectly predicted, the benefits presented may not all materialize or could be optimistic, as could the costs projected to mature the technology. Nonetheless, such technology assessments are both necessary and useful input to the technology selection process.

Technology Category: Enabling/Generic Technologies.

Summary Description: The material environments required in rocket engines, combined cycle engines, and pulse detonation engines are quite possibly the most stressful of any modern technology except, possibly, that of nuclear reactors. The operational factors for all these engines include:

Extremely high power densities
Temperature extremes
Steep temperature gradients
Severe thermal shocks
Rigorous mechanical loads
Extreme flow rates and pressures
Reactive propellants

Complex dynamics.

In addition, the pulse detonation engine has the potential of high frequency (~100 hz) pressure spikes of 20 to 25 times the pre-detonation pressures in the combustion chambers (as shown in Figure 1) adding a new dimension to the structural design considerations.

Even if weight was not an important consideration for these engines, it would be difficult to address these requirements and environments while still producing engines which have a long life and low maintenance. But weight is not only important, it is often of almost overriding importance.

The result is that most materials available and adopted for engine use are operated at their limits. Indeed the history of rocket engines, and the feasibility of these new engines, is to a large degree the history of the availability of new and better materials as shown in Figure 2.

The goals for future vehicles such as the Spaceliner 100 include increasing the engine thrust/weight to the point where engine thrust/weight is no longer a major driver in the vehicle design (getting off the "steep part of the curve") and then increasing it further to allow weight to be put back into the system to achieve the goals of long life and minimal maintenance.

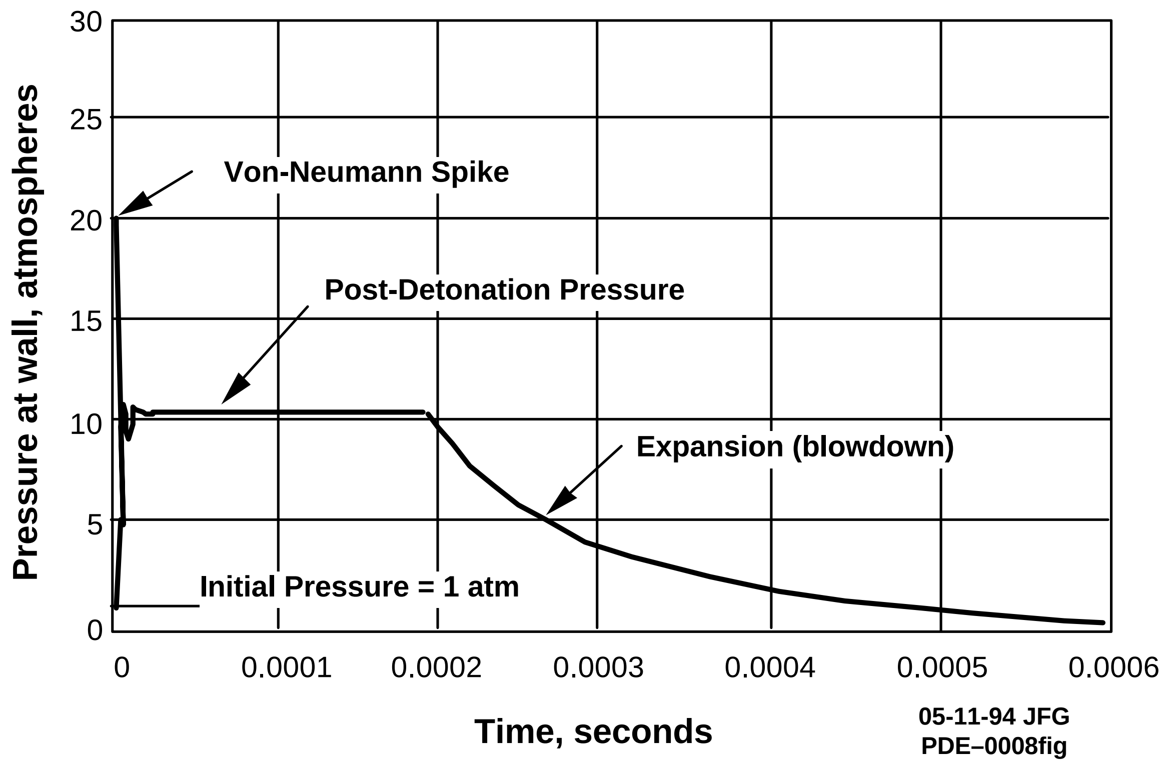

Figure 1. Combustion Chamber Pressure per Cycle for Pulse Detonation Engine.

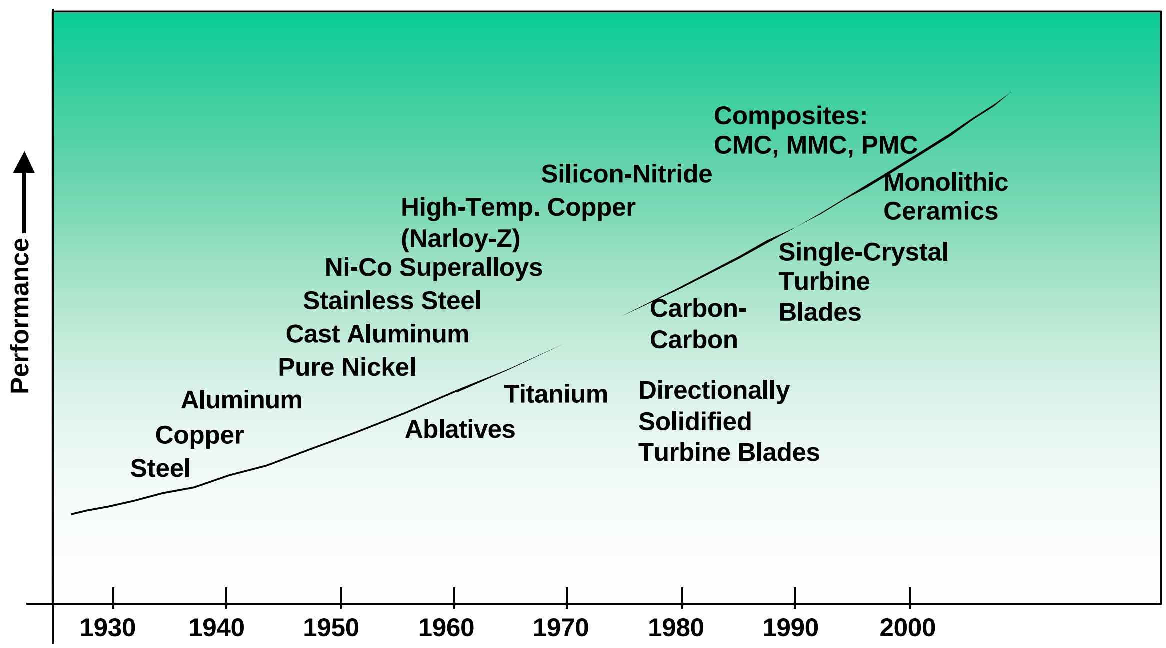

Figure 2. Progression of Materials Usage in Rocket Engines.

An example, in this case for a rocket engine, of how the thrust/weight must first be reduced to allow a reasonable vehicle design and then if reduced further becomes available to be used for engine life, lowered maintenance, vehicle weight growth, etc. is shown in Figure 3 which shows the impact of increasing the engine thrust/weight for a rocket engine being used in a SSTO application (amongst the most stressing applications). By the time the thrust/weight has reached 90, the engine thrust/weight is off the "steep part of the curve". An engine thrust/weight of 90 produces a reasonable vehicle design as shown in Figure 4 which shows that with such a thrust/weight (the "Long Life, High T/W O2/H2 Rocket Engine" bar) the dry vehicle weight is comparable to RBCC vehicles (even when they are using a very good RBCC engine thrust/weight of 32.7). Referring back to Figure 3 it is seen that even doubling the engine thrust/weight to 180 (the "Low Maintenance, Lt Weight Rocket Engine VTHL" bar) only reduces the vehicle dry weight by 20%. Although such a reduction is obviously useful, it is equally obviously no longer "driving". Engine thrust/weight increases above 90 can be used to improve the vehicle or to add margin as needed.

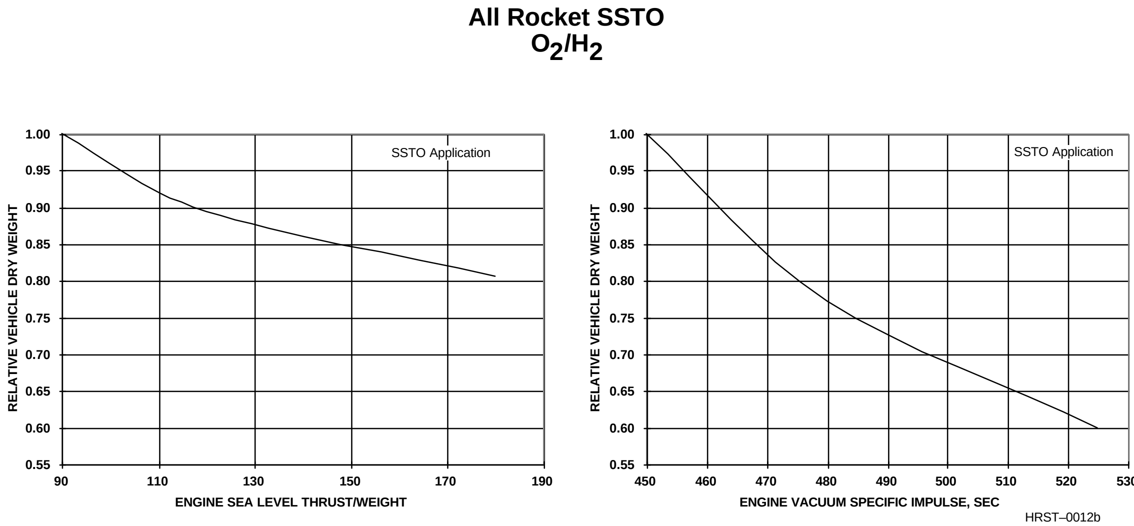

Figure 3. Impact of Engine Thrust/Weight and Specific Impulse on Rocket SSTO.

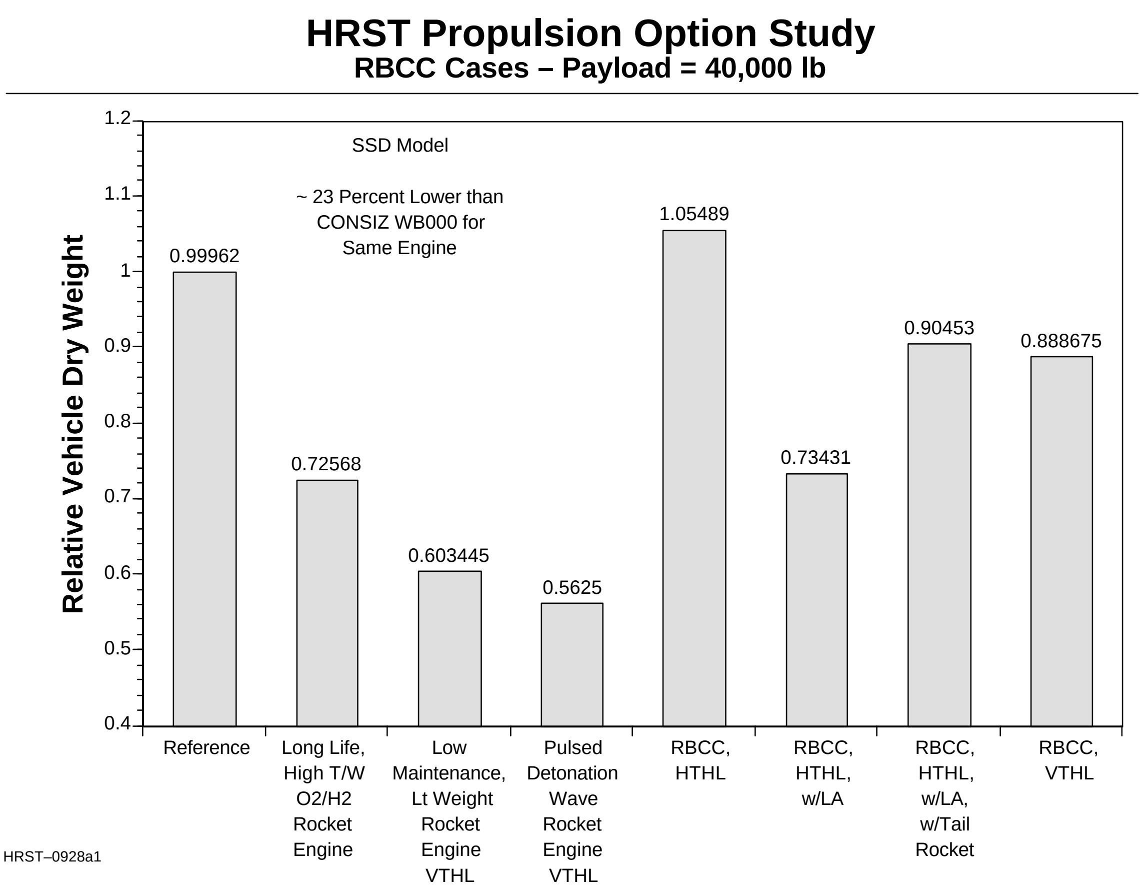

Figure 4. Comparison of Rocket Engines and - Vehicle Dry Weight

Curves similar to Figure 3 can be defined for the other engine technologies and threshold engine thrust/weight ranges derived. For RBCCs the target engine thrust/weight is probably around 25 - 35. For pulse detonation rocket engines it is around 50 - 60 because of the higher specific impulse compared to a conventional rocket engine.

The reasons to use advanced materials can be many, but for application to these types of engines, the most important reasons are:

- High strength
- High strength at elevated temperatures (or a specific temperature range of interest)
- High specific strength
- High specific strength at elevated temperatures (or a specific temperature range of interest)
- Material compatibility - the use of no coating or a very high resistance to a particular environment
- Reduced part counts - ability to be cast or formed into very complex parts, ability to integrate preform elements into a very complex single part.

The first four reasons directly effect weight, life, and operability. The last two directly effect life and operability. And the last can also lower weight.

<u>Types of Materials Being Considered</u>

Although many materials are being considered for specific detailed applications, the general thrust is in three categories:

- Composites
  - Metal Matrix
  - Ceramic Matrix
  - Polymer Matrix
- Ceramics
- Nanophase metals

A composite is a material consisting of a combination of fibers, whiskers, and/or particles in a common matrix. Figure 5 shows the possible combinations of interest. Glass, aramid, graphite, and boron fibers are being considered for use in polymer matrices, while materials such as alumina and silicon carbide are being considered for use in ceramic matrices.

	Reinforcement		
Matrix	**Metal**	**Ceramic**	**Polymer**
Metal	X	X	
Ceramic		X	
Polymer	X	X	X

Figure 5. Classes of Composite Materials.

Ceramics are composed of inorganic, nonmetallic materials treated by firing. This definition includes materials such as porcelain, refractories, and glass. Many of these materials possess high strength and hold their strength to high temperatures, but they also as a class tend to have low elongation at failure - they are brittle. Examples considered for engine use are Si_3N_4, SiC, and Al_2O_3 (alumina).

A nanophase material is simply a material such as aluminum, copper, or nickel superalloy that has been processed on a nano scale to produce a more uniform and consistent structure. Ideally the effect is a higher strength. These materials are used for improvements where a material is already being used and has desirable characteristics but more strength would be useful (e.g., a blade in a hydrogen pump) or where an improvement in some other property, such as hydrogen resistance, would be useful.

Figure 6 shows one more reason why materials of these types are being sought. Current state of the practice is to use superalloys for most engine parts. As can be seen in the chart, the rough specific strength (strength per pound of material) is not greatly different for many of these new materials versus the superalloys. However, the strengths of the superalloys begin to fall off at temperatures around 1,500 R and are generally significantly reduced by around 2,000 R. The new materials not only have somewhat higher specific strength, but they also retain their strength to much higher temperatures. There are two practical implications of this characteristic: first is the ability to design parts at higher temperatures at reasonable weights (e.g., ceramic composite turbine blades); second, as explained in the next paragraph, is a considerable reduction of variability, especially in the area of life, in the designs.

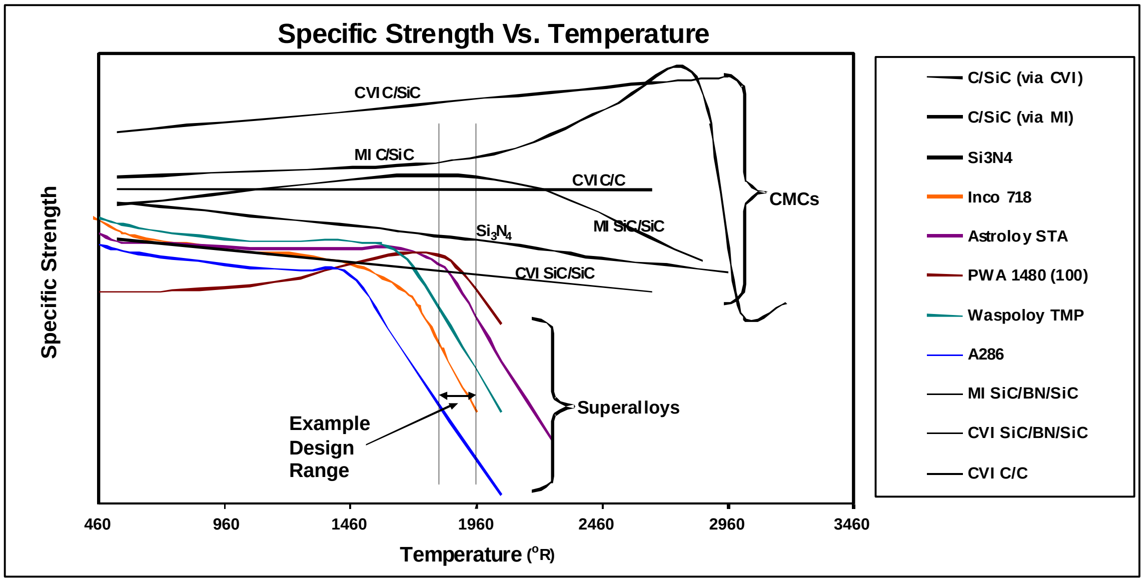

Figure 6. Comparative Engine Materials.

An example design range was shown in Figure 6. In that range, which is typical in engine design, using a superalloy requires an increased margin on the allowable strength used for design - in other words, an increased safety factor. An explicit temperature, except maybe the maximum expected, can not be used due to variations between engines and in the actual operating conditions each engine experiences. Additionally, in highly reusable engines, components wear at different rates in different engines, and thus the part will experience differing temperatures over its life and the same part will experience a different temperature history in different engines. Also, if the part experiences a temperature higher than the maximum designed for, the result is generally a greater reduction in life than expected for one cycle or mission. This material safety factor is normally not even seen in the design specifications because it is used to simply reduce the strength used when making calculations in the first place (design safety factors are then placed on that). The effect is uncertainty in the design, or in other words, variability. All of this in turn produces inspection requirements and increased maintenance because of life uncertainties. The new materials have constant strength in this temperature range. Consequently, the uncertainties are less and operation at a higher temperature than expected has minimal effect.

The nanophase materials are not shown in Figure 6. However, they are expected to possess slightly higher properties than their parent material.

Figure 7 allows a different way of looking at why these materials are being pursued. The figure just shows the operating point of a material and the capabilities of the material. Both are shown as statistical variations around these points. The difference between the centers (means) of the two curves is the margin in the design for the nominal case. The overlap of the tails of the two curves is a risk area. If some unusual or unexpected event causes the operating point to shift to the right and/or the material has less than expected capability for any reason, then there is "failure". "Failure" can mean real failure, i.e., something breaks, or, more likely, more life taken out of the part than is expected for one operation, cycle or flight.

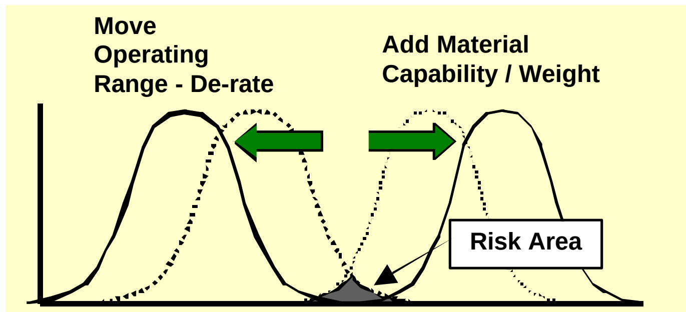

Figure 7. Failure Related to Operating Point and Capability.

The new materials have higher specific strengths and thus allow the curve of the capabilities of the material to be moved to the right without adding weight (often the curve can be moved to the right while still reducing weight). Because they generally have flatter property characteristics at high temperatures, the capability curve also "sharpens", i.e., the width of the curve gets smaller (although this may be counterbalanced by a wider distribution in properties due to material processing, but that, in turn, could be addressed by process technology development). Both of these characteristics mean that the amount of overlap of the tails of the two curves get smaller - there is much less risk area.

Work is ongoing to use metal matrix composites, ceramic matrix composites, polymer matrix composites, monolithic ceramics, nanophase aluminum, and advanced alloys for turbomachinery, thrust chambers, injectors, gas generators/preburners, nozzles, ducting, and RBCC heat exchanger backup structures.

Spaceliner Architecture / System / Subsystem Application(s): This technology applies to all rocket engine, pulse detonation engine, and combined cycle engine main propulsion elements in any of the Spaceliner 100 architectures. Subsets of the technology would also apply to OMS and RCS propulsion.

Current Technology Readiness Level (TRL):

Maturity of new materials for rocket, pulse detonation, or combined cycle engine application

Nanophase Materials	TRL 4
Aluminum	
Nickel Superalloys	TRL 3
Matrix Composites	
Metal	TRL 3
Ceramic	TRL 4
Polymer	TRL 4
Ceramics	
Si_3N_4	TRL 4
Other	
Cu-8Cr-4Nb (combustor liner)	TRL 4

Investments Required to Mature the Technology for Spaceliner. Provide a summary estimate of the dollar levels of investment by Government Fiscal Year (FY) beginning with FY 2001 to mature the candidate technology sufficiently for incorporation in a flight demonstrator *system* (at a TRL 6 for reference) which could include any and all elements of a Spaceliner 100 architecture.

Figure 8 shows an estimate of the costs required to develop to TRL 6 any one given material for use as a major component in a rocket or combined cycle environment.

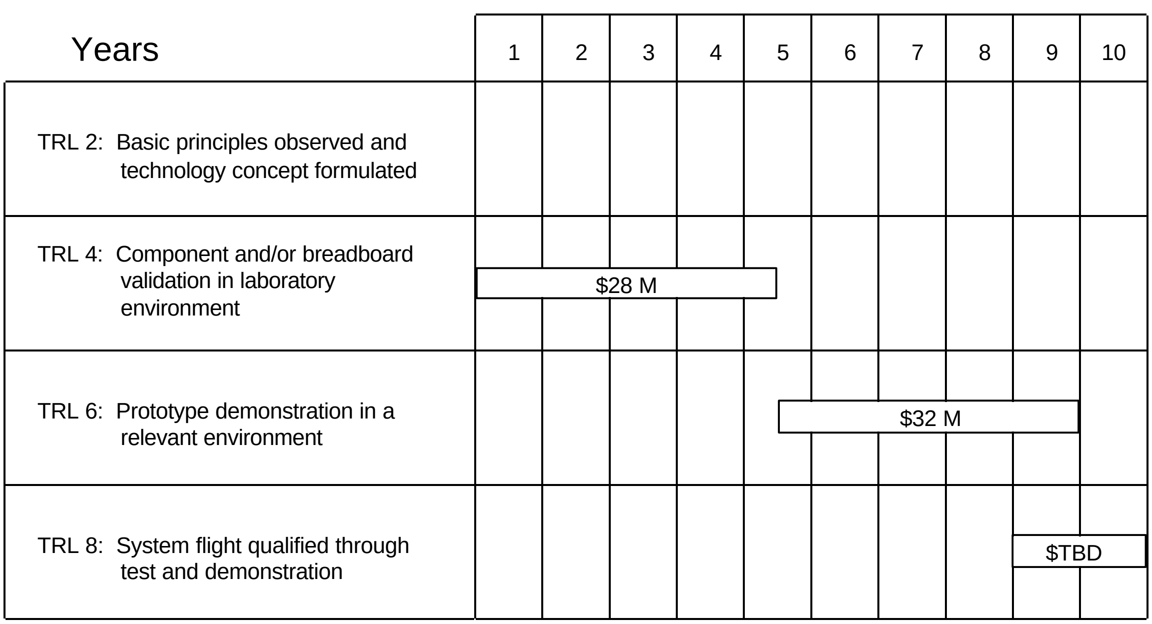

Figure 8. Technology Implementation Plan - Develop one new material for Inclusion as Major Component in Rocket or Combined Cycle Application.

Potential Benefits of the Technology to Spaceliner:

Rocket Engines

An example of the effects of using advanced new materials in a rocket engine was studied under the Highly Reusable Space Transportation (HRST) contract.

A baseline advanced O_2/H_2 rocket engine was designed and then the extensive use of advanced materials was applied to that design.

For the baseline engine the weight estimate was a bottoms up CAD design of the entire engine including all major and minor (e.g., drain lines, heat shield attachment flange) components. A design layout was generated for a FFSC cycle engine at 4,000 psi chamber pressure. The layout was then used for a more detailed weight determination as well as producing configuration drawings. A detailed weight statement of the SSME was used so that no element of a real, fielded, reusable engine was unaccounted for.

The weights included all the engine systems that would be in a reusable engine such as the SSME. Thus controllers, line insulation, gimbal attachments, drain lines, etc. were included. Installation specific systems such as the gimbal actuators and the engine heat shield were not included in the calculated engine weight. However, these items were explicitly calculated by the vehicle weight code.

The engine weight was calculated with a moderate number of near and midterm technologies included in the new engine. The new technology used was jet pumps as the boost pumps, turbomachinery specifically designed to lower cost and weight, EMA valves, and a limited use of advanced materials for the thrust cone, gimbal bearing, H_2 valve bodies, H_2 pump, gimbal actuator attach bracket, support struts, and the nozzle jacket.

Because few advanced materials were used and only for a few major engine components, there was weight margin in the estimate compared to methods which emphasize material approaches to lowering engine weight. Indeed, the material used for oxygen rich combustion gas compatibility, Haynes 214, is a relatively low strength material which will probably be replaced in future designs. This material was chosen to produce uncoated, long life operation even at the cost of additional weight.

Figure 9 shows the design point and characteristics of the engine. Figure 10 shows the procedures used for the weight calculation and Figure 11 shows the results.

- Design Point
  - Cycle – FFSCC
  - Chamber Pressure – 4,000 psi
  - Sea Level Thrust – 421,000 lbf
  - Area Ratio – 70.62
  - Fuel Turbine Operating Temperature – 1,100 ÞR
  - Oxidizer Turbine Operating Temperature – 1,100 ÞR

- Characteristics
  - Fuel Rich Fuel Turbopump
  - LOX Rich LOX Turbopump
  - Jet Pump Low Pressure Pumps
  - Propellant Duct Gimbal Accommodation on Vehicle Side
  - SLIC™ Turbomachinery
  - Uncooled Powerhead
  - EMA Valves
  - Preburner Injectors Gas/Liq Impinging Jet
  - MCC Injectors Gas/Gas Co-Ax
  - Redundant Laser Igniters
  - Autogenous Pressurization on Both Sides
  - Pump Conditioning Fluid Recirculated to Tank on Both Sides

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Figure 9. Design Point and Characteristics for Weight Calculations

- Overall Procedure
  - Various Individual Design Procedures Combined at CATIA Assembly Level for Packaging and in Spreadsheet for Weights

- Two Direct Design Procedures are Used
  - CATIA Solid Model (e.g., Hot Gas Manifold)
    - Designed as Individual Component
    - Wall Thickness Calculated
    - Minimums Applied in Model
      - 1.5 Factor for Dynamic Loads Applied to Wall Thickness if Appropriate
    - Solid Volume Returned to Spreadsheet for Weights
    - In Spreadsheet
      - Density used on Solid Volume for Weight
      - 1.02 Factor and 1.05 Factor Applied to Weight
  - CATIA Assembly Model (e.g., Duct)
    - Designed at Assembly Level for Dimensions, Clearances, and Packaging
    - Dimensions Returned to Spreadsheet for Weights
    - In Spreadsheet
      - Wall Thickness Calculated and Minimums Applied
      - Other Subcomponents Calculated (Flanges, Insulation, Insulation Shields, etc.)
      - Weights Calculated from Material Choices and Dimensions

- Other Procedures are Used For Some Components and May be Combined
  - Scaled (e.g., Valves)
  - Outside Reference (e.g., STME-100 for Controller)
  - Outside Model or Correlation (e.g., SLIC™ Turbomachinery)
  - Directly from SSME (e.g., Static Seals)

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Figure 10. Weight Calculation Procedure.

Advanced Booster Engine 4k Pc O2/H2

Weight Breakdown

- **Vacuum Thrust** **484,585**
- **Sea Level Thrust** **421,000**
- **H2/O2 Core Pc = 4000** **Nozzle exp. ratio 70**

DUAL MIXED PRE-BURNERS

Main Combustion Chamber					**496**
with injector and liner		CR = 2.92			
		NARloy	NiCo		
Regenerative Cooled Nozzle					**625**
		A-286	Titanium		
Turbopumps					
HPFP SLIC	**499**	n• AL | n• AL	Thermo-Span | RIM-D1, A286 TMP		
HPOP SLIC	**562**	INCO 718 | INCO 718	Haynes 214 | Haynes 214		**1061**
Pre-Burners					
FPB	**40**		Thermo-Span		
OPB	**334**		Haynes 214		**374**
Valves					**361**
Propellant Ducts					
FUEL	**265**		INCO 903		
includes repress., pump recir., drain, & cryo purge					
OXID	**358**		INCO 718		**623**
includes repress., pump recir., drain, pogo systems, & O2 hxr					
Fuel Hot Gas Manifold			Thermo-Span		**262**
Ox Hot Gas Manifold			Haynes 214		**198**
Controller, Harness, Sensors, & Ignition					**150**
Structure					**252**
Bolts & Misc. parts					**165**
			TOTAL		**4,567 lbs**
					106.10 Tvac/W
					92.18 Tsl/W

Figure 11. Weight Results - Long Life, High T/W O_2/H_2 Rocket Engine

With this engine defined, a second look was made to examine the impact of advanced materials. The Air Force, under a program called the Integrated High Payoff Rocket Propulsion Technology Initiative (IHPRPT) is examining methods to greatly reduce engine weight. One of the approaches taken has been the use of new materials, including their use for high temperature, highly stressed, complex parts. After examining some of the materials being considered, the use of Si_3N_4 for general use in an advanced rocket engine and the use of Cu-8Cr-4Nb for a combustor liner were selected for study. The Cu-8Cr-4Nb was chosen to potentially produce a lighter liner. The Si_3N_4 was chosen for more complex reasons and as a good example of the effects future advanced materials could have in rocket engines.

Si_3N_4 has some excellent characteristics for use in a rocket engine. It has about twice the specific strength of the metals used for most of the components in a rocket engine. It is impervious to either O_2 or H_2 at either very low or very high temperatures. Of the materials tested it has shown the best resistance to promoted combustion in hot oxygen. It's material properties remain fairly constant from deep cryo to ~3,000 R. These characteristics have major implications for increasing engine life while, at the same time, greatly reducing maintenance.

Parts made from Si_3N_4 must use a particular casting process which, at least when fully developed, lends itself to very complex parts. This could greatly reduce the number of parts in a rocket engine by not only combining major parts, but also casting in many small attached parts (cable raceways, insulation blanket attachments, etc.). The net effect is potentially major reductions in manufacturing and assembly costs and, more importantly, in logistics and maintenance.

The down side of the use of Si_3N_4 is that it has no ductility, low thermal expansion and in general must be designed and used differently than the metals currently used in rocket engines. There will be a significant learning curve to incorporating this material into rocket engines. It is also possible that all of the weight reduction potentially available will not materialize as the material is developed.

Figure 12 shows the methodology employed to examine the use of new materials. The CAD based design for the baseline advanced O_2/H_2 engine was examined component by component and Si_3N_4 or, for the liner, Cu-8Cr-4Nb was considered for substitution component by component. Figure 13 shows the results for the engine weight.

- **Methodology**
  - **Si_3N_4 for All Structural Components**
    - **Ducts**
    - **Manifolds**
    - **Preburners**
    - **Hot Gas Manifolds**
    - **Turbopumps and Housings**
    - **Main Combustion Chamber (MCC)**
    - **Injectors**
    - **Valve and Sensor Bodies**
  - **Cu-8Cr-4Nb for MCC Liner**
  - **Gr/epoxy and Al Components Unchanged**
  - **Integrate Harness into Components – Cast**
  - **Radiation Cooled Nozzle (C/SiC skirt)**
  - **No Pogo**
- **No Cycle, MR, Chamber Pressure, or Configuration Changes**

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Figure 12. Use of Advanced Materials.

Advanced Booster Engine 4k Pc O2/H2

Weight Breakdown

- **Vacuum Thrust** **484,585**
- **Sea Level Thrust** **421,000**
- **H2/O2 Core Pc = 4000** **Nozzle exp. ratio 70**

DUAL MIXED PRE-BURNERS

Main Combustion Chamber					**190**
with injector and liner		CR = 2.92			
			Cu-8Cr-4Nb	Si3N4	
Regenerative Cooled Nozzle					**218**
			Si3N4	Si3N4	
Turbopumps					
HPFP	SLIC	**388**	n• AL | n• AL	Si3N4 | Si3N4	
HPOP	SLIC	**310**	Si3N4 | Si3N4	Si3N4 | Si3N4	**698**
Pre-Burners					
FPB		**20**		Si3N4	
OPB		**103**		Si3N4	**123**
Valves					**209**
Propellant Ducts					
FUEL		**159**		Si3N4	
includes repress., pump recir., drain, & cryo purge					
OXID		**187**		Si3N4	**346**
includes repress., pump recir., drain, pogo systems, & O2 hxr					
Fuel Hot Gas Manifold				Si3N4	**107**
Ox Hot Gas Manifold				Si3N4	**54**
Controller, Harness, Sensors, & Ignition					**95**
Structure					**173**
Bolts & Misc. parts					**86**
			TOTAL		**2,298 lbs**
					210.90 Tvac/W
					183.23 Tsl/W

Figure 13. Results When Using Advanced Materials.

The result was a weight decrease of about 50 percent.

The performance of these two engines in the SSTO mission using a cylindrical winged body vehicle in a vertical takeoff/horizontal landing mode was shown in Figure 4 (as the "Long Life, High T/W O2/H2 Rocket Engine" and the "Low Maintenance, Lt Weight

Rocket Engine VTHL" bars). The effect of doubling the engine thrust/weight was a reduction in dry vehicle weight of about 17 percent.

Combined Cycles

Studies at Rocketdyne have shown RBCC weights to be composed of about 40 percent subsystem weights (rockets, turbopumps, ducting, preburners, etc., i.e., the "rocket" part) and about 60 percent the RAM/SCRAM flowpath, mostly the heat exchangers and their backup structures.

The rocket part of the RBCC can be reduced about the same as for a conventional rocket engine.

The use of advanced materials, such as polymer matrix composites can reduce the flowpath weight also by about half.

Consequently, the use of advanced materials can reduce the weight of RBCC about the same degree as in a conventional rocket.

The flowpath and any rocket components used in a TBCC should also be capable of weight reductions of about half. The gas turbine itself was not assessed.

Pulse Detonation Engines

Because a pulse detonation engine is a rocket engine in terms of its components, the use of advanced materials should also allow reductions in weight of about half compared to using current materials.

Summary

The use of advanced materials could produce sea level engine thrust/weights for O_2/H_2 rocket engines and pulse detonation engines on the order of 150 to 200. RBCC thrusts/weight could be on the order of 45 to 55.

The use of these materials could also greatly reduce part counts, remove the necessity of coatings and their inspections, reduce design variability, improve performance due to high temperature operation if desired, decrease operations costs, decrease the cost of logistics, and greatly increase engine life.

Potential Risks in Developing the Technology: The risk of developing any one material is that it will not, at least initially, produce all the benefits its proponents claim. However, most of the new materials address multiple goals such as lower weight, higher temperature operation, lower part counts, or less maintenance. The material will almost certainly produce a subset of these goals. Consequently the insertion of the new material will probably produce significant benefits, and, with further refinement, even more of the originally claimed benefits. The other major risk is schedule. Development of new materials often takes more time than initially thought. Secondary difficulties such as development of analysis methods, inspection versus process verification approaches, joining technologies, and multiple material design methodologies often add significant time to the overall development.

Information References:

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