Preliminary MIPCC-Enhanced F-4 and F-15 Performance Characteristics for a First-Stage Reusable Launch Vehicle

Kurt J. Kloesel,[1] Casie M. Clark[2]
NASA Dryden Flight Research Center, Edwards, California, 93523

Performance increases in turbojet engines can theoretically be achieved through Mass Injection Pre-Compressor Cooling (MIPCC), a process involving injecting water or oxidizer or both into an afterburning turbojet engine. The injection of water results in pre-compressor cooling, allowing the propulsion system to operate at high altitudes and Mach numbers. In this way, a MIPCC-enhanced turbojet engine could be used to power the first stage of a reusable launch vehicle or be integrated into an existing aircraft that could launch a 100-lbm payload to a reference 100-nm altitude orbit at 28 deg inclination. The two possible candidates for MIPCC flight demonstration that are evaluated in this study are the F-4 Phantom II airplane and the F-15 Eagle airplane (both of McDonnell Douglas, now The Boeing Company, Chicago, Illinois), powered by two General Electric Company (Fairfield, Connecticut) J79 engines and two Pratt & Whitney (East Hartford, Connecticut) F100-PW-100 engines, respectively. This paper presents a conceptual discussion of the theoretical performance of each of these aircraft using MIPCC propulsion techniques. Trajectory studies were completed with the Optimal Trajectories by Implicit Simulation (OTIS) software (NASA Glenn Research Center, Cleveland, Ohio) for a standard F-4 airplane and a standard F-15 airplane. Standard aircraft simulation models were constructed, and the thrust in each was altered in accordance with estimated MIPCC performance characteristics. The MIPCC and production aircraft model results were then reviewed to assess the feasibility of a MIPCC-enhanced propulsion system for use as a first-stage reusable launch vehicle; it was determined that the MIPCC-enhanced F-15 model showed a significant performance advantage over the MIPCC-enhanced F-4 model.

Nomenclature

C_D = coefficient of drag
C_{D0} = parasitic drag coefficient
C_L = coefficient of lift
I_{sp} = specific impulse
LEO = low Earth orbit
LOX = liquid oxygen
lbf = pound-force
lbm = pound-mass
M = Mach number
MIPCC = Mass Injection Pre-Compressor Cooling
NASA = National Aeronautics and Space Administration
OTIS = Optimal Trajectories by Implicit Simulation
P_s = specific power, Btu/lbm
RASCAL = Responsive Access Small Cargo Affordable Launch Program
3DOF+ = three degrees of freedom plus a pitch rotation
α = angle of attack, deg
$\eta(M)$ = compressibility drag coefficient as a function of Mach number

[1] Engineer, Code RA, P.O. Box 273, Edwards, California, AIAA nonmember.
[2] Student Intern, Code RA, P.O. Box 273, Edwards, California, AIAA nonmember.

I. Introduction

IN an effort to place more emphasis on the commercialization of space, the National Aeronautics and Space Administration (NASA) Office of the Chief Technologist (OCT) was re-formulated in February 2010. The NASA OCT has several responsibilities, including an over-arching program of three central components: 1) Early Stage Innovation; 2) Game Changing Technology; and 3) Crosscutting Capability Demonstrations. A sub-component of the Crosscutting Capability Demonstrations component, the Technology Demonstration Missions, with an associated potential funding level of $150M, was viewed as a potential opportunity to create a flight-test program.

A NASA Technology Demonstrator Mission combined with portions of a former Defense Advanced Research Projects Agency (DARPA) (Arlington, Virginia) program, that is, the Responsive Access Small Cargo Affordable Launch (RASCAL) program, could be developed into a viable program. The RASCAL program had investigated using Mass Injection Pre-Compressor Cooling (MIPCC) as a way of reducing the costs of access to space.[1] The DARPA MIPCC conducted ground tests on F100 engines with results that appeared promising, however, because of a reduction in funding the RASCAL program was minimized in 2006 and the subsequent design and construction of an airframe slowed to a halt. Since some MIPCC studies had been performed by General Dynamics in the 1970s (under the program name "Peace Jack"), it was considered possible to resume a MIPCC effort using an existing form of the F-4 Phantom II airplane - a supersonic remotely-piloted target drone designated the QF-4X.[2, 3] A performance examination of the potential use of a MIPCC-powered F-15 Eagle as a viable alternative to the F-4 airplane for a reusable first-stage launch test vehicle was practical, because the NASA Dryden Flight Research Center (Edwards, California) had three F-15 airplanes used specifically for flight research.

A. Mass Injection Pre-Compressor Cooling (MIPCC)

Aircraft performance at high altitudes and Mach numbers is constrained in part by materials heating limits and by decreased mass flow into the engine because of the thinning atmosphere. Mass Injection Pre-Compressor Cooling is a technique designed to mitigate these problems and provide increased propulsion capability. Engines utilizing an integrated MIPCC system, called MIPCC engines, contain a stage that injects a coolant, often a pre-determined fraction of water and liquid oxygen (LOX), into the engine at high performance points. Theoretically, the coolant effectively cools the compressor face, alleviating the high temperatures, and provides increased mass flow to the engine, which allows the engine to maintain moderate thrust levels at high altitudes. Previous analytical and ground-test studies have been conducted that evaluated the effectiveness of a MIPCC-based propulsion system. Those studies produced favorable results that lent credence to the MIPCC theory. In the present study, a MIPCC propulsion system was added to standard F-4 and F-15 aircraft simulation models and the resulting trajectories were evaluated using software tools. The F-4 and F-15 propulsion, aerodynamic, and vehicle data were compiled and input into the Optimal Trajectories by Implicit Simulation (OTIS) software program. Constraints such as initial velocity and weight were then defined and the outputs compared to published flight data as a means to verify the models. Once it was determined that the models were valid representations of the capability of the aircraft, the standard propulsion systems were altered based on theoretical MIPCC characteristics provided in a previous study.[4]

No attempt is made to evaluate the theoretical physics behind MIPCC performance improvement when compared to a traditional turbojet engine; previous MIPCC research results were used to alter the production F-4 and F-15 engine models.4 The goals of this paper are to: 1) evaluate the theoretical performance of the F-4 and F-15 aircraft with the addition of a MIPCC propulsion system; 2) discuss the feasibility of a MIPCC-enhanced F-4 or F-15 airplane serving as a launch platform to propel a payload to low Earth orbit (LEO); and 3) provide a recommendation of either the F-4 airplane or the F-15 airplane as the best candidate for a MIPCC project, from both a capabilities and a programmatic standpoint.

II. OTIS Modeling Thrust and Aerodynamics

Analysis was completed with the OTIS software, which is a tool used to perform trajectory studies. The OTIS software is written in the C computer language and is designed to optimize the trajectory of vehicles that are designated by the user. Vehicles examined in this study were approximated as a point mass in a simulation environment of three degrees of freedom plus a pitch rotation (3DOF+).[5]

A. Limitations of the OTIS Analysis

A primary limitation of the OTIS analysis is the extent of angle of attack traverses on the endpoints. The angle of attack, α, is an OTIS control variable and is allowed from +57 deg to -57 deg. An examination of a typical OTIS optimized trajectory shows that α is at these angles on the endpoints but quickly moves to 3 deg within a few seconds of the simulation. Flight at an angle of attack of of 57 deg is not an attitude that minimizes drag, however, therefore, 57 deg is an impractical angle for consideration and the performance loss due to these endpoint transitions is considered insignificant. As well, any trajectories that extend above 88,000 ft are linearly extrapolated by OTIS. In the test cases, the final conditions are limited in Mach number and altitude; some trajectories extend above 88,000 ft, but the effect is minimal. The limitations of the MIPCC engine analysis are discussed below.

III. The F-15 Eagle Airplane

The F-15 Eagle airplane is a twin-engine jet airplane designed by McDonnell Douglas for the air superiority role. A typical F-15 airplane has an empty weight of 28,000 lbm, a fueled weight of 41,455 lbm, and a final loaded weight of 44,500 lbm. There have been many versions of the F-15 airplane; the various versions utilize Pratt & Whitney F100-PW-100, -220, or -229 engines. Specifically, the F-15A airplane examined in this study uses two Pratt & Whitney F100-PW-100 engines, each with 25,000 lbm sea-level afterburner thrust. Engine data for these engines were obtained from the Pratt and Whitney Status Engine Estimated Steady State Performance Deck.[6]

A. The F-15A Streak Eagle Minimum Time to Climb

In 1975, the project given the name Streak Eagle was initiated and the F-15A airplane of serial number 72-0119 was altered to achieve a new goal: break the world's time-to-climb records held by the F-4B airplane and the MiG-25 (Mikoyan-Gurevich bureau, Soviet Union) airplane. Pilots Majors Willard R. Macfarlane, David W. Petersen, and Roger J. Smith broke eight time-to-climb world records with the Streak Eagle, culminating in an altitude of 98,425 ft in 3 min 27.8 s between January 16, 1975 and February 1, 1975.[7, 8] The eight record-breaking flights are detailed in Table 1.

Table 1. The F-15 Streak Eagle time-to-climb world-record-breaking flights.

Altitude (ft)	Time, (sec)
9,842.52	27.57
19,685.04	39.33
29,527.56	48.86
39,370.08	59.38
49,212.60	77.02
65,616.80	122.94
82,021.00	161.02
98,425.20	207.80

In order to achieve these high performance goals, the F-15A Streak Eagle was equipped with essential systems only, rendering the airplane 2800 lbms lighter than a production F-15A airplane.[9] The Streak Eagle was powered by two Pratt & Whitney F100-PW-100 engines (culled optimal F100-PW-100s), each with an approximated sea-level static thrust of 25,000 lb. The Streak Eagle was produced early in the F-15 airplane series, and was retired to the National Museum of the United States Air Force in December 1980.[7] The F-15A Streak Eagle airplane is shown in Fig. 1.

Figure 1. The F-15A Streak Eagle airplane.

B. The F-15A Steak Eagle Engine Thrust and Aerodynamics

The Streak Eagle airplane was a modified F-15A high-performance airplane capable of attaining altitudes of up to 103,000 ft and speeds in excess of Mach 2.0. The Streak Eagle data available were in the form of minimum-time-to-climb graphs, and, as such, thrust and specific impulse (I_{sp}) at maximum power level setting over a wide range of altitudes were needed in order to properly compare the Streak Eagle flight data with the outputs from the OTIS software. Thus, engine data were extracted from the performance deck for altitudes ranging between 0 and 87,000 ft at a maximum power level setting of 127. As well, each altitude was evaluated over Mach numbers ranging from 0.2 to 2.4. The resulting thrust and I_{sp} data were then formatted to the OTIS input specifications and placed in a data file external to the main input file.

The coefficient of lift, C_L , and of drag, C_D , were obtained from flight-test data presented in graphs provided in a paper by Haering and Burcham[10] for a range of Mach numbers and altitudes. These data were extracted using a scanning program, and a regression was then performed on the C_L versus α data to obtain values for the slopes in the linear regions for each Mach number. Each parasitic drag coefficient, C_{D0} , was determined for the range of Mach numbers by identifying the C_D at 0 deg α. The extracted data were then formatted and placed in the same file as the engine thrust and I_{sp} values.

C. F-15A Streak Eagle Model Validation

The OTIS model described above was run for endpoint altitudes of 49,212 ft; 65,616 ft; 82,021 ft; and 98,425 ft, and the output data generated were compared with McDonnell-Douglas data. As seen in Fig. 2, the OTIS model approximates the data at each point, with the closest correlation occurring above 30,000 ft.

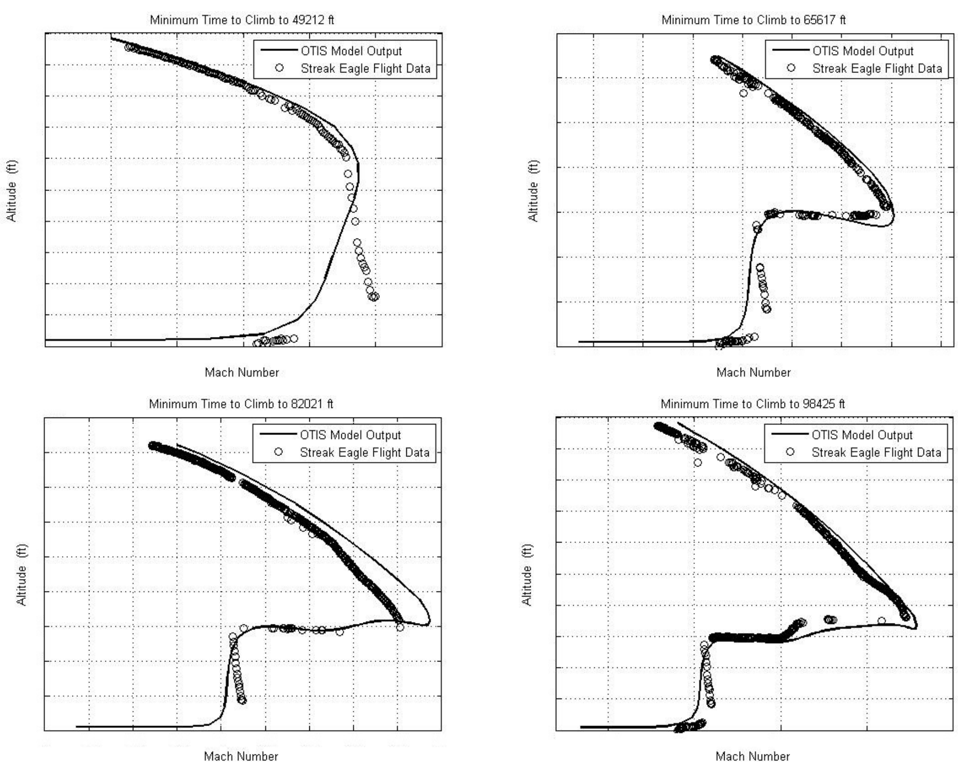


Figure 2. The minimum time to climb curves for the F-15A Streak Eagle OTIS software model and McDonnell-Douglas data. [9]

D. Developing a Model for the F-15A Eagle Airplane

The authors developed a working base model of the F-15A Eagle in OTIS. Initial conditions were supplied for a 3DOF+ system, which included inputs for the velocity, heading angle, altitude, longitude, latitude, and weight. Final conditions were also input as a first estimate to be used in the optimization process.

Conditions for the altitude, flight path angle, and final Mach number were also fixed to promote realistic outputs from OTIS. The altitude ceiling was set at 100,000 ft and the flight path angle was allowed to vary from +57 deg to -57 deg. A target Mach number was provided, along with upper and lower bounds based on previous flight-test data for each test condition.

The C_L and C_D are both functions of the lift curve slope, so the α was constrained to the linear region of the lift curve for each Mach number case run. The compressibility drag, $\eta(M)$, was assumed to be unity and thereby providing a more conservative estimate of the total drag in the subsonic regions. Along with aerodynamic specifications, two engines were specified and the appropriate code was written to reference thrust and I_{sp} data for a range of altitudes and Mach numbers. The lift curve slope and parasitic drag coefficient, C_{D0} , data needed to calculate C_L and C_D , and propulsion thrust and I_{sp} data were created in a tabular file and provided as input to the program.

IV. The F-4 Phantom II

The McDonnell Douglas F-4 Phantom II airplane is an in-line two-seat, air-superiority fighter with two General Electric Company J79 afterburning turbojet engines. The F-4 Phantom II airplane was the primary fighter-bomber airplane in the U.S. Air Force throughout the 1960s and 1970s. These F-4 aircraft also flew reconnaissance and anti-aircraft suppression missions (electronic jamming). A total of 5,195 F-4 Phantom II aircraft were built between 1958 and 1979. The F-4 Phantom II airplane has a top speed of over Mach 2.23, an empty weight of 30,328 lbm and a loaded weight of 41,500 lbm with a service ceiling of 60,000 ft. The main source of data was the F-4C airplane variant with two J79-GE-15 engines which can each deliver approximately 17,500 lbf of afterburning thrust. An F-4 Phantom II is shown in Fig. 3.

Figure 3. The F-4 Phantom II airplane at the NASA Dryden Flight Test Center, showing the flow observation tufts installed on the wings as part of the stall characteristics study.[22]

A. F-4 Phantom II Engine Thrust and Aerodynamics

The validity of the F-4 airplane simulation model was demonstrated by comparing it with the world time-to-climb records set during Operation High Jump in 1962.[11] Several simulations were performed and compared to the world records. The historic records indicate that a F-4H-1B airplane was used to set these records. There is no publicly available documentation regarding the modifications made to this F-4H-1B airplane used, but it is likely that in order to set the world altitude records, everything that was non-essential was removed from the aircraft (that is, radar systems and combat systems) and the airplane was tailored to reduce the aerodynamic drag as much as possible. The production F-4-E airplane has a dry weight of 30,328 lbm, whereas the F-4H-1B airplane has a dry weight of 28,000 lbm. A sweep of initial simulation weights (5,000 lbm per sweep step) indicated that a dry weight of between 20,000 lbm and 25,000 lbm would place the simulation in the range of the actual record. These simulations were initially performed with unmodified simulation sample files; these are labeled “original simulation” in Table 2. It is understandable that the ground crews would have gone to great lengths, similar to those in the Streak Eagle case, to reduce the weight of the airplane. It is possible that the removed weight was in the range of 2000-5000 lbm. As well, the F-4H-1B airplane used J79-GE-8A engines, which are rated at 17,000 lbf at maxium afterburner.[12]

Table 2. The F-4 Phantom II airplane simulation results compared to 1962 records.

Altitude (ft)	Record (sec)	|%| Difference Original Simulation	|%| Difference Reweighed F-4
9,840	34.523	36	4.1
19,700	48.787	30	2.4
29,500	61.629	30.7	2.1
39,400	77.156	36.2	4.7
49,200	114.548	33.4	3.7
65,600	178.5	37.8	0.8
82,000	230.44	41.3	1.09
98,400	371.43	N/A	3.7

B. F-4 Phantom II Minimum Time to Climb

Articles regarding the mathematics of supersonic minimum time-to-climb profiles began to appear circa 1954[13] and Bryson et. al. published climb profiles in 1962 and 1969.[14, 15] Although these methods and numbers could not be directly associated with the F-4 aircraft, in a review published by Bryson in 1994 the caption under the climb profile states that the airplane used is an F-4.[16] Other sources include the F-4 test cases that are supplied with the simulation software distribution. Figure 4 shows a comparison of these profiles, indicating that the 1994 Bryson climb profile is very similar to the OTIS simulation software example cases. In addition, using Mattingly's AEDsys software[17] with figures of 0.78 wing loading and 0.89 thrust-to-weight ratio, the specific power (P_s) energy curves indicate that the zoom dash occurs at approximately 30,000 ft, which is consistent with the Bryson numbers. The added height on the supersonic dive typically indicates some differences in thrust or drag in the transonic regime.

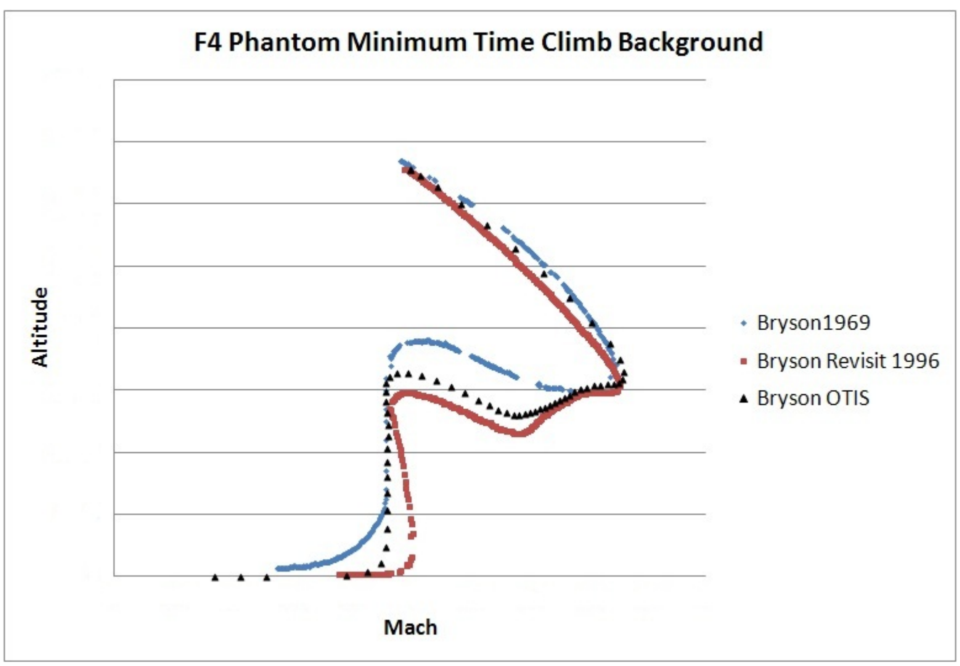


Figure 4. A comparison of F-4 Phantom II airplane minimum time to climb trajectory profiles.

C. F-4 Phantom II Model Validation

The original simulation F-4 example was initially set to 42,000 lbm and a starting velocity of 200 ft/s. The simulation results indicated that a reduced initial weight appeared to provide a reasonable solution. Simulation solutions were considered valid when the implicit solution matched the explicit solution. The lines of constant specific energy presented on the graph were generated from the same aerodynamics/thrust database that calculates the optimum trajectory.

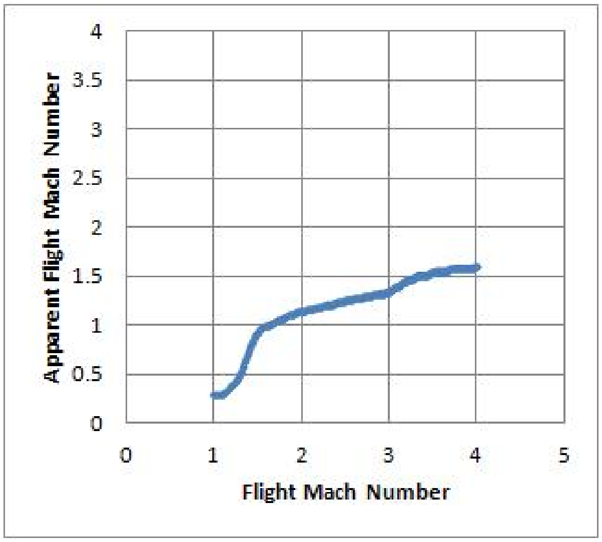
V. MIPCC-Enhanced F-4 and F-15 Capabilities

Previous analysis indicates that a MIPCC-enhanced vehicle would be capable of reaching a specific energy state of 420.2 Btu/lb-m.[4, 18] The F-4 and F-15 simulations were modified to simulate the MIPCC enhancements. Original maximum specific energy state optimizations were then performed again with the goal in mind of reaching these specific energy states.

A. MIPCC Thrust and Isp Models

Trajectory modeling typically employs tabular engine performance data that are presented in the form of thrust as a function of Mach number and altitude. Tabular modeling data can also include thrust as a function of throttle setting, but in the present modeling effort the engines were assumed to be operating at full afterburning thrust. A typical turbojet data-set will show the thrust diminishing as the altitude increases, but the afterburning thrust will increase with Mach number. The increase with Mach number cannot continue indefinitely, as the turbomachinery eventually reaches materials temperature limits and other physical limitations caused by supersonic flight. A MIPCC-enhanced engine will extend this envelope in both Mach number and altitude. The Mach number performance extension occurs as a result of direct cooling of the inlet air as a result of the injection of water or LOX or both; thus, the engine operates at an apparent Mach number that is lower than the actual flight Mach number. A similar argument holds for the altitude limitations: the injected water serves a function similar to that of the inert nitrogen present in the air, and provides the additional mass flow at the air-starved higher altitudes, causing the engine to experience an apparent altitude that is lower than the actual altitude. At higher altitudes, the LOX injection provides the appropriate amount of oxidizer to maintain adequate burning. The original engine performance tables can be modified by the use of apparent Mach numbers and altitudes.

Thrust and fuel consumption curves were obtained, implemented, and tested as described above regarding the Streak Eagle and the F-4H-1B records. In order to convert this information to a MIPCC simulation, these data were transformed and scaled using the apparent altitude and Mach number graphs that appear in references 4 and 19. In this technique, the two graphs supplied in Fig. 5 were used to extend the engine models. Using existing thrust numbers and I_{sp} numbers of Mach number and altitude, the tables are then filled applying a one-to-one correspondence with the apparent Mach number and altitude up to the new Mach number and altitude limits. The application of the MIPCC translational graphs is far from exact, and due to the lack of availability of actual test data on both MIPCC J-79 engines and F100-PW-100 engines, this analysis represents the first order of magnitude of approximation. The MIPCC scaling graphs were chosen because they allowed the most convenient and straightforward method to provide a preliminary result without exhaustive engine modeling. It is left for future studies to refine these details. The MIPCC impact on the I_{sp} was modeled using the additional water and LOX massflow graphs shown in the references (not shown in Fig. 5) where the I_{sp} decreases as a result of the additional massflow.[18, 19] Additional detail on the F-4 airplane was added by using thrust and fuel flow measurements obtained from flight-test reports.[20] The F-4 flight-test data were linearized as needed to extend the tables in the subsonic regions. In this simulation, the F-4C airplane was reasoned to be the more likely final candidate due to its availability, as opposed to the F-4E airplane, which is still seeing limited service in countries outside the United States. This change reduces the available thrust due to the difference in the J79-15 and J79-17A engines by approximately 500 lbf at sea level. It is noted that the additional drag due to external stores can alter the performance results by up to approximately 15 percent, depending on the aerodynamic shaping and positioning of the store.[21]



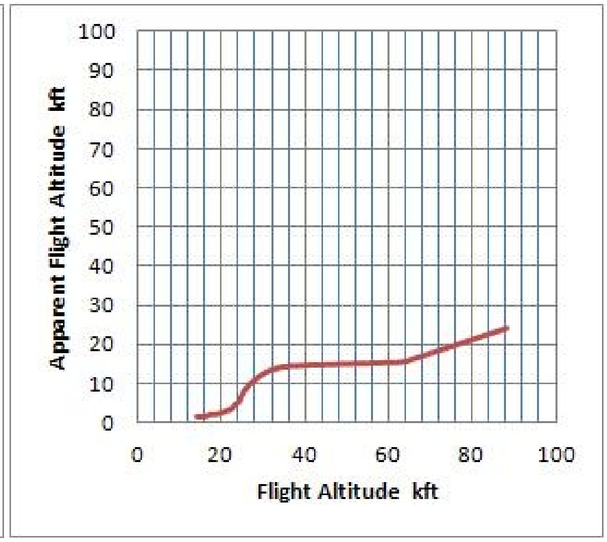


Figure 5. Flight Mach number versus apparent flight Mach number; and flight altitude versus apparent flight altitude.[4]

B. MIPCC Capabilities and Comparison Assessment

The traditional use of the specific excess power curves (P_s) and related variants (specific excess fuel consumption) are used to graphically determine the minimum time-to-climb and fuel-to-climb optimized paths. The OTIS software can generate these trajectories and allows for the direct input of lift, drag, and thrust tables with multiple dependencies and user-customized dependencies, that are not necessarily directed at the design of the modern jet airplane of fixed configurations. The use of these curves in conjunction with OTIS allows the user to compare the generated paths directly with known P_s graphs to gain a deeper insight into the nature of the optimized path. The lines of constant specific energy presented in this paper were generated from the same aerodynamics/thrust database that calculates the optimum trajectory. The input deck was changed to explicit mode only and allowed to fly for 0.50 s and scanned over the altitude and Mach number to provide lines of constant specific energy. This technique was applied to all of the graphs contained herein to generate the contours of constant specific energy. As a side note, this research has identified a capability of the OTIS software that provides an automatic generation of a family of specific excess power curves to allow rapid visualization of trajectory senarios. The method presented herein demonstrates that the contours of constant P_s can be directly generated from the OTIS software database and allows OTIS to perform any spline fitting of the tabular input data to complete the contours. The application of the OTIS-generated P_s contours elucidates the nature of the aerodynamic lifting combined-cycle access-to-space discussion.

C. The F-4 MIPCC and F-15 MIPCC Specific Excess Power Contours

In the case of the application of this technique to MIPCC-enhanced turbomachinery, the P_s contours produced beyond Mach 1 begin to significantly deviate from the traditional turbomachinery plus drag contours. An example is shown in Fig. 4, and leads to the question of whether these computer-generated curves are indeed a valid representation of the examined system. In a traditional set of P_s contours, the $P_s = 0$ bounds the upper high-altitude regions because typical air-breathing turbomachinery becomes starved for air and because of the diminishing thrust related to the engine design that cannot accommodate hypersonic propulsion. In order to better understand these curves, the F-15 model with the associated drag and lift was converted to an all-rocket form, that is, the turbomachinery tables for the F100-PW-100 engine were replaced with rockets that had a fixed I_{sp} of 300 s and a fixed thrust of 30,000 lbf. The P_s contours that were generated for the all-rocket F-15 airplane are depicted in Fig. 6. The all-rocket F-15 airplane demonstrates P_s contours that incorporate drag when the thrust has little or no dependency on altitude or Mach number. In this case, the lines of constant P_s contours increase in the high-altitude supersonic region as the graph is traversed from left to right, so as the all-rocket F-15 airplane achieves a greater altitude and speed, the numerator in the excess power equation diminishes because of thinner atmosphere; this increase is not offset by the increase in dynamic pressure.[13] This region, approximated by the lower boundaries of an altitude of 40,000 ft and a speed of Mach 1.5 is designated herein as the “mimic rocket P_s region.” As the vehicle speed increases at lower altitudes, the vehicle encounters the $P_s = 0$ limits as the numerator drag increases as a result of higher dynamic pressures. An examination of the MIPCC-enhanced turbomachinery P_s contours demonstrates that the propulsion system becomes more rocket-like in its system function as the engines are supplemented by the on-board water and LOX. Thus, MIPCC is an inexpensive combined-cycle technology that can bypass the creation of a new combined-cycle engine technology that would be an order of magnitude higher in cost.

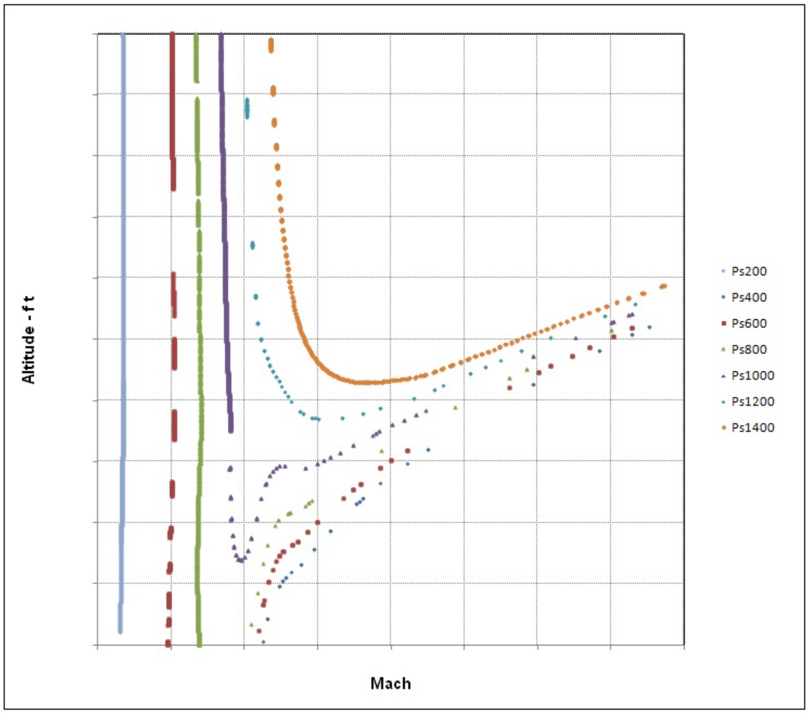


Figure 6. The P_s specific excess power contours for the all-rocket F-15 airplane.

The minimum fuel climb trajectories for the F-4 MIPCC and the F-15 MIPCC enhancements highlight some interesting similarities and differences. Figures 7 and 8 show the rocket-like transition of increasing lines of constant P_s at higher-altitude supersonic conditions. These figures also show the typical low-altitude supersonic limitations due to the increase in dynamic pressure. A striking difference, however, occurs as the vehicles attempt to penetrate the supersonic barrier. This difference is directly related to the generational technology maturity.

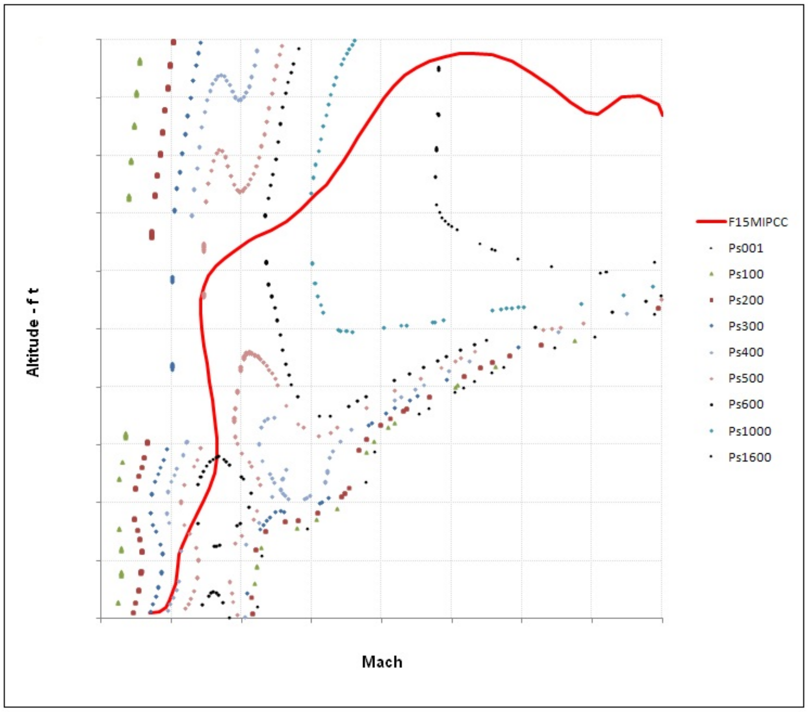


Figure 7. The specific excess power contours for the MIPCC-enhanced F-15 airplane.

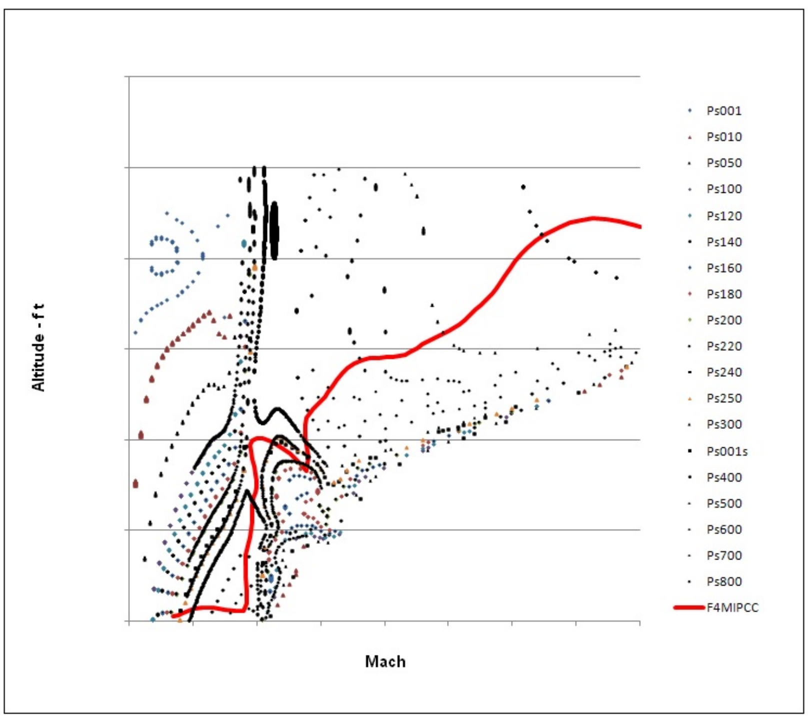


Figure 8. The specific excess power contours for the MIPCC-enhanced F-4 airplane.

At the heart of this matter are the thrust and drag characteristics of each airplane, as shown in the F-4 MIPCC-optimized trajectory, Fig. 8. The MIPCC-enhanced F-4 airplane must execute the classical

Rutowski-Bryson-Boyd transonic penetration dive, converting potential energy into kinetic energy before entering the mimic rocket P_s region.[13] The simulated MIPCC-enhanced F-15 airplane with the F100-PW-100 engines has enough thrust to climb to a higher altitude, and does not have to execute the transonic penetration dive in order to enter into the mimic rocket P_s region (Fig. 7). The useable payload is assumed to be the second stage of a rocket system that could possibly deliver a small payload to LEO.[21] The take-off weight of the simulated MIPCC-enhanced F-4 airplane is 47,000 lbm, while the take-off weight of the simulated MIPCC-enhanced F-15 airplane is 49,500 lbm. A key point of this study is that the F-15 airplane has a significant advantage over the F-4 airplane as the candidate for MIPCC conversion, because the MIPCC-enhanced F-15 airplane consumes less fuel and has more remaining capacity for return to base, as shown in Table 3 and Table 4. The weight designated as "fuel consumed" incorporates both water and LOX as a composite number which is formed from the I_{sp} numbers. One explanation is the difference in the thrust-to-drag ratios of the aircraft. Since the F-4 airplane has more drag, it has to execute a supersonic penetration dive and has to perform a lower-altitude supersonic climb, which consumes more energy. In addition, the MIPCC-enhanced F-4 airplane time to climb for a minimum fuel climb is longer. It is recognized that both aircraft would require other modifications to the airframe and inlets, and the limits of the stock F-4 and F-15 aircraft are approximately Mach 2.2 and Mach 2.5, respectively. Thus, the F-4 airplane has an inherent disadvantage from an overall systems design perspective. The F-15 airplane easily outperforms the F-4 airplane in delivering a usable payload to the desired conditions with a large margin of spare capacity for such considerations as fuel needed to return to base and added weight for cryogenic storage. From a programmatic viewpoint, given inevitable scope creep or weight creep, the F-15 airplane is a far better candidate for program success.

Table 3. The F-4 MIPCC and F-15 MIPCC optimized trajectory for a target specific energy of 274.66 Btu/lbm for clean configurations.

Description	F-4 MIPCC	F-15 MIPCC
Take-off Weight (lbm)	47,000	49,500
Remaining Fuel Capacity (lbm)	4,647	9,968

Table 4. The F-4 MIPCC and F-15 MIPCC optimized trajectory for a target specific energy of 420.01 Btu/lbm for clean configurations.

Description	F-4 MIPCC	F-15 MIPCC
Take-off Weight (lbm)	47,000	49,500
Remaining Fuel Capacity (lbm)	1,356	8,616

In the context of this paper, a usable payload is the ability to deliver 100 lbm to a 100 nautical mile altitude orbit at 28 degrees inclination from the two given specific energy states.

D. The F-15 MIPCC Drag Increment

The above analysis demonstrates theoretical capacities available for an airplane of clean configuration, that is, there are no stores hanging from the wings or underbelly of the aircraft. In actual practice, additional drag would be caused by a rocket or a water/LOX fuel tank that would need to be attached to the vehicle. A prediction of the induced drag increment requires the use of computational fluid dynamics (CFD) which is not in the scope of this paper. Thus, at this point it is enough to state that this exists and is not included in this analysis.[21]

VI. Conclusions

The Mass Injection Pre-Compressor Cooling (MIPCC) -enhanced F-4 Phantom II airplane and F-15 Eagle airplane (both of McDonnell Douglas, now The Boeing Company, Chicago Illinois) were evaluated using optimal trajectory techniques. It was determined that each of the two MIPCC-enhanced airplanes were capable of delivering a usable payload to 274.66 Btu/lbm and 420 Btu/lbm specific energy states in which a usable payload is defined as the ability to deliver 100 lbm to a 100-nm altitude orbit at 28 deg inclination. The MIPCC-enhanced F-15 airplane retains significant advantages in excess capacity, while the MIPCC-enhanced F-4 airplane has little excess, exposing it to more programmatic risks. The excess capacity of the MIPCC-enhanced F-15 can be translated into the weight of the fuel required to return to a landing strip; this advantage enhances the operational risk margin. The most important and unique conclusion of this paper is that the optimized climb trajectory of the MIPCC-enhanced F-15 airplane remains subsonic for altitudes well above 30,000 ft (up to approximately 65,000 ft) and thus provides more gravitational potential energy for a subsonic payload release. This capability provides an important advantage because the dynamics of supersonic store separation can become complex and consume additional project resources.

When considering air-launch first-stage reusable platforms, the MIPCC turbomachinery enhancement offers a more economical combined-cycle rocket-like performance improvement compared to developing a completely new combined propulsion program. This paper offers a preliminary investigation of MIPCC modifications to the F-4 airplane and the F-15 airplane; a thorough systems engineering study is required to formulate an advocacy initiative. More detailed studies would include an in-depth collection of existing MIPCC-related ground engine testing or thermodynamic engine cycle modeling or both. Additional trajectory and performance studies should include the drag due to the external rocket and any additional MIPCC hardware that changes the outer aircraft aerodynamic shape. The compression ramp inlet system on both the F-4 airplane and the F-15 airplane must be modified to accept MIPCC technology. A follow-on inlet study should provide analytical and/or computational fluid dynamic analysis that demonstrates that the water and liquid oxygen droplet size and phase change as they traverse the length of the relevant inlet system is sufficient to provide an effective MIPCC thrust enhancement. Mass Injection Pre-Compressor Cooling enhancement studies should also include MIPCC effects on inlet flow distortion and on the lifetime of the compressor blades.

The National Aeronautics and Space Administration (NASA) F-15 research aircraft offer the potential to perform flight-test development on first-stage useable launch vehicle programs. A NASA MIPCC-enhanced F-15 airplane offers a significant performance advantage over other available supersonic airframes.

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