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EARLY AEROSPACEPLANE PROPULSION RESEARCH; MARQUARDT CORP; ca 1956-63

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ABSTRACT

This is a brief summary of the very early days of Aerospaceplane propulsion and concept research, from a viewpoint based in the Astro Division of Marquardt Aircraft Company in the years listed, with some view into later times that were on Bill Escher's watch and other's. The following speakers will discuss other groups who were pursuing the same goals by various routes. Our chief purpose is to bring out background information that may be of value to members of this workshop and future workers in the field.

Many old reports have been amassed by Battelle, (Ref 1), but we notice that most of the earliest work in Marquardt Company Reports is omitted. (Some have since been supplied to Battelle, and are now in their files). Also several ICAS and AGARD proceedings which are not cited carried U.S. work to a world audience. And Swithenbank and others overseas also contributed to the field.

Organizations and People: There were three main groups (Figure 1) doing the engine research and conceptual work; Marquardt, APL/JHU, and GASL. Several companies were involved in engine development and production, and no less than seven major airframe companies were doing active design studies. There is not enough room here to even list the many people involved, but a few key players must be named. At APL there were Avery, Dugger, and Billig, who is with us today. At GASL, Tony Ferri, and SanLorenzo, who is here today. At Marquardt/ASTRO, some key people on our team were Carl Builder (my good right arm), Gene Perchonek, and Al Goldstein. There were also several staff specialists, such as Artur Mager, G.V. Roa, Paul Arthur, who assisted in such areas as hypersonic flow, external burning, heat transfer, equilibrium chemistry, etc. And Roy Marquardt himself, who knew how to draw together a team of rather wild horses and keep them aimed in useful directions.

Technology in Hand: The state of engine and airframe technology at those times must be understood to make sense of the effort (Figure 2). Operational kerosene fueled ramjets were routinely flying Mach 2-3 in the Bomarc and Talos interceptors. One Marquardt ramjet had accelerated a Lockheed X-7 test vehicle to about Mach 4.7 in an all-out test, holding it at nearly 1 "G" until the fuel ran out. But the recovered engine and airframe were badly overheated, and not reflyable. Titanium skins, carbon/carbon, and composites were not yet available. Engines used the heavier stainless steel, Inconel, and superalloys in high temperature parts. Ablation heat shields had been developed for Reentry Vehicles, but radiation cooling was still primitive.

Technology in Development: Prototype liquid hydrogen fueled ramjets with regenerative cooling were in development for Mach 6-8 operation. The inlet and exhaust nozzle area ratios of such engines were very high, and inlet starting and stability issues were not well understood. Internal heat transfer rates could exceed those of LH_2/LOX rockets, which were still under development. The total internal exposed area had to be minimized so that the total cooling load would not exceed the regenerative fuel cooling capacity. The resulting engine designs were unusual in appearance.

Ramjet Technology: Many related propulsion technology developments were under way at Marquardt and elsewhere (Figure 3). There were tests of many different ramjet fuels, including hydrogen, hydrocarbons, boron hydrides, pentaborane, tri-ethyl aluminum, tri-ethyl boron, boron and aluminum slurries, and powered metals. There were tests of both liquid propellant ramrockets (with Rocketdyne), and solid propellant ramrockets (with Thiokol). A rocket-convertible ramjet engine called the "Hyperjet" was proposed for Aerospaceplane use. Tests and analyses were begun of a rotary jet-bladed compressor, as proposed by Foa, with either rocket or LACE as a jet source. Propulsion and maneuvering by external free-stream burning was also analyzed and tested.

LACE-Related technology: The Liquid Air Cycle Engine was invented at Marquardt in 1958, causing great excitement. It was first proposed to the Admiral Radford Committee by Marquardt and Boeing for first stages of expendable space boosters. But we soon realized that the engine raised the possibility of a single stage reusable space booster with airplane-type operation, as first reported in 1959 (Ref 2).

During the following three years, the LACE concept combined with the Aerospaceplane concept led to a proliferation of engine and engine system inventions in which most of our group and many from other companies were caught up. The basic low weight and high thrust of the LACE were remarkable. But the engine used 6 to 8 times more fuel than the engine could burn. First there was Carl Builder's basic scheme to economize on the fuel, followed by several variations on the theme. Next, various engines were hybridized to it to usefully burn the excess fuel. A few of these were the Ramlace, Scramlace, Superlace, Nuclear LACE, Lace turborocket, and LACErocket. There were probably 50 to 100 variants examined.

The use of Slush hydrogen, a slurry of liquid and solid, was proposed to reduce the excess fuel use. It could be used or recycled to the tanks. Liquid air could be stored in low to medium Mach number flight, to be burned as oxidizer later, in rocket mode. The oxygen could be separated from the air, for storage without the nitrogen. Archie Gay and Bill Bond at General Dynamics /Convair seized upon this route very early in the effort, and exploited it to the limit.

Perhaps the most difficult problem we had was that in such a flurry of invention, it requires about a hundred times more manpower to do adequate design studies, weight analyses, performance analyses, and system trade-offs on each concept than it takes to invent it. Our efforts to manage this problem are discussed below.

Supersonic Combustion: Supersonic combustion in a detonation wave, with subsonic or transonic wave exit flow had been demonstrated in our labs and others. We felt that the resulting "shock" losses would be too great, and that for very high Mach number flight we must have combustion with supersonic exit flow, which we titled "Hypersonic Combustion", a name that never took. Our test people demonstrated the process. This reduced the estimated diffusion and combustion losses, so that analysis indicated we could exceed rocket propellant specific impulse to orbital speed and beyond.

This fed back immediately into our Aerospaceplane efforts, extending our sights beyond the Mach 6-10 maximum, to any speed that could be endured by the vehicle in the atmosphere.

Hardware and Testing: A large amount of experimental work was done to support these various proposals. Air liquefaction was demonstrated in 1960, using an Air Research heat exchanger, followed quickly by the addition of a rocket engine to burn the products. Supersonic combustion, of both internal and external burning types was demonstrated, using pebble bed heaters to attain full temperature simulation to about Mach 7+. Ramrocket mixing and combustion tests were run, using Rocketdyne rockets.

Scramjet for the X-15: A small Scramjet was designed and built for the X-15, starting in 1961. It was tested and flight ready about 1965. But a dummy engine was flight tested, and caused burn-off of part of the X-15 lower tail. Shortly after, the X-15 program ended.

Lace for the X-15: A detailed design also was made of a simple LACE engine for the X-15 vehicle. This machine would have had a thrust/weight ratio of about 25, and an I_{sp} of about 800 sec. By not crowding the state of the art, it could have bought us invaluable flight experience at a very modest price. Its was not built: one of our greatest regrets.

Computational Tools: Analyses of engine performance and weight, and system performance were the chief Achilles' heels of these efforts. It is easy to invent new engine and system concepts many times faster than they can be analyzed. Adequate analytical tools generally were not available. Where they were possible, the computer capacity was woefully inadequate. And each new Aerospace firm that entered the fray had to discover anew that their design and performance analysis tools were inadequate, and set about painfully upgrading. Marquardt kept ahead of the large and growing industry effort with a remarkably small team.

Simplified Cycle Analysis: Computers were too slow to do full thermodynamic property computations for equilibrium combustion gas mixtures in cycle analyses. Some of the constants involved were still under dispute. Perfect gas-based analyses became useless above Mach 3 to 4. Air and combustion gas mixture Mollier diagrams were being painstakingly calculated and drawn by Carl Builder and others, but their use was tedious.

Starting in 1957 we developed simplified methods of cycle analysis that could bridge across the supersonic and hypersonic regimes successfully. This required a change of focus from temperature, Mach number, and delta T, as used in transonic and supersonic analysis to the right parameters for hypersonic propulsion, which are enthalpy, flight velocity, and heat of combustion. The change of focus greatly clarified our thinking on new engine concepts.The only publications of these methods are Ref 3, and the Appendix of Ref 4.

Boost Effective Specific Impulse: The forced wedding of aircraft and rocket trained personnel in Aerospaceplane design caused (and still causes) great confusion. The two groups define fuel efficiency as specific impulse versus specific fuel consumption. They deal with gravity and drag differently. And they differ in emphasis on cruise versus acceleration. In our efforts to rationalize these opposing viewpoints, we always expressed air-breathing performance as specific impulse, and then applied system and trajectory-based gravity and drag corrections in such a way that air-breathing performance could be integrated, albeit numerically, in the conventional rocket performance equations.

$$I_{speff}(V) = I_{sp}(V)[1 - D/T - (W \sin\beta)/T] \qquad (1)$$

$$\ln(W_2/W_1) = -1/g \int dV / I_{speff}(V) \qquad (2)$$

This formulation allowed rapid graphical or numerical analyses of system performance. It was spot-checked, of course, against the full trajectory analyses of various aircraft firms, and not only gave sufficiently accurate results, but often found flaws in the more complex programs. It also led to a natural presentation form on semi-Log paper that gives physical understanding of various system and engine comparisons and relationships.

Vehicle Concepts:Because of the intimate integration of engine and vehicle performance, we found it necessary to do our own preliminary vehicle designs. To answer critics who said the required weight fractions were impossible, in 1959 we proposed a "Flying Air Mattress" type of pressurized thin shell structure that gave hope of reaching the required weight. The 1960 version of the "Mattress" is shown in Figure 4a.

The very low thrust coefficient of the scramjet above Mach 10 led to much controversy over whether the engines could be sized large enough to drive the vehicle. Figure 4b was our attempt 1960 to illustrate how to turn the vehicle into a "flying engine" that we contended could continue to a Mach number of 20 of higher. Heating and material problems were admittedly severe.

These drawings and models were displayed in discussions with various airframe design groups. They had some effect on industry concepts. They were also used as "strawman" configurations for engine and system performance comparisons in various in-house studies.

Rules of Thumb: While history may be interesting, or at least amusing, to review, its real value is found when you find information relevant to the present and the future. I have looked over this material for the advice most relevant to the RBCC workshop. My choice is a couple of rules of thumb (Figure 5) that led to what I used to call "Lindley's Law", a statement of semi-despair.

Dozens of times, we or other teams in the chase, came up with a brilliant new engine concept or system concept, that promised to give us the payload margin to insure a successful single stage to orbit. Always, when we ran the total system weight and performance to ground, a year or more later, weight increases and performance losses required by the new concept ate up the profit, and we ended up at slightly less than zero payload. Out of this sad experience were born the following conclusions:

1. All new and better air-breathing SSTO concepts will have a better I_{sp} and therefore deliver more total weight to orbit.

2. After extensive analysis, a vehicle weight increase and performance losses will be found that exactly offset the weight gain.

3, The final result for every promising new propulsion or vehicle system therefore will be exactly the same, namely:

PAYLOAD TO ORBIT EQUALS EXACTLY -1% OF GLOW

With the improvements of modern materials and thermal protection systems, the baseline may have moved up to +1% or +2%. But the basic principle that bright new ideas get ground down to equality as reality enters the analysis is still with us!

In the first analysis of an improved concept, we tend to gloss over "small"things that come back to haunt us; weight of air-breathing inlets, their variation with Mach number, effects of air-breathing trajectories on TPS weight, scale effects on weight fraction, fuel density effects on weight fraction, etc. It usually takes a great deal of analysis to find the "second order" effects that can make or break a new concept. Don't get too enthusiastic too soon!

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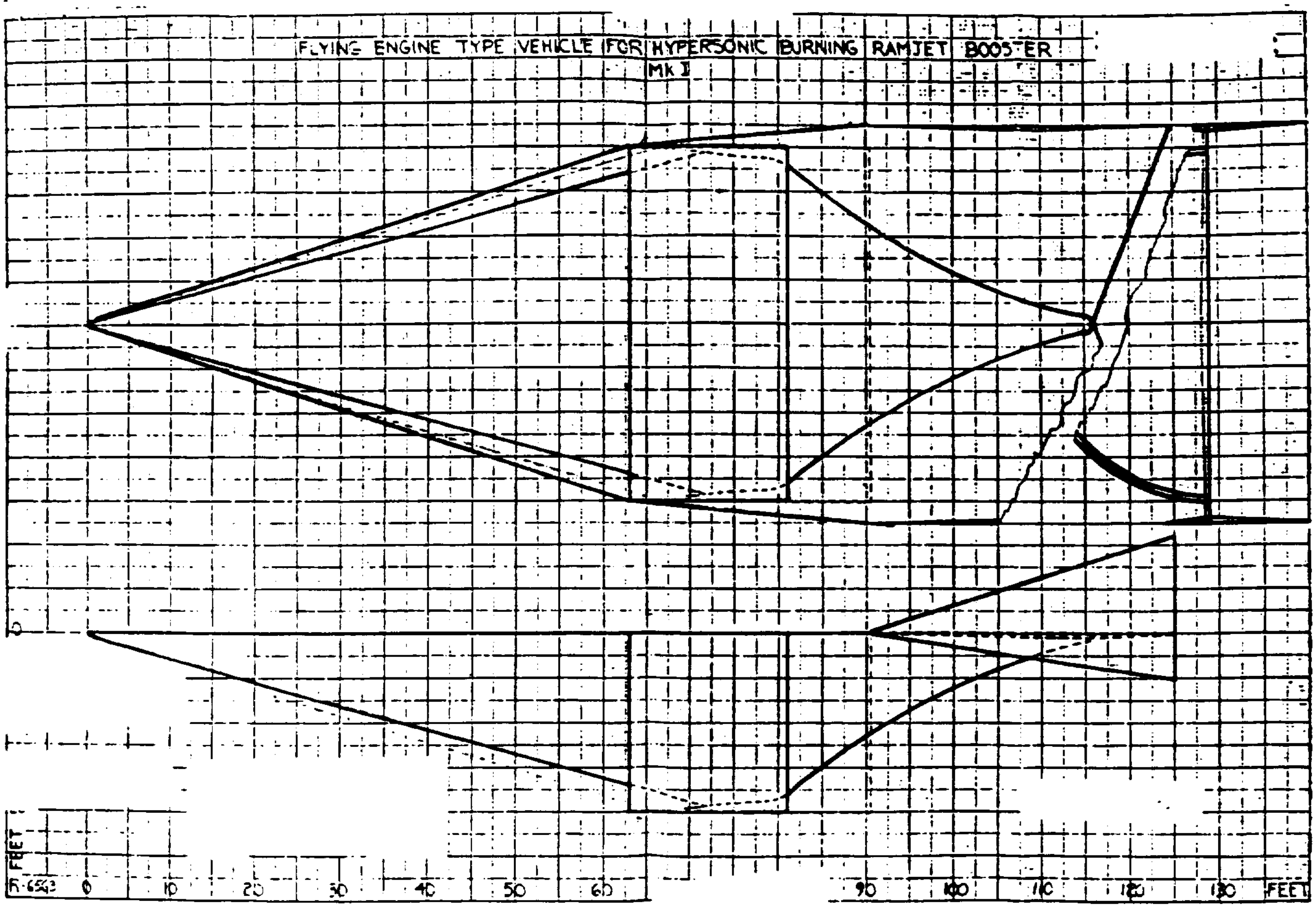

RULES OF THUMB

-COMPARED TO ROCKET POWER:

- ALL A/B TYPES WILL HAVE HIGHER I_{sp} OVER SOME SPEED RANGE
- A/B TYPES WILL DELIVER MORE WEIGHT TO ORBIT
- ALL A/B/TYPES WILL BE HEAVIER; THEREFORE:
- MOST OF THE EXTRA WEIGHT DELIVERED TO ORBIT WILL BE VEHICLE

LINDLEY'S LAW; 1962

-FOR ALL THE "BEST" A/B ENGINE TYPES YOU CAN INVENT, THE ORBITAL PAYLOAD WILL BE THE SAME, NAMELY -1% OF GLOW!

- AMENDMENT, 1975: MAKE THAT **0%**!
- AMENDMENT, 1990: MAKE THAT **+1%**!
- AMENDMENT, 1990: FOR ALTITUDE LAUNCH: MAKE THAT ~**+2%**!!

EARLY AIR-AUGMENTED ROCKET, RAMJET, SCRAMJET WORK

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APL/JHU

(Paper Not Received in Time for Printing)