Note by Joe Sylvia: This was the Final Submission to hopefully win the Contract.

Identification and Significance of Problem or Opportunity

Mass Injection Pre-Compressor Cooling (MIPCC) is a promising technology that can permit conventional jet engines, normally limited in speed and altitude, to propel aircraft to substantially higher altitudes and velocities. By injecting coolant ahead of the compressor and using its heat of vaporization to cool inlet gasses, the engine can operate at substantially higher velocities without exceeding temperature limits. An additional feature of this process is a significant increase in thrust that can be used for added acceleration or climb to higher altitudes.

Because the concept depends on a relatively simple kit modification of existing jet engines, it can be fielded near term without need for extended engine development. It can be used either to augment the performance of existing aircraft, or to propel a new generation of high performance aircraft that can benefit from rapid climb and acceleration performance as well as the high efficiency cruise normally associated with conventional jet aircraft.

To explore this technology opportunity a number of organizations have independently entered into Phase-I research programs designed to build an analytical foundation for the technology as well as conduct limited proof of concept hardware demonstrations. Through the course of their Phase-1 efforts several organizations have developed a relationship of cooperation that has lead to this combined proposal for continued Phase II study.

This Phase II effort is led by HMX, Inc., in a teaming arrangement with MSE-Technologies, Inc. and Spath Engineering. This team proposes to take the next step in development by pursuing a full-scale hardware demonstration under representative flight conditions using a high performance engine. The program will include the preliminary design of a full-scale flight-type MIPCC system for use with this engine.

The team's combined skills and background in propulsion system analysis, program management, hardware development, and testing represent a unique asset that can be applied to bringing this promising technology to operational status.

Summary of Phase I Efforts

All team members conducted independent engine cycle analysis to evaluate the viability of MIPCC operation when applied to a variety of turbojet and turbofan engines. They also conducted investigations into the material and mechanical limitations of these engines when used in high performance MIPCC environments.

To compliment the analytical effort, a parallel hardware program was undertaken to demonstrate MIPCC operation and evaluate hardware concepts. The focus of this undertaking is Spath Engineering's effort to assemble an MIPCC test capability based on a J85-GE-5 turbojet engine. By placing injector/duct assemblies ahead of this engine, team members can evaluate injector concepts and demonstrate MIPCC concepts within the limitations of sea level test conditions. Two injector/duct assemblies are scheduled for test during Phase-1 using this test rig. One, produced by Spath Engineering, will use water/LOX injection with an injector developed in cooperation with MSE. A second duct provided by HMX will be used for LAIR injection demonstration.

Plans have been developed to further modify the J85 test rig in a manner such that the jet exhaust can be used as a source of warm gas for testing injector configurations at elevated temperatures representative of inlet gasses at high Mach numbers. The use of this rig for preliminary testing of injector systems will significantly reduce the cost and time needed to qualify injector systems for full-scale high-speed testing.

Summary of HMX, Inc. Phase 1 Analysis. The HMX cycle analysis was intended to assess the performance potential of the MIPCC concept when applied to existing turbojet engines. Engines considered were the J85-GE-21, a representative small turbojet engine, the J79-GE-17 a representative large turbojet engine, and the F100-PW-100, a representative large, low-bypass, turbofan engine. Since one of the guidelines for the study was to evaluate operation based on minimum engine modification, all analysis was conducted with engines running within their normal operating envelopes. Normal temperature, pressure, RPM, compressor surge, and internal flow velocity limits were never exceeded.

Three injectants were considered in the analysis: water, liquid air (LAIR), and liquid oxygen (LOX). All injection was ahead of the compressor. Although direct injection into the afterburner was an option allowed in the study, it was not pursued since it was felt that maximum performance would be gained if all injectants participated in pre-compressor cooling. In addition, the required modifications to the afterburner would violate the "minimal engine modification" guideline and could necessitate extended qualification testing.

Cycle analysis was accomplished using the Navy/NASA Engine Program (NNEP89). An associated software element, CMGEN was used to generate compressor and turbine maps for use within NNEP engine decks.

Initial comparisons were made with the engine set at full throttle and flown along a trajectory that results in constant net engine thrust. Altitude and delivered Isp were used as figures of merit. As velocity increased along these trajectories, injectant was added to limit pre-compressor temperatures to those acceptable to the engine being considered. Results of early J85 analysis are shown in figure 1 and are representative of the trends exhibited by all engines.

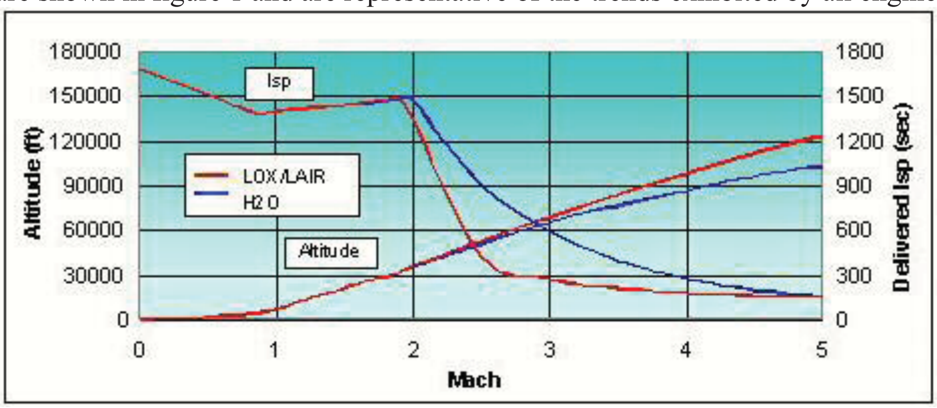


Figure 1 – Representative Constant Thrust J85 Engine Simulation Data

Conclusions drawn from this early analysis included:

1) Water injection delivers higher Isp than oxidizer injection due to its high heat of vaporization.
2) Oxidizer injection has higher thrust potential compared with water due to a higher mass flow rate and the ability to sustain maximum afterburner temperature. This is indicated by the superior altitude capability of the oxidizer injection case.
3) Using water injection, overall engine performance declines at high speed due to cooling effects of water in the afterburner, as well as reduced oxygen concentration in the combustion gasses.
4) LOX provides no significant improvement in performance relative to LAIR due to the afterburner temperature limit of existing hardware.

The results of this early analysis focused further efforts in the follow ways:

1) Pure LOX was dropped from consideration since its performance was no better than LAIR. This reduced the effort needed to investigate the effects of high oxygen concentration on engine materials and also minimized the need for engine modification and material substitution.
2) Although pure water injection promised increased Isp performance, it also carried significant risk of engine flameout due to the reduced oxygen concentration and cooling effects that exist when high water flow rates are used to cool inlet air at high velocities. Because of this, later studies included the use of relatively small quantities of oxygen to augment water injection in

an effort to minimize the performance degradation and avoid the chance of burner blowout or quenching.

HMX Mission Analysis. While this initial fixed-thrust comparison was valuable in understanding the relative merits of different injectants, it was recognized that the resulting trajectory was not necessarily representative of the optimum acceleration trajectory needed for RASCAL missions.

Boost trajectories as required by RASCAL are generally dominated by acceleration requirements where high thrust is often more advantageous than impulse. This is due to the increase in gravity and drag losses during extended acceleration periods. Consequently, an increase in engine thrust, even at relatively low impulse, can result in decreased overall liquid consumption since acceleration time decreases out of proportion to the increase in liquid flow.

Early engine cycle analysis showed that two distinct paths were available for engine operation. Using water, maximum Isp could be obtained. Using LAIR, maximum thrust could be obtained. Comparative trajectory simulations were needed to determine which approach produced the greater overall mission performance.

Although mission analysis was not among the HMX Phase I tasks, it was necessary to develop trajectory simulations to effectively trade propulsion options. These simulations were accomplished using NASA's Program for Simulation of Optimum Trajectories (POST) along with aerodynamic characteristics of a representative boost aircraft configuration provided by Pioneer Rocketplane Corp. The aircraft was scaled for each engine option by maintaining a constant initial wing loading and thrust/weight ratio.

The trajectory followed a two-step sequence to maintain maximum engine thrust. Maximum engine thrust is produced when engine pressure is at its limit. However, if a path that results in maximum engine pressure is flown early in the trajectory, the airframe would experience sever dynamic pressure loads. For this reason the trajectory was initially limited by maximum airframe dynamic pressure instead of maximum internal engine pressure. A maximum dynamic pressure load of 1,000 psf was selected for purposes of initial analysis since this is roughly the limit set for many commercial business jets.

This maximum dynamic pressure trajectory was flown until it intersected a trajectory path limited by the maximum allowable internal pressure of the engine. At this point, the trajectory transitioned to the path of maximum engine pressure and followed it until the end of the simulation at Mach = 5. A graphic representation of this trajectory is included in figure 2.

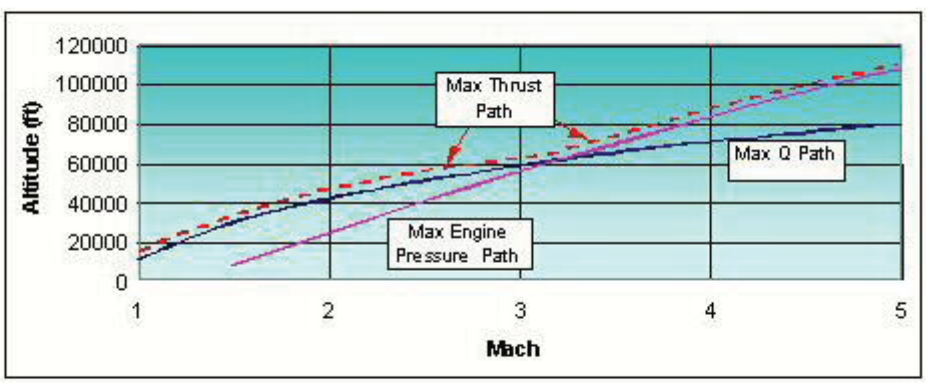


Figure 2 – Maximum Thrust Trajectory Profile

Initial ascent and run-in to this trajectory as well as an end of trajectory kick-up maneuver were not included in this early analysis since these regions are highly dependent on airframe configuration. The trajectory was initialized at an altitude of 20,000 ft and a velocity that developed 1,000 psf dynamic pressure (approximately Mach = 1.2). Performance comparison was made by determining the minimum propellant required to accelerate along the selected path. The simulation was terminated at M=5 and approximately 108,000 ft.

Engine models were developed to deliver maximum thrust along the proposed trajectory path. Although the low-bypass F100 exhibited lower relative performance than either pure turbojet, all engines delivered roughly similar trajectory performance trends. Representative data for the J85 is presented figure 3.

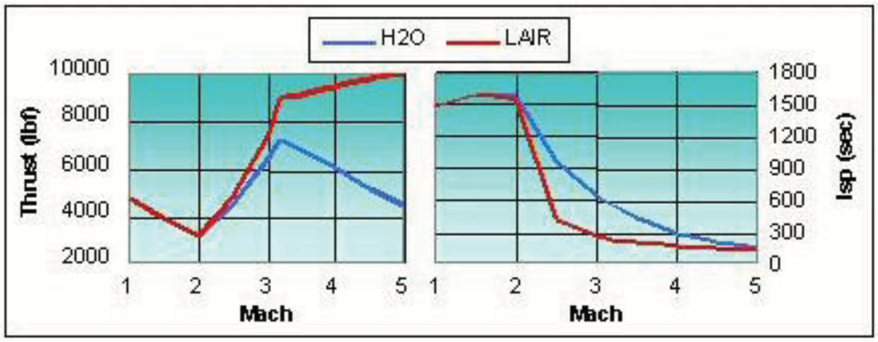


Figure 3 – Representative J85 Engine Data for Maximum Thrust Trajectory

This data set clearly illustrates the primary differences between water and LAIR injection. While the Isp of the water injection system remains higher than the LAIR system till late in the trajectory, thrust performance drops off rapidly.

Although not included on the plot, water based systems, with small quantities of oxygen added to maintain constant oxygen concentration, were also studied. This had performance characteristics that fell between the two extremes of water only and LAIR only injection.

HMX Trajectory Simulation Conclusions. These initial trajectory studies indicate that mission performance delivered by both water and LAIR MIPCC systems is roughly identical. As expected, the higher thrust delivered by LAIR injection compensated for its lower delivered specific impulse. Over the trajectory studied, LAIR provides a small (2 – 3%) reduction in propellant use. Since the un-modeled run-in and end of trajectory kick-up maneuver are highly dependent on delivered engine thrust, this slight advantage is expected to remain when the total mission trajectories are integrated.

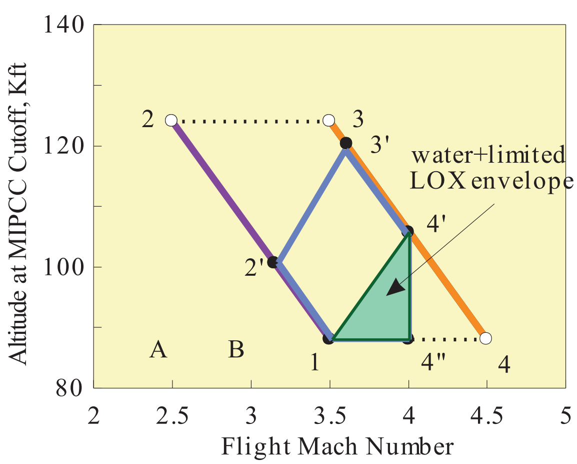
HMX Phase 1 Conclusions and Observations

1) Cycle analysis confirms that high thrust can be delivered by modifying existing jet engines for MIPCC operation. These engines can be operated at extreme altitudes and velocities without exceeding normal operating limitations.
2) Either water or LAIR can be used. They deliver similar integrated trajectory performance.
3) Water injection is accompanied by cooling of both the main and afterburner combustors. This creates a risk of burner blowout or instability. Theoretically, co-injection of oxygen with water can alleviate this problem. Such a system would deliver thrust nearly equal to a LAIR system, and Isp midway between a pure water system and a LAIR system. Integrated trajectory performance is either equal to or slightly better than a LAIR based system, depending on the amount of oxygen needed to stabilize combustion. However, protracted testing may be required to determine operating limits of this 2-liquid system since high water vapor concentration tends to effect combustion velocity even in oxygen rich environments.
4) HMX has selected a LAIR based system for further study in Phase II for the following reasons:
   - Integrated trajectory performance is roughly equal to other injectant choices.
   - There are no limitations on engine operation due to high injectant flows. The engine always operates in an environment that it is designed for.

- Since there are no saturation problems at low velocities, significant levels of thrust augmentation can be gained at any velocity. This is particularly useful for takeoff boost and transonic acceleration.
- There are no oxygen-rich materials and systems concerns.
- There are no engine control system modifications required.
- The compressed Phase II schedule with limited testing time available for system debugging or problem solving demands an approach that minimizes risk. LAIR provides the lowest risk solution in a fast paced, success-oriented program. If the engine runs on air it runs on LAIR.

Summary of MSE, Inc. Phase 1 Analysis. MSE conducted a parallel cycle analysis of the MIPCC concept applied to both turbojet (TJ) and turbofan (TF) engines. This analyses was conducted with the purpose of identifying and selecting the most demanding and the most promising operation modes, as well as evaluating engine behavior when different coolant combinations were injected into the engine.

Initial analyses focused on four zoom maneuver endpoints derived from the DARPA/Johns Hopkins' University (JHU) flight envelope. Injectants studied were either water or LOX and water. Although additional afterburner injection of oxidizer was considered, most analysis focused on pre-compressor injection only. The examined flight envelopes are given in Figure 4.



Points 1-2-3-4 – The DARPA/JHU envelope for MIPCC cutoff

Points 1-2'-3'-4'-4" - MSE envelope for MIPCC operation using LOX and/or LOX/water injectant.

Points 1-4'-4" – The MSE envelope for MIPCC operation with water-dominated injectant.

Figure 4 - Flight envelopes for the end of zoom maneuver

MSE analysis suggests that the point 1 region is appropriate for the zoom end maneuvers when water alone is injected. However, minimum use of oxidizer may still be required for stable combustion. The point 4' and 4" regions are recommended for water-dominated injection with moderate (25%-35% of the combined injectant flow) LOX addition in front of the compressor.

During the course of this analysis, DARPA expressed little interest in Point 1 and requested that MSE examine a Mach = 4.7 point at an altitude of 100,000 ft. The customer suggested a multidimensional matrix approach for engine data presentation that will be useful for trajectory evaluations. MSE is currently pursuing this approach and the desired end-point will be included.

"Limited Oxidizer Use" Concept. A concept of the limited oxidizer use was developed to counteract potential combustion problems and losses associated with high water flow during water-only injection. In this approach, water is used as the only coolant until the afterburner (AB) temperature becomes too low to sustain normal operation. At this point, oxidizer is also injected ahead of the compressor in amounts required to keep the oxygen concentration and AB temperature at reasonable levels. This technique is designed to avoid AB blowout, engine parts oxidation, and AB overheating problems without any design and material changes. The limited oxidizer use approach forms the basis for further water-based development and testing in Phase-2.

Figure 5 explains the concept of the limited oxidizer use. These pictures are drawn for the selected points of the zoom maneuver end, namely the previously selected Points 1, 4', 4. These figures show parameters crucial for the twin problems of AB blowout and material oxidation resistance. The recommended engine operational range is defined by Figure 5a.

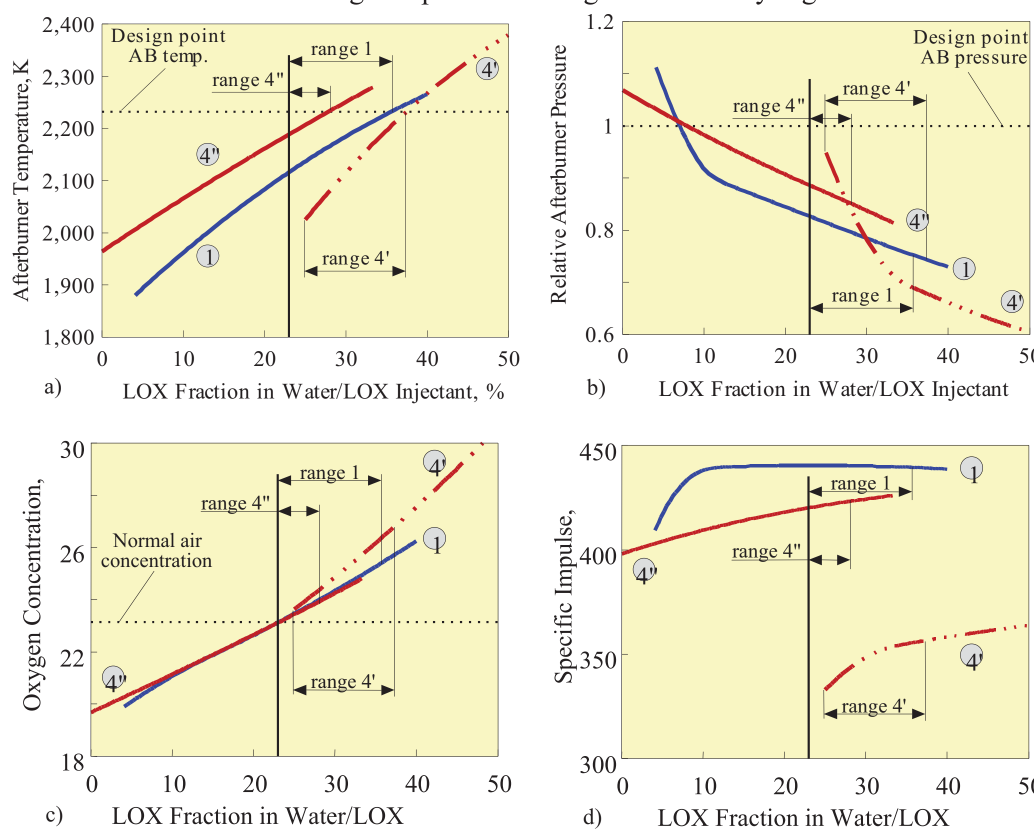


Figure 5 - Combustion parameters as a function of LOX fraction in water/LOX injectant for selected MIPCC engine zoom maneuver operational modes 1, 4', and 4"(see Figure 4).

This range is restricted from the left by oxygen concentration in the air/water/oxygen mixture equal to normal oxygen concentration in the air (23.15% by mass). From the right, it is restricted by AB temperature equal to the design point temperature. The requirements of natural oxygen concentration and normal AB temperature can be met with a LOX/water ratio of between 23% and 37%.

One of the design issues to be addressed in the MIPCC development project is oxidation of the engine structures in an oxygen-rich environment. According to Figure 5c, "limited oxidizer use" approach avoids this issue since reasonable modes require oxygen concentration in front of compressor in the range of 23 - 27 mass %, which is only slightly above normal. It is believed that oxidation, AB overheating, and AB blowout problems can be avoided without any design or material changes.

Limited oxidizer use will simplify the first stage of the launcher by minimizing the amount of required on-board oxidizer. At some conditions, on-board oxidizer can be totally eliminated. This concept is feasible if done in a prescribed manner, which includes first-stage acceleration to the "MSE triangle" in the flight envelope for the zoom maneuver end (see Figure 4).

Figure 6 shows water and LOX injection schedules that provide reasonable MIPCC (80% of the SLS thrust) operation at reasonable internal engine parameters. Figures 6a and 6b compare the required amount of water and LOX injectants relative to the SLS airflow rate. Water curves are shown in green, and LOX curves are shown in blue. Point numbers correspond to Figure 4.

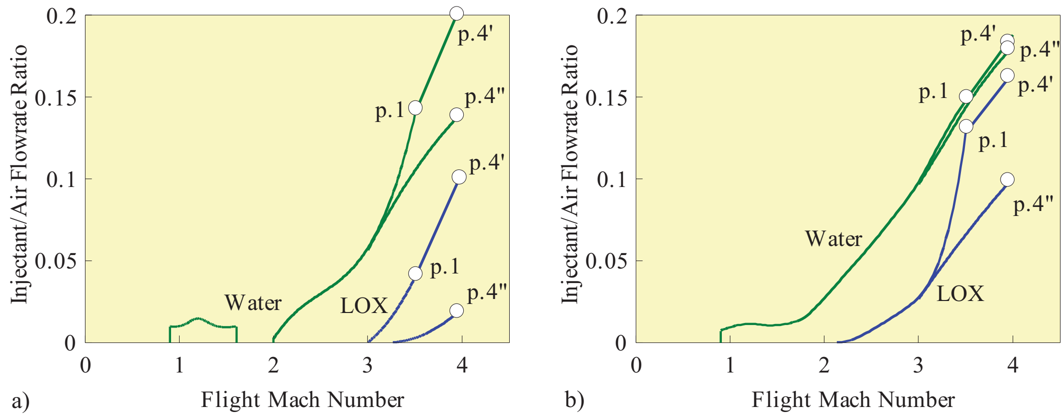


Figure 6 – Relative water/LOX ratio for simulated turbojet (a) and turbofan (b) engines.

It was determined in previous studies that a small amount of water injection in the transonic regime helps to increase overall fuel efficiency. Therefore, in the shown evaluations, this approach was also employed. Water injection in the amount of 1%-1.5% of the airflow starts at Mach=0.9 (injection on this mode is *optional* for MIPCC and the RASCAL launcher). The further schedule is different for both the TJ and TF in the examined case. It was assumed that engine thrust should be on the level of 80% of the SLS thrust. The TJ can meet this condition without water injection after the transonic regime is over at Mach 1.6; the TF cannot, as it requires water injection. The TF also requires earlier initiation of LOX injection, since the bypass containing water reduces AB temperature more substantially than in the TJ.

Point 4" can be considered as the most comfortable point for the engine. The TJ- and TF-based MIPCC engines are both feasible. The latter is less adaptive and consumes more LOX, as well as more total water+LOX injectant.

Preliminary Vehicle Synthesis (HySID Vehicle). MSE, and AFRL evaluated the use of MIPCC in an example launch vehicle configuration. In this project, AFRL was provided a cycle analysis data set that maintained constant engine thrust after initial acceleration. AFRL/PR used this data the evaluate performance of the Boeing HySID configuration while using MIPCC. Although neither vehicle nor propulsion system were optimized, the exercise showed that MIPCC appears capable of propelling a launch vehicle to the desired altitude, Mach number, and flight path angle. The resulting configuration mass at the examined zoom end point was 58% of the gross takeoff weight.

MSE Phase I Conclusions and Observations

1) Pre-compressor injection of water/LOX injectant provides reasonable performance for turbojet and turbofan engines through the majority of the DARPA/JHU zoom end envelope.

2) To resolve the potential oxidation and blowout problems, MSE has suggests the limited oxidizer use concept. A rather narrow oxidizer fraction range (0%-30% of the total injectant flow) will focus ground test with the ultimate goal of demonstrating MIPCC operation without oxidizer injection.

3) The "MSE triangle" is recommended as the MIPCC engine cutoff destination. It is within the DARPA/JHU envelope and covers trajectory points at higher Mach numbers and lower altitudes.

4) As a result of preliminary vehicle analyses performed by AFRL, water/LOX injection appears to be capable of attaining the desired altitude, Mach number, and flight path angle.

5) MSE and AFRL are in the process of conducting systematic analyses of an MIPCC-powered launcher concept. MSE is currently completing a 3-dimensional preformance matrix for the F100 engine to be used in this analysis.

6) MSE proposes water-based injection with limited oxidizer use as the basis for further development and testing in Phase-2.

Summary of Spath Engineering Phase 1 Effort. Spath Engineering also conducted engine cycle analysis using NEPP. This modeling has been used primarily to predict the performance of the J85-5 test rig during sea level static runs. Initial engine modeling focused on matching model performance with expected delivered engine performance running both with and without water injection. This model will be refined once static engine testing begins. Later modeling will correlate theoretical N2O, LOX, and LAIR injection with testing of these injectant materials.

A great deal of Spath's effort has been focused on preparing the J85-5 engine test rig for sea level static testing of MIPCC configurations. The rig is shown in figure 7.

Figure 7 – J85-5 Mobile Test Rig

The test set-up is mobile and the associated components such as the fuel supply, injectant supply, engine air-start system, and data acquisition and control systems are modular. Modular construction allows easy adaptability to various experiments pertinent to development of MIPCC for the RASCAL program. Experiments during the phase I will include injection of water, N2O, LOX, and LAIR to gain experience with turbine engine MIPCC and examine critical issues such as compressor case overcooling. The J-85 test rig can be advantageously used during a phase II program for vitiated flow vaporization studies and further examination of droplet transport times. Use of the J-85 test rig will save many hours of more expensive testing in AEDC facilities.

Phase II Technical Objectives

The objective of the Phase II program is to design, fabricate, and test a full-scale MIPCC augmented turbojet system. An existing large military engine will be used to validate the ability of MIPCC technology to perform at the extreme flight conditions that are needed to support RASCAL mission requirements. The end result of this effort will be a preliminary design for a flight-type MIPCC system.

Technical Approach to Satisfy Phase II Objectives. The team will address this technology by pursuing two complimentary paths of MIPCC injection testing both water/LOX injection as well as LAIR injection. This dual approach was selected to ensure a successful demonstration within a limited Phase II schedule, and to furnish technical options as requested by potential RASCAL customers.

Both systems will be tested in the J-1 facility at AEDC using nearly identical physical setups or in the F-106 as proposed in Appendix A and B. Both the water/LOX duct supplied by MSE and the LAIR duct supplied by HMX will have similar installation characteristics.

Water/Lox System. A water/LOX injectant combination will be tested using the "limited oxidizer use" approach to overcome the adverse effects of high water flow on combustor operation. This approach was selected because it promises simplified logistics as well as the potential for eventual water-only operation after further development and later modification of engine hardware.

MSE is developing the injector arrangement for this option. As illustrated in figure 8, it consists of a bank of 5 supply headers spaced across the inlet duct. 26 injector orifices are distributed along these headers to evenly distribute liquid across the inlet flow. Multiple banks of this 5-header arrangement will be placed along the length of the duct about 1 foot apart to accommodate maximum injectant flow rates. Both hydraulic and air-assisted atomizing injector tips are being considered.

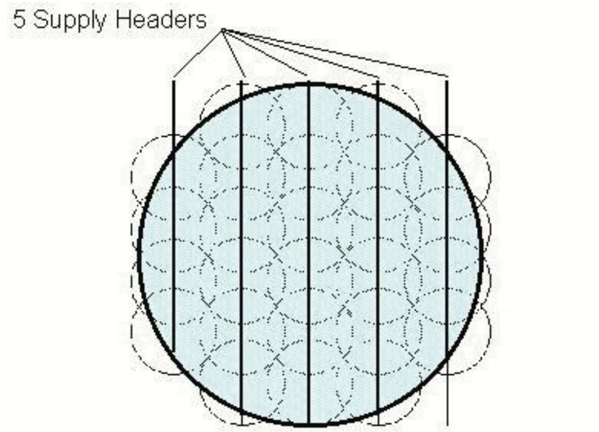


Figure 8 – MSE Injector Configuration: 5 Headers, 26 injectors

MSE is currently in the process of the final selection of the water spray system. Four types of hydraulic and air atomizing nozzles have been considered in close contact with three vendors. Air atomizing nozzles are the best performers when considering required pump horsepower, droplet size, and evaporative distance; however, the atomizing air required at the maximum flow rate may require as much as 50 SCFM of compressor bleed flow. For this reason, hydraulic nozzles are the most likely candidate for the water injection system. Swirl type nozzles have been pre-selected on a performance and cost basis. Particularly, these type of nozzles provide the shortest distance for 80% of water evaporation, as well as the lowest section blockage (percentage of the frontal area blocked by spray bars) among the examined types. Table 1 gives the summary of the major parameters.

Table 1. Characteristics of the selected water spray system.

Spraying System	Water pressure	Number of nozzles	Orifice/Droplet size	Distance, 80% evaporation	Blockage
L-66	500 psi	78	0.066"/45 μ	17 ft	20%

This L-66 (vendor's designation) system has been sized for an F 100-229 turbofan engine with a 36" inlet duct ID. This configuration allows for a more flexible water flow control without generating additional distortion. A preliminary design based upon a hydraulic hollow cone swirl type nozzle (L-66 spray system) has been developed. This configuration provides the shortest evaporative distance, and the lowest section blockage ratio of the water spray systems investigated to date. The L-66 system is based on a maximum flight Mach number of 4 and dynamic pressure of 1000 psf. This requires a maximum water injection of flow rate of 195 gallons per minute (GPM).

The radial penetration of the duct provides an even distribution of water spray throughout the cross section of the duct and should minimize the temperature distortion at the engine compressor face. The attachment of the spray manifold is accomplished with bulkhead fittings and will allow the injection angle of each spray tube to be adjusted from 0 (air flow direction) to 180 degrees. The water injection duct length for this configuration is approximately 3 ft.

Air atomizing and hydraulic (impinging and swirl) nozzle configurations are being investigated. Optimization of these nozzle systems requires minimizing the blockage ratio while maintaining small pressure drops through the manifold system while minimizing the required supply pressure (HP) while maintaining a reasonable evaporative distance.

The evaporative distance of the spray system is a function of the relative velocity between the water droplets and air (residence time), droplet size, and duct temperature. The relative velocity between the water and air is a function of the spray pressure and injection angle, and the droplet size is a function of the pressure and spray nozzle. Therefore, the injection pressure and angle must be optimized to provide the minimum evaporative distance while maintaining the horsepower levels within the limits of the engine accessory drive unit. Additionally, the available inlet length must be considered and will limit the spray system duct length (both water and oxidizer). This optimization will be the focus of the water injection system design task.

MSE intends to obtain a commercially available model TESSTM from Southwest Research Institute (SwRI) which predicts trajectories and evaporation rates of dilute sprays. This model includes liquid properties for water, alcohols, and hydrocarbon fuels. It is used to predict polydisperse droplet-size distributions and changes in distribution caused by droplet evaporation and the loss of droplets due to wall collisions.

LAIR System. The LAIR based system has similar integrated trajectory performance relative to water/LOX and was selected as a minimum risk approach to ensure operation within the compressed Phase II schedule, and to satisfy the needs of potential RASCAL customers.

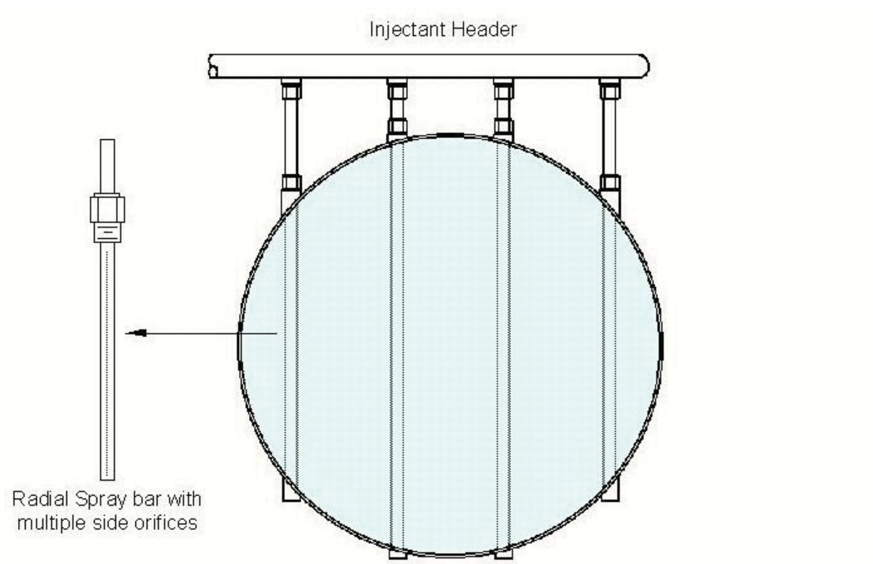


Figure 9 – HMX Injector Configuration: 4 Spray Bars, Side Drilled Spray Orifices

Because engine performance does not vary with increasing quantities of LAIR flow, only a few test points will be needed to qualify the system. The LAIR approach requires no engine modification or engine control reprogramming. In addition, it should encounter no combustor stability or blowout problems since the engine will always be running in an environment identical to a standard engine without MIPCC operating under normal conditions.

Because it can be installed on existing engines with essentially no modification or impact on basic operating characteristics, the LAIR system developed during Phase II should be highly transportable to other engines. Once the injector assembly demonstrates satisfactory vaporization characteristics, it could be used on any engine of comparable size. New engine installations should require minimum testing to qualify.

The injector arrangement for LAIR being developed by HMX is plumbed in a similar manner to the water/LOX system provided by MSE. However, HMX is using a drilled-orifice injector array rather than pre-manufactured spray tips. As illustrated in figure 9, the radial spray bars are drilled along their sides with either impinging or non-impinging orifices. Impinging orifices are the most promising since they provide the smallest droplet size. As with the MSE approach, multiple banks spray bar panels will be installed along the length of the inlet duct to accommodate full injectant flow.

Hot Duct Testing. To support injector development, the team will utilize a "Hot Duct" injector apparatus based on a modified Phase-1 J85 test rig. This setup will be valuable for debugging the injector and demonstrating adequate vaporization and injectant distribution before the assemblies are committed to integrated MIPCC/engine testing in the J-1 test facility. This early testing will avoid using schedule-critical time at AEDC as well as save considerable cost. A single test at M=3, near the limit of the J-1 tunnel, could cost over $100k due the time required to achieve maximum temperature. In contrast, the J85 Hot Duct rig can deliver similar gas flow temperatures with an overall test cost of less than $5k. This is especially important since injector development and debugging could be an iterative process requiring several turns of hardware development before it is mature enough for integrated engine testing. An additional feature of the Hot Duct rig is that it can generate temperatures simulating flight at greater than Mach 4. This is considerably in excess of the AEDC J-1 capability.

System Schematic. To illustrate the features of the proposed MIPCC systems, a "System Schematic" has been developed that illustrate the anticipated flight-type installation and identify engine/aircraft interfaces (figure 10).

System features include:

- No modifications to base engine are required. Sensor set that controls MIPCC system is already present on engine. Either these can be used directly, or similar redundant sensors can be installed.
- Coolant flow is regulated to maintain desired inlet temperature as sensed by the fan discharge temperature (TT2-5C). This location is preferred over sensing ahead of the fan since un-vaporized liquid ahead of fan could produce a false reading. Temperature ahead of fan will be backed out from resulting temperature behind fan.
- Gas generator pressure (PB) is monitored to avoid over-pressurizing engine while flying high-performance acceleration trajectory.
- For water/LAIR operation, monitored fan turbine inlet temperature (FTIT) to derive AB inlet temperature and AB pressure (PAB) may be needed to control oxygen injection and maintain appropriate AB combustion characteristics.
- Although no engine control modification is anticipated for LAIR operation, water/LOX injection may require adjustment of EEC gains.
- LAIR system layout is identical to water/LOX system with the elimination of water supply subsystem and FTIT and (PAB) sensor connections.

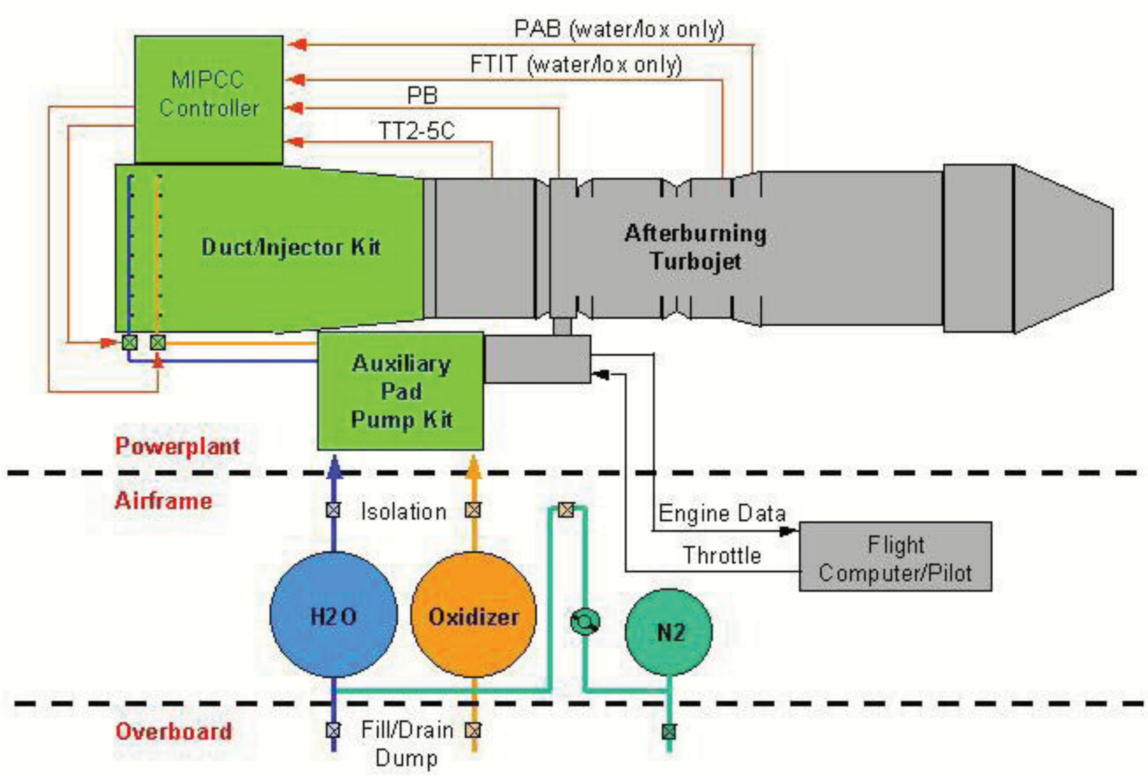


Figure 10 – MIPCC System Schematic

Summary of Objectives. In summary, the Phase-II program will be composed of three principal elements:

1) *The primary objective of this effort will be the full-scale demonstration testing an F100 or J75 engine at representative flight conditions while using MIPCC technology. This testing will be conducted in either the AEDC J-1 facility or in flight using an F-106 (see Appendix A) and will demonstrate both water/LOX and LAIR injection options.*
2) *A second objective of this Phase-II effort is continuing to refine the analytical base for MIPCC technology specifically as it relates to the engine selected for full-scale demonstration. This will be accomplished by expanding the data envelope as well as increasing the model resolution through incorporation of test data.*
3) *A third objective is of Phase II will be to develop a preliminary design for a flight weight MIPCC subsystem. It is intended that the Phase II MIPCC modified engine will meet RASCAL performance requirements and the system can be transitioned into a flight system with minimum modifications.*

<u>Work Plan: Task Description</u>

1) Continued Engine Cycle Analysis – The engine cycle analysis begun in Phase-1 will be continued using decks specifically designed for the F100 or J75 variant used in Phase-II testing. A full data package will be prepared that can be used by airframe customers in RASCAL mission evaluation. Test data will be integrated into the models to improve resolution.
2) MIPCC Test Planning – The team will perform test planning for integrated MIPCC engine testing. Test objectives and procedures will be developed to enable testing of the engine at critical RASCAL flight conditions.

3) Control System and Data Acquisition System –Task 3 will involve the design and analysis of the instruments and controls required to operate the system. The goal of this task is to provide a protective and fail-safe operating environment for the engine at the extreme flight trajectories. Issues such as system response time, shut down procedures, injection duration, and system interlocks will be identified and investigated. Critical instruments will be identified and consequences of their failure will be analyzed. Instruments with long procurement processes will be ordered with at least one spare to minimize down time or canceling of scheduled test points. This task will also include identifying engine control issues including emergency shutdown.
4) AEDC Option– The team will work with AEDC staff to coordinate any necessary modifications to J-1 facility that may be required to facilitate testing. This includes consideration of engine mounting and instrumentation as well as facility modifications necessary to accommodate test duct section installation. The team will facilitate the modification of existing equipment, or the addition of new equipment necessary to support MIPCC operation including injectant tankage and feed systems as well as control and instrumentation of MIPCC hardware. The team will acquire an F100 engine and spare for use in integrated MIPCC testing. The team will arrange for any maintenance or modification needed to ensure satisfactory engine operation.
5) F-106 Flight Testing Option – The team will work with our proposed subcontractor, Destiny Aerospace, to prepare two F-106 aircraft to support the flight test program. The aircraft will be returned to flying status, modified and instrumented to support MICPCC data collection and flown as required.
6) Prepare “Hot Duct” Test Rig – The Phase-I J85 test rig will be adapted to supply hot gas to representative injector/duct test sections. This apparatus will serve as a low cost tool to debug injector assemblies and ensure adequate function before proceeding with more costly time-critical integrated engine testing at AEDC or in-flight.
7) Prepare Injector/Duct Assemblies – The team will design and fabricate two injector/duct assemblies for use in MIPCC testing. One duct will use Water/LOX injection and the other LAIR injection.
8) Hot Duct Testing – The team will conduct injectant vaporization testing of the duct/injector assemblies using the J85 Hot Duct test rig. Once satisfactory operation has been demonstrated they will be used for full scale integrated MIPCC testing on the chosen engine.
9) Full-scale MIPCC Testing – Full-scale MIPCC operation of the selected engine will be conducted in the J-1 facility at AEDC or in-flight using the F-106. These tests will include integrated injector/duct operation at critical RASCAL flight conditions within the limits of the test simulation capability.
10) Flight-type MIPCC Design – Based on Phase-I and II experience, the team will prepare an integrated preliminary design of an MIPCC system that meets flight requirements. A design review for this effort will be scheduled 11 months after start of Phase-II.
11) Documentation – All tasks will include a preliminary level of documentation that will be combined at the end of the study and integrated into a final report with the appropriate conclusions and recommendations for additional research and development. This will be a continuous "level-of-effort" task. All other reports will be provided in accordance with prime contractor requirements. The team will prepare a final report detailing the results of the Phase-II effort within 30 days of completion of the final work task.
12) Reviews – The team will support required reviews. Project-level reviews will occur weekly; HMX corporate reviews will occur monthly, and prime contractor/customer reviews will be conducted as required by the sub-contract.
13) Travel – The team will travel for testing, test support/planning, coordination and reviews.

Work Plan: WBS/Schedule

Task	Months											
	1	2	3	4	5	6	7	8	9	10	11	12
1. Continued Engine Cycle Analysis												
2. MIPCC Test Planning												
3. Control System and DAS												
4. AEDC Option												
4. F-106 Flight Testing Option												
5. Prepare "Hot Duct" Test Rig												
6. Prepare Injector/Duct Assemblies												
7. Hot Duct Testing												
8. Full-scale MIPCC Testing												
9. Flight-type MIPCC Design												
10. Documentation												
11. Reviews												
12. Travel												

Related Work

Each of the team members performed work related to this Phase II proposal as described in their Phase I Interim/quarterly reports and in this proposal beginning on page 3.

Relationship with Future Research or Research and Development

The modification of existing turbojet engines for MIPCC operation results in an engine with high thrust capability that can fly at extreme altitude and Mach number while maintaining its original cruise efficiency. Significant commercial and military markets, as well as space launch applications exist for this technology. As an example, a supersonic business jet would need to accelerate quickly to cruise altitude and speed in order to maximize performance. An MIPCC modified engine could provide this rapid acceleration while maintaining the engines originally optimized cruise efficiency.

The promise of this technology warrants continuing development of MIPCC beyond the scope of this Phase II research effort. Continued effort should be directed toward improving the operability of MIPCC systems and developing conversion kits for appropriate engines.

Commercialization Strategy

HMX and our team do not expect to enter the commercial market for the development and production of turbojet or turbofan engines for hypersonic aircraft, drones or boost-gliders. To begin with, there is currently no existing market for the revolutionary capability that MIPCC brings to proven turbine engine technology. It is a market that will have to be developed. In addition, the capital cost of turbine engine development and production is well beyond the ability of even a group of small businesses to meet. (Accordingly, a schedule for commercialization and market size of possible commercial products cannot be provided at this time but will be developed during the course of Phase II as results warrant.)

However, there is a current business model for modification of turbofan engines that we will try to emulate. As noise control has become a major factor for the certificated airline and business jet community, a business of developing "hush kits" to quiet jet engines has become popular and profitable, allowing many aging jet aircraft to continuing to operate while meeting stringent noise standards.

The technological path we have chosen to pursue towards MICC functionality is particularly suited to this model. We now believe, and will prove during Phase II, that existing turbojet/turbofan jet engines may be operated with little or no modification to the core engine components. It is reasonable to assume that such additions as pumps on existing power takeoff pads, minor control systems tuning and other similar "tweaks" of certified engines may be performed while not invalidating the data base of existing operating engines. The principal additions our team would propose during a commercialization activity would be the addition of the duct and inlet modifications plus the engineering and development support required by airframers who will build the vehicles that may employ MIPCC propulsion.

Therefore our strategy is to accumulate patent protections and trade secret rights, plus practical analysis, development and engineering skills, so as to be able to work in tandem with airframers to service both government and commercial marketplaces. We will build engine modification kits as required (here the option we present for use of the F-106 offers a further opportunity to demonstrate the "transportability" of our MIPCC technology among a number of different engines). Finally, if the option for the F-106 is approved, we will use it as a marketing tool to interest a wide variety of airframers in the potential of MIPCC.

Personnel

The HMX team consists of Program Manager (PM) Gary C Hudson and Principal Investigator (PI) Bevin C. McKinney. Other personnel will participate as appropriate.

Gary C. Hudson – Program Manager – CEO

Mr. Hudson is a founder and former Chairman of the Board of Directors and CEO of Rotary Rocket Company, where he was responsible for raising $33 million of private financing and managing 70 people and 150 contractor personnel during the nearly four year Roton development program. His experience includes both management and engineering in high-tech, entrepreneurial settings.

In 1994 he co-founded HMX, which designs and develops innovative aerospace propulsion systems. In 1982 he co-founded Pacific American Launch Systems, Inc. As President and CEO of PacAm he was directly responsible for financial and strategic planning as well as oversight of engineering, marketing, and operations during design and development of the Liberty. Liberty was a small expendable launch vehicle, which underwent prototype engine testing for the US Army Strategic Defense Command on behalf of SDIO at Edwards Air Force Base, California.

In January 1994 he received the "Laurel" award from Aviation Week & Space Technology "for the vision, drive and competence that have pushed [single-stage-to-orbit and reusable launch vehicles] to the front of the US launcher agenda."

Bevin C. McKinney - Principal Investigator – Chief Technical Officer

Bevin McKinney began his engineering career as a naval architect after studying marine engineering at the University of California in Berkeley. While engaged in consulting activities during the 1970s, he became professionally active in field of space development.

This activity led to his co-founding an early private space launch venture, which successfully conducted test-launches of large hybrid propelled rockets from the Pacific Ocean in 1984. In 1985, he co-founded American Rocket Company, which continued to develop the unique, non-explosive hybrid rocket motor as a commercial project. Mr. McKinney served at American Rocket as Vice President, Chief Designer, and was instrumental in bringing hybrid propulsion from a laboratory curiosity to full scale flight status. He was responsible for developing and testing numerous hybrid motors including the 250,000 lb.-F thrust DM-01, which is currently the world's largest hybrid motor. He has been responsible for more than 500 rocket motor test firings.

In 1994, Mr. McKinney left American Rocket Company to co-found HMX. In 1996, he co-founded Rotary Rocket Company to pursue the development of the innovative Roton launch vehicle concept for which he was awarded a US Patent in 1998. While at Rotary he was responsible for propulsion system development, including the development of the first commercial liquid oxygen cooled regenerative engine, which was designed to operate at 2400 psi.

Since 1999 he has conducted numerous analytical studies investigating augmented turbojet cycles for use in high-speed aircraft and space launch vehicles. These efforts led to the conception of the CoolJet cycle.

The MSE team consists of Principle Investigator (PI) Dr. Vladimir Balepin and Project Manager Mr. Chris Ossello. Other personnel will participate as appropriate.

Dr. Vladimir Balepin, Principal Investigator. Staff Scientist, 23 years experience

- Ph.D., Aerospace Propulsion Engineering, Central Institute for Aviation Motors, Moscow, Russia (1986).
- M.S. Aerospace Propulsion Engineering, Moscow Aviation Institute, Moscow Russia (1979).
- B.S., Aerospace Propulsion Engineering, Moscow Aviation Institute, Moscow Russia (1977).

Experience: Prior to joining MSE in 1997, Dr. Balepin worked at aerospace and propulsion institutions in three countries. He has 13 years experience in theoretical, experimental, and conceptual research at the Russian Central Institute for Aviation Motors (CIAM) in the fields of rocket engines, air-breathing engines, and combined cycles for hypersonic propulsion. Dr. Balepin also completed 3 years of experimental and conceptual study at the Japanese National Aerospace Laboratory (NAL) coupled with design and analytical and experimental study of air precooling for the Air Turbo Rocket Expander (ATREX) engine at the Japanese Institute of Space and Astronautic Science (ISAS). He participated in hardware development for the ATREX Cycle and the first test firing of the precooled turbomachinery. He has worked at Techspace Aero Co. of Belgium, conducting experimental air separation and conceptual studies as part of the Future European Space Transportation Investigation Program (FESTIP) of the European Space Agency (ESA). His main research achievements are in integrated cycles, heat transfer/cryogenic experimental studies, and development of the precooled ATREX engine. At MSE, Dr. Balepin conducts experimental and system studies for a NASA Langley Research Center (NASA-LaRC) *Low Speed Systems Research for Air-Breathing Hypersonic Vehicles Project* and NASA-MSFC *Advanced Propulsion Concepts Project* as a Principal Investigator (PI). He is also PI for a USAF SBIR Project *A New Rocket-Based Combined Cycle for Reusable Launch Vehicles*, and for a DARPA SBIR Project *Mass Injection Precompression Cooling Turbine Engine*.

Dr. Balepin has more than 60 publications on related research, 15 Russian patents, 2 U.S. patents, and 2 U.S. patents pending.

In 1996, Dr. Balepin received the Society of Aerospace Engineer's Arch T. Colwell Merit Award for the study titled *Rocket Based Combined Cycles for Single-Stage Rockets*. In 1999, he received the Defense and Space Engineering/Technical Achievement Award from the American Institute of Aeronautics and Astronautics (AIAA) Pacific Northwest Section. Dr. Balepin has chaired and co-chaired propulsion sessions in numerous international aerospace meetings. In

2001, he was included in *2000 Outstanding Scientists of the 21st Century* by the International Biographical Society, Cambridge, England.

Chris Ossello, **Project Manager.** Analytical Engineer/Scientist, 6 years experience

- B.S., Engineering Science, Control Systems, Montana Tech of the University of Montana, Butte, Montana (1997).
- Graduate level courses in Control Theory; Montana Tech of the University of Montana, Butte, Montana.
- Graduate level courses in Mechanical Engineering, Montana Tech of the University of Montana, Butte, Montana

Experience: Mr. Ossello has worked in various theoretical, computational, design, and experimental projects providing expertise in systems control, supervisory control and data acquisition (SCADA), computer modeling and simulation, thermodynamics, fluid mechanics, gas dynamics, and various computer languages (C, F77, F90, Visual Basic, Java), and C/F90/F77 OpenGL interfacing. Past projects include air emissions tracking/monitoring for chrome plating and a complete restructuring of the SCADA system for the Plasma Ordnance Demilitarization System (PODS) developed at MSE.

Mr. Ossello is currently working in magnetohydrodynamic (MHD) accelerator modeling and performance estimations, electron beam modeling, chemical equilibrium and kinetics for MHD and combustion problems, as well as turbojet and turbofan engine performance mapping for two stage to orbit (TSTO) launchers and rocket based combined cycle (RBCC) engines.

The Spath Engineering team consists of Mr. Terry Spath. Other personnel currently assigned to Phase I will participate as appropriate.

Terry Spath

Mr. Spath worked for a contractor to the AFRL during development of the 100,000 pound thrust RPTF in Socorro. His duties were rocket test stand engineer and technician. Previous applicable experience includes four years as a flight test engineer and pilot for Learjet in Wichita, Kansas. He was a structural loads analyst for Rockwell International in Downey, California on the Space Shuttle Orbiter. Mr. Spath is an 8,000-hour Airline Transport Pilot (ATP) with a Learjet Type Rating. Additionally, he holds a FAA Airframe and Powerplant (A & P) Mechanic's License with Inspection Authorization. He received his A&P license from Northrop Institute of Technology in Inglewood, California. He graduated from the University of Washington in Seattle with a BS in Aeronautics and Astronautics.

Facilities and Equipment

HMX team personnel will perform all Phase II work tasks, either at HMX team facilities or leased facilities available under existing agreements. All tools, apparatus, and software needed to complete the work tasks listed are currently owned or otherwise available to the offeror. Facilities where work will be performed comply with all Federal and state regulations.

The HMX team requests continuing use of the J85-5 employed by Spath and HMX during Phase I. In the event testing is performed at AEDC (note Appendices A and B) F100 engines will be required, serial numbers XXXXXX and XXXX currently located at Tinker AFB.

Consultants

Each HMX team member may or will use many contractors in support of this proposal, for analysis and fabrication and testing tasks. Space does not permit a through discussion of these contractors but details are available as required by the government during negotiations.

Prior, Current, or Pending Support of Similar Proposals or Awards

HMX, Inc. is not currently funded by any Federal agency to engage in equivalent work related to the subject of this proposal, nor has it received any previous funding from any Federal agency for equivalent work with the exception of the Phase I SBIR. HMX does have one proposal currently submitted to another Federal agency (NRO) for work on rocket-cycle CoolJet propulsion unlike to the scope of work proposed herein.

Appendix A. Testing Options

A critical issue in Phase II is the method of testing the MIPCC technology under conditions of temperature and pressure that adequately replicate the environment found in flight powerplants. Historically, this is the problem upon which many previous attempts to provide high thrust high-Mach number airbreather engines have faltered. It is important to learn the lessons of past problems with testing and to determine the optimal method for both collecting the required data points while at the same time providing the most value for the investment of program dollars. Having a residual testing and validation capability throughout the RASCAL Phase III effort would also be useful, in our view.

The two options that we present here are:

- Ground testing at AEDC (Arnold Engineering Development Corp.), and,
- Flight testing via a government-owned F-106 Delta Dart aircraft.

Our original intent, after characterizing the injection system and duct in the vitiated hot gas test rig at and HMX site in Mojave, was to conduct an abbreviated test program at AEDC in order to provide a testing environment for the engine and duct assembly which replicates as much as possible of the projected flight profile of the RASCAL first stage RLV. By picking just a few data points, we would be able to reduce testing costs at AEDC and serve the goal of anchoring the NEPP performance calculations. However, this priced option for Phase II would cost the government approximately $2.1 million based on a ROM estimate from AEDC. Unfortunately, AEDC testing does not simulate the maximum inlet temperatures nor the actual trajectory to be flown by the RASCAL vehicle. In addition, this is the charge for a limited testing window, and further significant funds would have to be expended if future testing were required, as may well be the case based on our experience with both ground and flight test programs for both aircraft and rocket vehicles.

Recently an alternative option (F-106 flight testing) has presented itself. We began by considering this option as only a possible add-on to the testing program that includes the hot gas duct tests at Mojave and the AEDC tests, but cost increases at AEDC plus the limits on tunnel performance have made this "add-on option" a viable contender to take the place of ground testing. Table A1 offers some comparisons.

Table A1. AEDC vs. F-016 testing	AEDC	F-106
Basic Cost	$2.1M	$1.056M
Schedule Flexibility	Dec 2002 to April 2003	Dec 2002 to end of RASCAL Phase III
Demonstrated Mach Number at Basic Cost	3.0	2.7
Cost to Reach M4.7 100KFt Test Point	Unavailable	+$470,000
Cost to Simulate Complete RASCAL Trajectory	Not Possible	+$800,000

The F-106 will also be capable of serving as a test platform for other RASCAL technologies, as is described in the discussion of the priced option in Appendix B. Bottom line cost for the full F-106 effort including exo-atmospheric flight operations is $2.326 million.

The HMX team recommends a very careful consideration of the F-106 option as an alternative to AEDC.

Appendix B: MIPCC Phase II Flight Test Proposal

1.0 Flight Testing MIPCC Technology. The ultimate purpose of DARPA's development of MIPCC technology is to power a re-usable first stage launcher for the RASCAL orbital launch system. As MIPCC engine development enters Phase II, obtaining real world data from actual MIPCC hardware is a program goal. Data points can be obtained from ground testing jet engines in test cells. However, the ultimate demonstration of technical development will always remain actual flight testing. We here propose to DARPA a cost-effective flight test program for MIPCC hardware. This will allow DARPA to collect hard MIPCC performance data early enough to mitigate several areas of technical risk in the in the MIPCC and RASCAL development programs.

We propose using an F-106 Delta Dart as a flying testbed for our MIPCC techniques. We believe that this unique aircraft has multiple features that make it ideal to for this purpose. We believe that such a flight test program, utilizing the F-106, could be performed quickly, within an affordable budget, and yield invaluable risk mitigation and performance.

2.0 Flight Test Program. Destiny Aerospace will be our F-106 MIPCC Flight Test subcontractor. Their flight test team has considerable experience with F-106 operations and testing.

Figure B1. F-106A with Payload Bay Open.

This proposed test program is presented as a series of options to DARPA. These options are presented as a three-phase flight test program. With some phases, there are additional options that DARPA can exercise. In this way, the accomplishment of modest flight test goals leads to the opportunity to pursue more advanced test objectives, in incremental funding steps.

2.1 Aircraft Reactivation. It is recommended that at least two aircraft be detailed for this program as they can provide back up, chase plane and on-site spare parts for each other. Harry Brannam, F-106 Program Manager, AMARC, has given our subcontractor, Destiny Aerospace, a quote of 3.5 months and no more than $160,000 per aircraft to restore these two aircraft to full Air Force Technical Order flight standards, at the AMARC depot.

Our first choice in aircraft would be tail numbers 90130, an "A" model, and 90158, a "B" model. Activating the two-seat "B" model would give us the option of having a flight test engineer onboard some MIPCC test flights.

2.2 MIPCC Installation. After acceptance flights, (three flight hours planned) the two test aircraft would be flown to Mojave Airport, California, where the MIPCC flight testing will be performed. There, BAE Flight Systems will supervise the addition of a water-based MIPCC system to the F-106, under the direction of Spath Engineering. A 48-channel Data Acquisition System will be installed. The aircraft life support system will be upgraded to support aircrew members using full pressure suits for high altitude operation. We have budgeted $360,000 for these modifications and two months to perform the work.

We have budgeted $200,000 for flight analysis to determine the dynamic stability envelopes for the F-106 at high Mach number and the necessary changes to the flight control system control coefficients, if any are required. The F-106 has already been flown to Mach 2.7. Because of its classic delta wing configuration it is expected that it can be flown out to Mach 4-5

2.3 MIPCC FTP 1 (MIPCC Flight Test Phase 1). Upon completion of hardware modifications and the flight dynamics analysis the aircraft would begin a series of graduated test flights. These would start with basic operation of the MIPCC system. We would start with static ground tests of the installed system and then begin flying at 30,000 and 40,000 foot altitudes and at speeds varying from subsonic to Mach 2 operation. We have budgeted 2 hours of ground testing and 8 hours of flight testing for this phase at a burdened rate of $8,000/hour for F-106 test operations. After successful completion of these basic tests, we would move up to running the aircraft at 80,000 feet and Mach 3. We have 10 hours of flying planned for these 80K/M3 test flights. This test series will validate the basic MIPCC scheme for the RASCAL program.

RISK REDUCTION: *The successful completion of this test phase will reduce the risk that projected operational performance of the MIPCC system does not meet actual installed flight experience. It will provide real world validation of computer simulation models. To the degree the simulations are in error, it will allow for recalibration early in the development program, assuring that design assumptions can be met. It will further mitigate risks associated with cost of installing a flight qualified MIPCC system, system complexity questions and difficulty of use.*

This task can be accomplished for a total budget of **$1,056,000**. We designate this MIPCC Flight Test Phase 1 (**MIPCC FTP 1**).

2.4 MIPCC FTP 2 (MIPCC Flight Test Phase 2). The next goal of the flight test program will be to operate the MIPCC system at 100,000 feet and Mach 5. For this a Thermal Protection System (TPS) would be added to protect the airframe during hypersonic flight. We have budgeted $310,000 to add the necessary TPS (as discussed in Section 3.5 below) to the F-106 airframe. We would devote 20 hours of flight testing to this portion of the flight development program. During this phase we can also experiment with different expansion cones for the engine exit flow. Success in this flight regime will be a historic milestone in MIPCC technical development.

RISK REDUCTION: *This test phase will provide answers to several of the major questions of MIPCC propulsion: At what altitude and airspeed does the water injection cease to support engine combustion? At what point does afterburner combustion become unstable? What are the trade-offs in airspeed vs. altitude? What are the thrust curves? Incorrect assumptions in these flight regimes could have far-reaching negative consequences for the RASCAL program. The hard data from this flight test phase will significantly reduce that risk. Additionally, we can conduct Angle-of-Attack (AoA) tests to determine its effect MIPCC performance at these extreme altitudes and speeds.*

Finally, it will allow us to demonstrate early in the RASCAL program effective TPS techniques. We can gain experience with TPS durability, including sensitivity to rain and dust. This will reduce the risk that a RASCAL team will design in a TPS that does not work or is not operationally practical.

This would add an incremental cost of **$470,000** to the budget above. We designate this **MIPCC FTP 2**.

2.5 MIPCC FTP 3. A final option would be to add a simple peroxide Attitude Control System (ACS) to the F-106 airframe and use it to flight test the full RASCAL first stage exo-atmospheric ascent and decent profile. This will allow us to evaluate the MIPCC system during rapid changes in speed and altitude. We can also verify computer simulations of optimum ascent trajectories. This would be highly useful data for the RASCAL Phase II teams to use in their Critical Design studies.

This peroxide-based ACS installation will be performed by experienced HMX engineers and technicians, who designed and build the Roton ATV peroxide rocket engines similar to the ones used on the X-15 rocket plane. This installation with pitch and yaw nozzles in the nose and roll nozzles on the wings, is budgeted at $560,000. We would provide 30 hours of flight testing to perform these exo-atmospheric test flights.

This would add an incremental cost of **$800,000** to the budgets above. We designate this **MIPCC FTP 3** (MIPCC Flight Test Phase 3 Exo-atmospheric).

RISK REDUCTION: The operation of a MIPCC system during rapid changes in speed, altitude, angle-of-attack and throttle settings will be difficult to simulate in a ground-based test cell. To the degree that a particular performance point can be simulated in a test cell, this final test phase, as well as the previous test flight phases, will provide a model for demonstrating how to successfully extrapolate test cell data to an operational flight system. Successful demonstration of exo-atmospheric operation over this dynamic flight regime will reduce the risk that there are unknown limitations to utilizing MIPCC technology in this way.

In summary:

MIPCC FTP1	$1,056,000 (minimum required to replicate AEDC)
MIPCC FTP2	$470,000
MIPCC FTP 3	$800,000

If DARPA were to exercise all of the MIPCC Flight Test options proposed here, the total budget would be **$2,326,000.**

Once we have our MIPCC F-106 flying testbed in operation, it will also be possible to explore flight testing the effects of injecting LAIR or LOX into the afterburner. RASCAL Phase II contractors may also wish to use these MIPCC equipped F-106 flying testbeds to test selected technologies they will need for their RASCAL systems in avionics, TPS, ACS and MIPCC thrust augmentation.

The existence of a test aircraft capable of Mach 5 flight and exo-atmospheric operation will be a resource that is likely to find uses in other related Air Force, Navy and NASA research programs. DARPA's development of this flying laboratory will not only benefit its RASCAL program by reducing numerous technical risks in that project, but may be the enabler of numerous new technology developments in other branches of the DoD, which is part of DARPA's mission.

3.0 Selection of the F-106 as Testbed. While several high performance aircraft could conceivably be used for different portions of the proposed project, we believe that the F-106 has a number of unique advantages that make it the optimal aircraft to carry out all portions of this MIPCC flight test program.

3.1 Payload Bay. The F-106 has a large internal payload bay, measuring 16 feet in length, 55 inches in width and 32 inches in depth. This large space can be used to hold water tanks, liquid air tanks, LOX tanks, pumps, plumbing, and instrumentation. The payload bay is located directly under the inlet area of the F-106, where we will add the MIPCC spray rings and nozzles. The F-106 has ample room between its J-75 turbojet engine and airframe to facilitate the addition of LOX lines (or liquid air or N2O) feeding back to the afterburner.

3.2 Inlet Cooling. The inlets on the F-106 are air-cooled. Bleed air from the engine compressor is piped to the two inlets, where it escapes out multiple small holes in the inlet surface, keeping the inlet cool. This feature will greatly facilitate our high Mach test flights.

3.3 Diffuser Length. The F-106 inlet diffuser is almost 12 feet in total length. This gives us a considerable area in which to place the MIPCC injection system, allowing us to explore optimum spray ring and nozzle installation. The twin inlets ducts converge into a single duct 45 inches in front of the engine compressor.

3.4 Convergent/Divergent Exit Nozzle and J-75 Jet Engine. The F-106 is one of the few jets that have a convergent-divergent exit nozzle. We know from the MIPCC literature that if we can fully expand the exit flow from a MIPCC equipped engine operating at altitude, an additional

10% increase in thrust can be obtained. The F-106 is ready to be fitted with different sized expansion cones to test the benefits of adding this configuration.

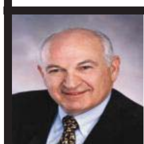
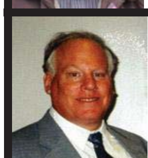
The F-106 J-75 engine is stainless steel throughout. It has a reputation as a very rugged engine. Modern jet engines use more “advanced” materials such as titanium compressor blades, which may be more sensitive to the injected fluid. The stainless steel J-75 will give us the widest range of permissible liquids and operating conditions to test in.

We know from several F-106 pilots that they flew the aircraft on “unofficial” zoom flights to 85,000 feet and they report that the standard J-75 maintained thrust throughout the flight profile. With MIPCC augmentation, it will clearly go higher.

3.5 Thermal Protection. To conduct flight tests of our MIPCC system at Mach 4 to 5, it will be necessary to have our test aircraft equipped with a TPS to protect against aerodynamic heating. At Mach 3 plus, it will be necessary to upgrade the aircraft’s windshield transparencies. The F-106 already has a classic wedge-shaped windshield designed for high Mach flight., so it will be a straightforward job to install new high temp transparency plates into the existing windshield frames.

Another area of heating, if we wish to push the MIPCC tests out to Mach 4 to 5, will be the leading edges of the wings. The F-106 uses rolled aluminum sheet that is folded and formed to make the leading edge of the wing. It will be a simple operation to unscrew this from the wing and replace it with formed high temp stainless steel or even titanium. Other potential hot spots will be protected accordingly.

3.0 Key Personnel. Destiny has an experienced F-106 flight test team in place to accomplish this program. Each possesses the necessary management, engineering, flight-testing or F-106 experience to successfully execute this proposal.

	**Tony Materna, MIPCC F-106 Flight Test Program Manager** • 20 years of engineering management experience • 7 years of test instrumentation expertise • Former USAF pilot, NORAD
	**Marshall Kaplan, Ph.D., Chief Engineer** • 30+ years of hypersonic vehicle experience • Chief engineer on expendable and reusable launch vehicles • Instrument-rated pilot with 3,600 hours flight experience
	**Mark Stucky, Director of Flight Operations and Testing** • Experimental test pilot, USAF, NASA • 4000+ hours in fighter aircraft, including F-16, F-18, SR-71, F-106 • Chief Test Pilot on NASA F-106 Eclipse Tow Program
	**Joseph Sylvia, F-106 O&M and Modifications** • 40+ years of aircraft A&P experience • 23 years as F-106 O&M manager • F-106 ground instructor for test pilots
	**David Pine, Director of Cost Modeling** • 26 years of government aerospace program management • Dir. of Systems and Cost Analysis at NASA HQ • Selected to rebuild NASA’s independent cost estimating

Joe Fromme, Weights and Mass Balance Analysis

- 35+ years of aerospace project engineering
- Expert on mass balance and dynamics
- Experimental aerodynamicist

Cost Proposal