

OUTBRIEF – LONG LIFE ROCKET ENGINE PANEL

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ABSTRACT

This white paper is an overview of the JANNAF Long Life Rocket Engine (LLRE) Panel results from the last several years of activity. The LLRE Panel has met over the last several years in order to develop an approach for the development of long life rocket engines. Membership for this panel was drawn from a diverse set of the groups currently working on rocket engines (i.e. government labs, both large and small companies and university members). The LLRE Panel was formed in order to determine the best way to enable the design of rocket engine systems that have life capability greater than 500 cycles while meeting or exceeding current performance levels (Specific Impulse and Thrust/Weight) with a 1/1,000,000 likelihood of vehicle loss due to rocket system failure. After several meetings and much independent work the panel reached a consensus opinion that the primary issues preventing LLRE are a lack of: physics based life prediction, combined loads prediction, understanding of material microphysics, cost effective system level testing, and the inclusion of fabrication process effects into physics based models. With the expected level of funding devoted to LLRE development, the panel recommended that fundamental research efforts focused on these five areas be emphasized.

INTRODUCTION

LLRE panel members were selected as knowledgeable representatives of the many groups currently involved in the development and construction of rocket engines. This included representatives from NASA Marshall Space Flight Center (MSFC), NASA Glenn Research Center (GRC), Air Force Research Laboratory, Pratt & Whitney, Rocketdyne, Aerojet, Allison, Sierra Engineering, Purdue and University of Tennessee Space Institute in an attempt to include government centers, both large and small businesses, and university researchers in developing this initiative. Individuals volunteered their time and travel resources to discuss the problems inherent in developing a LLRE and assemble a plan of action to make these engines possible. The LLRE goal is to enable the design of rocket engine systems that have life capability greater than 500 cycles, meet or exceed current performance levels (Specific Impulse and Thrust/Weight) with a 1/1,000,000 likelihood of vehicle loss due to rocket system failure.

The LLRE panel was formed in order to develop community input and ownership of a NASA initiative for Long Life Rocket Engine technology. Reviewing NASA's long term space transport and potential reusable launch vehicle (RLV) concepts made the need for a LLRE clear. Previously, NASA has funded work in this area without an overall needs analysis or much initial input from the propulsion community outside of NASA. It is hoped that a more inclusive overall needs viewpoint on LLRE will better focus improvements to LLRE technology

NASA's overall propulsion goals are to develop and field the technology to bring about low cost / high safety access to space. Figure 1 shows the "big picture" development plan as it stood in July 2001. At a top level, NASA planned on developing several generations of reusable launch vehicles (RLVs), enabled by the latest technology, fielding a lower cost and higher safety vehicle. During the spring of 2000 the NASA 3rd Generation (3rd Gen) propulsion project office had determined that all of the likely 3rd Gen airbreathing propulsion concepts for access to space required the use of rockets for some portion of the mission. After examining these concepts cost and reliability, NASA realized, that although current performance levels for rocket engines resulted in viable vehicle concepts, the current reliability and cost levels were vastly inferior to that needed for a 3rd Gen system. (The 3rd Gen project office goals were 100 times cheaper and

10,000 times safer than current launch systems.) After modeling several 3rd Gen systems that met these reliability and cost goals, the LLRE goals of 500 mission cycles and 1/1,000,000 loss of vehicle requirements were developed.

The task for the LLRE panel was to develop a 15-yr plan to reduce development risk and cost of a 500 mission class rocket engine system. This included the identification of Life-Limiting Phenomena (Technical Challenges), strategic approaches to reducing the life-impact of each phenomenon, and a plan for the development of tools, materials, and databases to enable the strategic approaches (develop a roadmap and ROM costs). Where necessary the panel was to assume SSME and/or RL10 engine conditions and service level requirements of military jet fighter engines. Ideally the panel would look for synergism with the Integrated High Payoff Rocket Engine Technology (IHPRET) plan and NASA's 2nd Generation projects. The consensus was that, in order to meet the LLRE goal, we would need to break the current inertia of incremental improvements to rocket engine life.

On January 14, 2004, the president directed NASA to implement a new vision of human and robotic space exploration (See Figure 2). This vision has re-organized how NASA is approaching propulsion development with the cancellation of all the near term rocket engine system development (except the Integrated Powerhead Demonstrator project). NASA is planning on using existing propulsion technology to begin replacing the shuttle in the 2010 timeframe with an emphasis on expendables.

RESULTS AND DISCUSSION

In order to better understand the reasoning behind the initiation of the JANNAF LLRE panel the former method of selection of rocket engine technology tasks will be described. The first step in selecting 3rd Gen propulsion tasks was for the Advanced Space Transportation Project (ASTP) office to solicit internal technology proposals in quad chart or white paper format. These proposals were then grouped into fundamental and cross-cutting (component level typically) technologies. A government selection team composed of technical experts for each of these groups would then rank and prioritize the proposals on a consensus basis over several days – modifying the proposals as needed. This author participated over several years in this process including leading the cross-cutting technologies group in the April 2001 selection.

This method had the advantage of being very flexible and involving those inside of NASA who were working the technologies. However it also had several disadvantages. Perhaps the most important disadvantage was that technologies were selected without an overall long term strategic plan. Additionally, existing and newly proposed tasks were all funded from the same budget and with our habit of putting increased funding in out years we had to reduce existing tasks budgets to fund new interesting tasks. Other issues hampered the process, like not receiving many proposals in areas considered priority, insufficient time in the process for research, and little to no input from industry, academia or DOD. Individuals working on the technology selection process worked these and other problems as they came up but there was large consensus that the process itself needed change.

Early in 2001 the ASTP office set up a team inside of NASA MSFC to examine the technology prioritization process and assemble an integrated LLRE plan. Also at about this time the value stream¹ based approach was being developed as a technology prioritization process. ASTP selected this process for use by the team working on the LLRE plan. The value stream process is simply a structured method of relating technology tasks to high level goals. The process does this via three steps: 1. Identify the technical shortfalls, 2. Develop approaches to solve these identified shortfalls and, 3. Assemble an integrated long term plan. The MSFC LLRE team laid out the technology roadmaps that different technical groups inside of MSFC had developed (i.e. turbomachinery, combustion devices, etc.). Using these plans as a starting point the team started to develop the technical shortfalls for a LLRE.

There was some initial confusion as a LLRE hadn't yet been defined clearly and the value stream process itself was evolving. The team examined life limiting phenomena in a LLRE and

grouped them into five categories: environment (prediction, detection and understanding), operations methodology and cycle selection, design tools, manufacturing and materials, and test / qualification. Within these categories the MSFC team then attempted to list methods and the resulting tasks to reduce or eliminate the life limiting phenomena. An example of this chain of reasoning, from identifying shortfalls to developing an approach, is shown in Figure 3. The MSFC team recommended dedicating a full time multi-day activity to perform this task, as well as providing for industry input. This work formed a good background for the JANNAF LLRE panel kickoff meeting.

JANNAF - PANEL MEETING - JULY 12TH, 2001

Our first panel meeting was July 12th, 2001 at the JANNAF 50th Joint Propulsion Meeting in Salt Lake City, UT. Panel members agreed that developing an integrated plan on how to enable a LLRE would be beneficial. Initial discussions were productive but very scattered as all the panel members agreed that no one incremental technology improvement would make a LLRE possible. As all members wished to avoid motherhood charts and produce a workable useful plan they pressed for a definition of the level of resources to be made available. NASA planned to dedicate approximately 3-5 million dollars per year toward LLRE development. With this resource level and the desire for current performance levels the panel felt developing a plan would be very difficult. The panel members agreed to work on the problem in their respective organizations as time allowed and meet again at a later date. The SSME was chosen to provide the reference engine conditions due to the large amounts of test data, although some felt that military jet engine requirements were a better fit to the cost and life goals of the LLRE.

Many of the LLRE Panel members have experienced the tendency toward global coverage "motherhood" solutions when trying to solve problems of a broad nature. The group as a whole wanted to be as specific as possible given the difficulty. The panel recommended that a more clear definition of LLRE would help to determine the technical shortfalls. The panel also recommended that a larger group with a broader technical background be assembled to determine the technical shortfalls. The panel decided to focus on LOX/LH2 with the possibility of adding LOX/HC later. Each member brought a list of the reasons why they thought LLRE aren't currently possible, and the majority of the time was spent identifying technical shortfalls and approaches to solving them. A large list of technology shortfalls and possible approaches to solve them at the engine system level and the combustion devices level were defined. Figure 4 is an edited list of the system level technical shortfalls identified at the meeting. The panel recommended pulling together a larger group with a broader technical background for several days to do this in a more complete fashion. The panel also recommended several retired experts be members of this larger group.

NASA MSFC/GRC - LLRE WORKSHOP - OCTOBER 16-19TH, 2001

As recommended by the JANNAF panel, NASA MSFC/GRC put together a three day LLRE workshop to assemble the technical expertise for determining the LLRE technological shortfalls and selected a "reference" engine system as described below. The workshop participants were divided into two groups: engine hardware design and development specialists (Macro-technologists) and engineering capability specialists (Micro-technologists) as shown in Figure 5. The morning of the first day of the workshop introduced the Value Stream¹ process we were going to use and went through the reference engine system. The remaining time in the workshop was spent developing technological shortfalls, grouping them, and presenting them back to the group.

The reference engine system selected for the LLRE workshop was a rocket based combined cycle engine (LOX LH2) using a staged combustion cycle during air augmented rocket / pure rocket modes and expander cycle during airbreathing modes, as shown in Figures 6 to 10. This engine cycle was selected in order to drive the discussion to answer the most complete set of issues preventing achieving the LLRE goal rather than selecting a simpler cycle that might

In order to effectively perform life prediction, the material property database and prediction capability needs to be significantly enhanced. A fundamental understanding of material microphysics needs to be developed. The future is "designer" materials as significant enhancement of alloy properties is unlikely. Since the designer needs a material database for each material combination in its specific application, fundamental physics-based material property prediction is necessary to overcome the prohibitive costs of testing each configuration.

As an intermediate step, designers need enhanced databases for existing materials (e.g. creep data for welded copper). Extending and enhancing MIL-HDBK5 to include additional relevant materials would address the needed material properties short fall but this step by itself was not felt to be sufficient to reach LLRE goals. Additional work to better understand degradation mechanisms and the joining process (in brazing, welding, etc.) would also be excellent intermediate goals.

COMBINED LOADS PREDICTION

In order to perform physics based life prediction designers need to know the combined loads on the structure. This knowledge must include transient and steady state (which is typically a dynamic state around a steady average) loads. These combined loads include: aerofluid, mechanical, thermal, and acoustic. All the component and system level induced loads must be known. As in the materials shortfall, detailed knowledge of all the induced loads cannot be obtained by testing specific configuration but must be predicted from the fundamental physics. Expected limitations in instrumentation, testing cost and multiple configurations make the current standard of "calibrating" CFD and other design tools to a specified configuration insufficient to support the necessary life prediction.

FABRICATION

In order to calculate the life of an as-built (versus as-designed) component fabrication process control effects must be included in the physics based life calculation models. This will require enhanced non-destructive examination and testing techniques to be developed.

COST EFFECTIVE SYSTEMS TESTING

Apart from the ability to accurately predict the life of a component of a system or even the entire system is our ability to validate the life and or reliability without full scale life testing. When the life prediction of an engine system is five or ten cycles, testing to life on every engine or even just a fleet leader is fairly cost effective. However, when the life is 100 or more cycles, the testing cost alone become prohibitive. A methodology of lower cost testing involving accelerated aging or scaling needs to be developed. Panel members felt that even if we had a LLRE available today we wouldn't be able to validate the life. Development of fundamental scaling tools at the system and component level to allow smaller scale systems tests or lower cycle testing to validate higher cycle life is needed. Methods to expedite new materials and fabrication processes into flight need to be developed.

COMMENTS

Several side issues of note came up in the performance of this task and are addressed here away from the main discussion. During the last panel meeting in Destin, FL the panel converged on the set of five categories of technical shortfalls, mentioned above, preventing the development of a LLRE. Although the list in hindsight seems obvious, achieving this agreement was a significant success. One other opinion noted during this last meeting was that it might be much easier to achieve LLRE goals through selection of the engine cycle (e.g. expander cycle over staged combustion) and how engine transients are handled rather than solving these five fundamental shortfalls.

The value stream process used by the LLRE workshop and JANNAF panel worked great for pulling out technical shortfalls and grouping them. However, it was of less use in prioritization especially in the case where you have an extremely large set of technical challenges and a limited and fixed set of resources. Its major contribution was providing a rigorous process.

Given the redirection of NASA's priorities with the new exploration initiative (Figure 2) the continuation of the LLRE technical tasks is in question. As manned space is a priority and a higher launch rate is needed for support of this exploration initiative, this author feels that LLRE technology tasks will continue to be funded at some base level. With the extended timeframe for RLV development, the LLRE panel recommendation to focus on fundamental research tasks is even more applicable.

SUMMARY AND CONCLUSIONS

Over the last several years, the JANNAF LLRE panel has met, NASA has held a multi-day workshop, and many meetings have been held in order to determine the technical shortfalls between our current technological capability and that needed to build a LLRE. The model LLRE would have life capability greater than 500 cycles while meeting or exceeding current performance levels (Isp and Thrust/Weight) with a 1/1,000,000 likelihood of vehicle loss due to rocket system failure. The JANNAF panel has reviewed all of the shortfalls and reached a consensus opinion that the primary issues preventing LLRE are a lack of: physics based life prediction, understanding of material microphysics, cost effective system level testing and the inclusion of fabrication process effects into physics based models. With the expected level of funding devoted to LLRE development, the panel recommended that fundamental research efforts focused on these five areas be emphasized.

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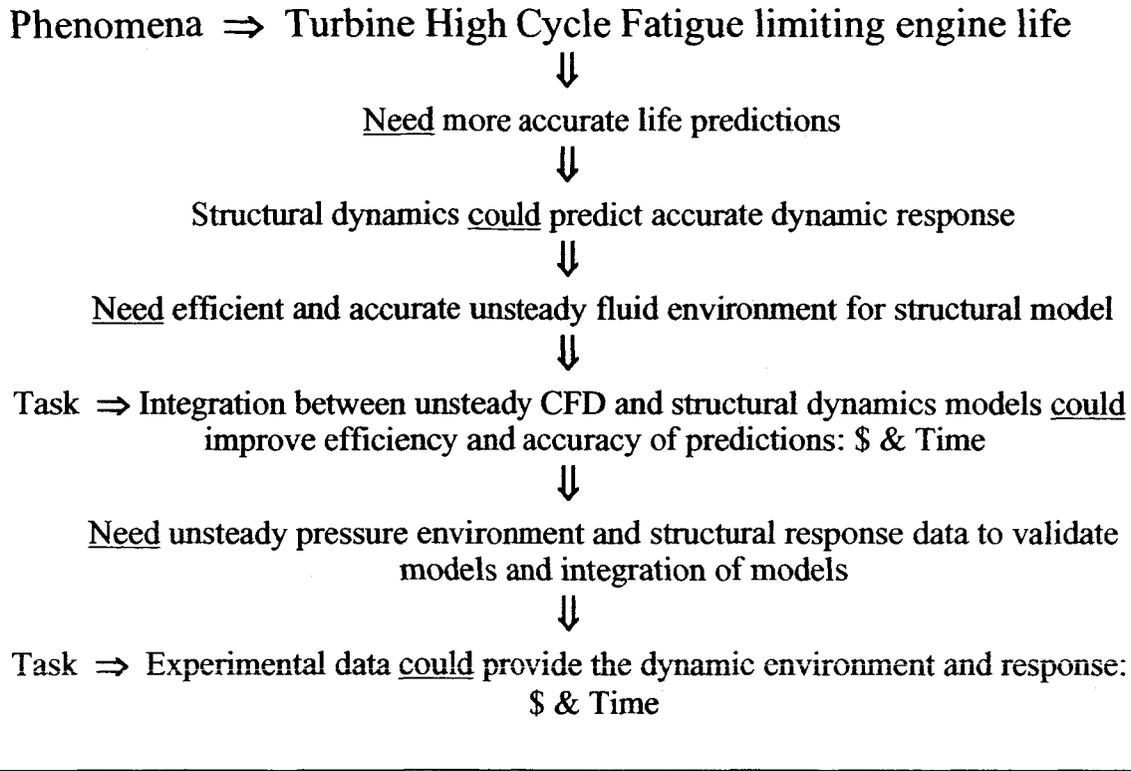


Figure 3: Example translating technical shortfall into tasks.

- Load Prediction (Environment) - Predictability
 - Component interactions
 - Measurement capability
 - 3D database (Real one)
- Control Transients
 - Decouple start/shutdown
- HCF / LCF
- Derate or add margin
 - Increase T/W to allow margin - steady state operation sizes the engine
- System life/reliability prediction & verification (life expended prediction)
- Cost Effective design/test/verify
- Accelerated design tools/process
- Insufficient database - materials - operations - fabrication
- Engine cycle selection - Expander? / ORSC?
- Fundamental Scaling ---- given limited testing
 - lack of scientific method/basis that works
- Lack of testing to failure -- needed to validate margin
- Life cycle cost model
- Examine assumed (historical) safety precaution assumptions

Figure 4: Partial list of system level technical shortfalls from July 2001 meeting.

- Two groups of experts:
 - Engine Hardware Design and Development Specialists (Macro-technologists)
 - Ma 1 -- Engine System (Including Integration)
 - Ma 2 -- Combustion Devices & Ignition Systems
 - Ma 3 -- Turbopumps
 - Ma 4 -- Valves and Actuators
 - Ma 5 -- Ducts, Lines and Related Seals
 - Ma 6 -- Avionics/Control System/IVHM/Instrumentation
 - Ma 7 -- Vehicle Operations
 - Engineering Capability Specialists (Micro-technologists)
 - Mi 1 -- Design and Predictive Capability
 - Sub-group 1 -- Non-metallic materials, including PMC and CMC
 - Sub-group 2 -- Metallic materials, including MMC
 - Sub-group 3 -- Aerodynamic and fluid dynamics
 - Sub-group 4 -- Structural dynamics and rotordynamics
 - Sub-group 5 -- Structural , mechanics and thermal
 - Sub-group 6 -- Combustion physics and acoustics
 - Sub-group 7 -- Software design and validation
 - Sub-group 8 -- Life/reliability and cost predictive tools
 - » Panel 1 -- Life/reliability tools
 - » Panel 2 -- Cost tools
 - » Panel 3 -- Simulation tools (end-to-end life cycle) (input is missing)
 - Mi 2 -- Design Validation Capabilities (Facilities, instrumentation, etc.)
 - Mi 3 -- Fabrication and Fabrication Process
 - Mi 4 -- Quality Engineering and Quality Assurance
 - Mi 5 -- Fielding and Operations

Figure 5: LLRE Workshop participants specialties.

- **LO₂/LH₂ RBCC**
- **SSTO HTHL**
- **No launch assist**
- **Staged combustion cycle for rockets/ejectors**
 - SSME/X33 experience
 - Pc ~ 3000 psia
- **Expander cycle for RAM/SCRAM fuel pump**
 - RL10 experience
- **20K-900Klbs S/L static thrust ETO capability of engine**
 - Engine to includes OMS capability
- **4 powerpacks**
- **16 thrusters/powerpack**
- **500 missions before depot maintenance/2000 mission life**
- **Six-9's reliability (LOC/LOV)**
- **2 person ground crew**
- **24 hour turnaround**
- **Cost: Dev. + Ops = \$TBD**

Figure 6: Reference engine system characteristics.

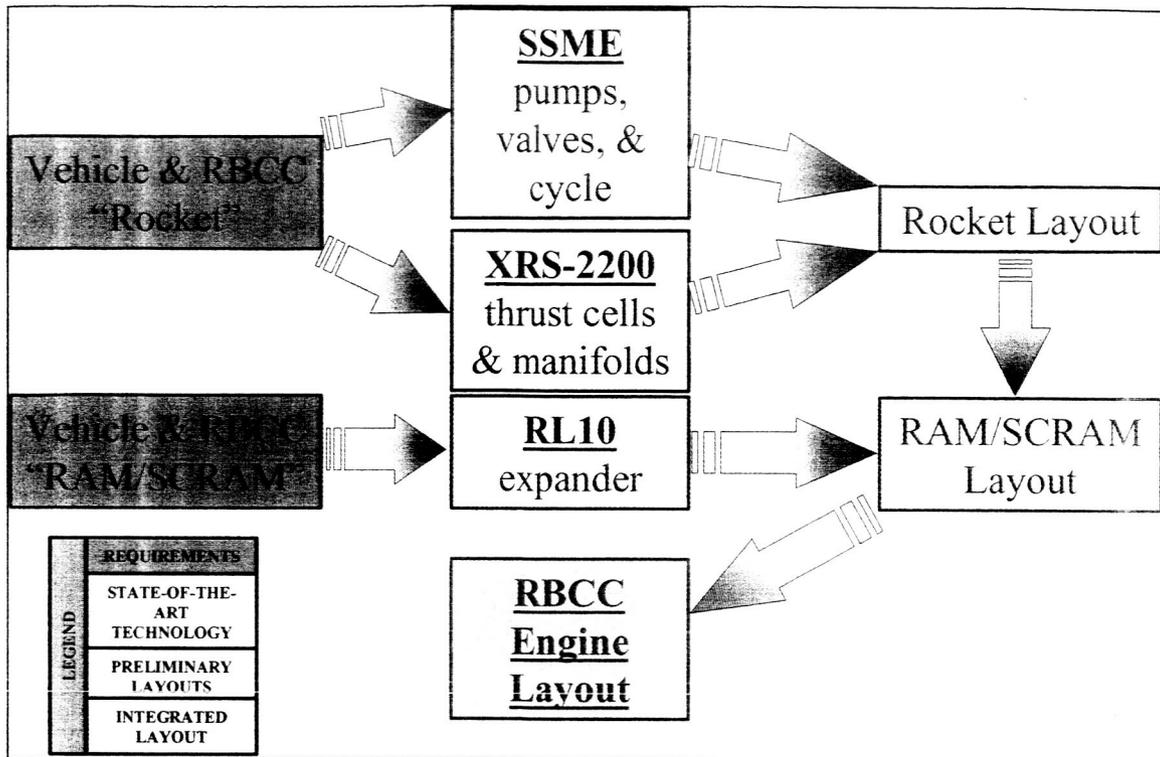


Figure 7: Reference engine layout heritage.

Air Augmented Rocket Mode (Mach 0 to ~ 3)

- Thrusters Firing
- Inlet Open, Air Entrainment & Fuel Afterburning

Ramjet Mode (Mach 3 to ~ 6)

- Thrusters off
- Inlet Capturing Air & Scheduled to Provide Compression
- Fuel Burned Subsonically With Captured Air

Scramjet Mode (Mach 6 to ~ 12)

- Thrusters off
- Inlet Capturing Air & Scheduled to Provide Compression
- Fuel Moved Forward & Burned Supersonically With Captured Air

Rocket Mode (Mach 12 +)

- Thrusters on
- Inlet Closed for Final Ascent to Orbit

Figure 8: Rocket Based Combined Cycle engine operation concept.

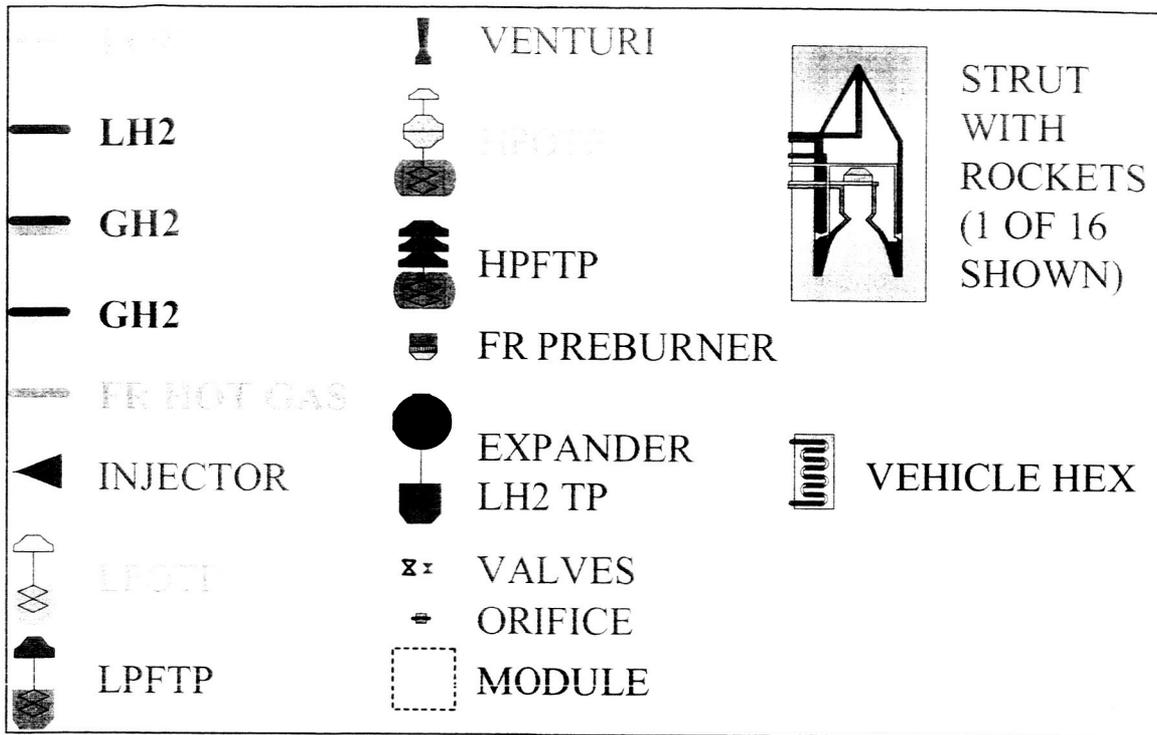


Figure 9: Engine schematic legend.

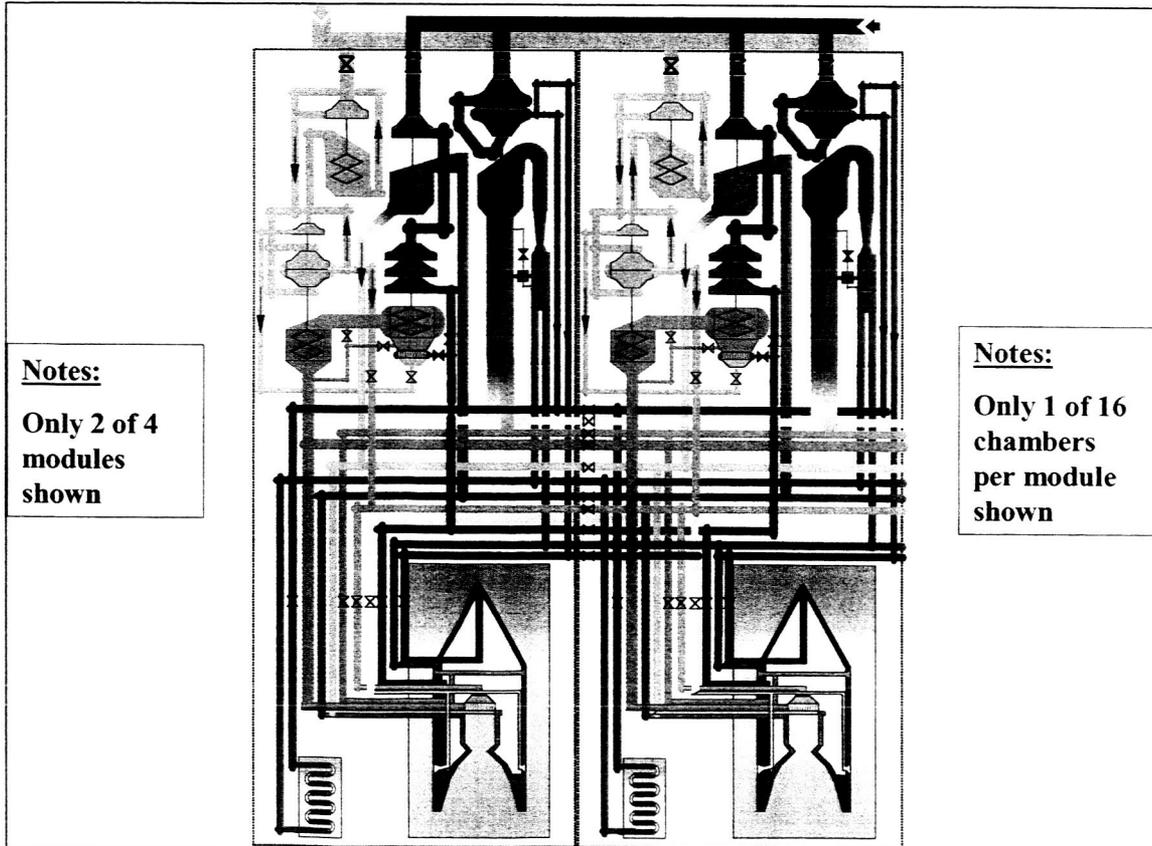


Figure 10: Reference engine system schematic.

Figure 11: LLRE Workshop - summary of output.

Macro-technologists

Simplicity

Modularity and standardized interfaces

IVHM - integrated vehicle health management (open architecture). State-based maintenance (maintenance on demand).

Open vehicle architecture and rapid qualification

Micro-technologists 1 -- Design and Predictive Capability

Sub-group 1 -- Non-metallic materials, including PMC and CMC

Need an integrated effort that recognizes the time horizon (on the order of 15 years) for development of a new material.

Lack fundamental understanding of degradation mechanisms, life models and processing consistency reliability.

Lack of integration in the design of attachments and the demonstration of sub-elements/subcomponents.

Need to Redesign Components to take advantage of Advanced Materials and Methods – this is not being done.

Sub-group 2 -- Metallic materials, including MMC

Engine Systems – Inadequate design level materials databases for candidate materials. Without a proper design level database, either the hardware will be over-designed OR reliability cannot be guaranteed at the desired level.

Valves – Materials to withstand hydrogen embrittlement at 1800R/6000psi. Currently used materials lack hydrogen embrittlement resistance at these temperatures and pressures

Main Thrust Chamber Assembly (TCA) – Lack of work on coatings that can extend life. Coatings have not been extensively tested in a TCA environment and will need to be developed and verified in an appropriate environment.

Lines and Ducts – Inadequate methods/processes to reduce joints and complexity. Recommend friction stir welding of ducts and lines to reduce joints and complexity be developed.

Turbopumps – Lack of materials specifically developed for quick chill turbopumps.

Sub-group 3 -- Aerodynamic and fluid dynamics

Lack of understanding of pump geometric features and flow physics that lead to good performance over a wide flow range.

Inability to rapidly predict unsteady turbine aero loads and effectively transfer them to structural dynamics analysis

Inability to predict transient startup fluid environment in turbines and pumps

Inability to model/predict pump inducer cavitation

Sub-group 4 -- Structural dynamics and rotodynamics

Turbopump - Safety/Reliability - Rotor Support/Control –Dynamic Stability & Bearing Life

Turbopump - Wide Throttle Range/Long Life Turbine Components - HCF and LCF of Turbine Components

Engine System - Feasibility/Functionality - Combined Engine System Loads Predictions

Sub-group 5 -- Structural, mechanics and thermal

Lack of reliability models. Quantifying reliability of system when making design decisions on part. What are the SOA reliability models that currently do this job?

Methods for designing/redesigning as technologies evolve. The engine system is going to evolve to the reliability and life goal and therefore should be designed for redesign and flexibility.

Fatigue properties covering the range of environments with limitations identified (i.e., HCF life minimum at 1000degR).

Technologies required in materials, cooling techniques, development instrumentation, flow field uniformity.

Sub-group 6 -- Combustion physics and acoustics

Shortfalls included in other subgroups

Sub-group 7 -- Software design and validation

Engine Controller Electrical Hardware Life: highest quality parts will still not meet 500-mission life and maintainability requirement.

Instrumentation Electronics Hardware Reliability: highest quality parts will still not meet 500-mission life and maintainability requirement. Management, Development, and Test of Controls Software: Documenting requirements and understanding the failure modes (and software's role in accommodation) of such a complex concept will be a challenge using today's techniques. Verifying these requirements will also be a problem with current test methodology.

Prognostic/Diagnostic Algorithm Development, Integration, and Test, and Real-time use: Needed.

Sub-group 8 -- Life/reliability and cost predictive tools

Panel 1 -- Life/reliability tools

Physics based life prediction methods are needed to model thermo-mechanical loading (LCF, HCF, Thermal), environmental effects, and their interactions

Improved probabilistic analysis methods are needed to insure combustion devices meet 3rd Gen reliability goals

Component level life prediction / reliability models are needed to support Integrated Engine Health Monitoring

More advanced materials including discontinuously reinforced and continuously reinforced composition are needed for combustion devices to meet 3rd Gen life goals

Panel 2 -- Cost tools

Gathering historical data - difficult to interperate and obtain needed data.

Way of doing business - how you operate business significantly affects cost.

Manipulation of historical analogies to future estimates

Panel 3 -- Simulation tools (end-to-end life cycle)

No input provided

Micro-technologists 2 -- Design Validation Capabilities (Facilities, instrumentation, etc.)

Analysis - Vast improvements in gathering validation data required in order to enhance predictive capability

- Simulation - Current capabilities insufficient as alternatives to test and demonstration

- Test - Full scale system level or subsystem level testing is not cost effective

- Inspection - Enable IVHM instrumentation as a viable means of verification

- Demonstration - Full scale vehicle demonstration is cost prohibitive - Vehicle demonstration risk require extensive verification

Micro-technologists 3 -- Fabrication and Fabrication Process

Design to alleviate tight tolerances

Current SOA materials and manufacturing processes are not conducive to the goals of LLR

Current combustor wall material does not satisfy combustor reliability constraints

Infrastructure does not exist for CMC production. (These materials are leading candidates several application in the Long Life Rocket Engine.