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Marquardt's Mach 4.5 Supercharged Ejector Ramjet (SERJ) High-Performance Aircraft Engine Project: Unfulfilled Aspirations Ca.1970

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ABSTRACT

The Supercharged Ejector Ramjet (SERJ) engine developments of the 1960s, as pursued by The Marquardt Corporation and its associated industry team members, are described. In just three years, engineering work on this combined-cycle powerplant type evolved, from its initial NASA-sponsored reusable space transportation system study status, into a U.S. Air Force/Navy-supported exploratory development program as a candidate Mach 4.5 high-performance military aircraft engine. Bridging a productive transition from the spaceflight to the aviation arena, this case history supports the expectation that fully-integrated airbreathing/rocket propulsion systems hold high promise toward meeting the demanding propulsion requirements of tomorrow's aircraft-like *Spaceliner* class transportation systems. Lessons to be learned from this "SERJ Story" are offered for consideration by today's advanced space transportation and combined-cycle propulsion researchers and forward-planning communities.

AUTHORS' PERSPECTIVES

As active participants in NASA's advanced space transportation development field (see "Acknowledgments" section of the paper), the authors express some concern that the relevance of the engine development history related here, to such ongoing spaceflight activities, will not always be clear to the reader. After all, the propulsion application focus covered is high-performance military *aircraft,* not reusable space transports. A further concern we have is that, since the SERJ engine never evolved beyond its exploratory-development entry status -- no full-scale engines were ever built or flown -- this project may be viewed as an "also-ran" non-success, therefore, presumably one not contributing significantly to the advanced propulsion knowledge base.

But we believe otherwise. The fact that this engine, as a type (a combined-cycle airbreathing/rocket propulsion system), was tentatively accepted in its day as a real candidate aircraft powerplant by government and industry personnel "in the aviation business," is viewed as a major plus for the cause of spaceflight. NASA's announced *Spaceliner 100* technology-roadmap initiative firmly asks for a future "aircraft-like" space transportation system. Clearly, its highly-challenging flight-safety, operational-dependability and ticket-price affordability goals, strongly urge a full understanding and informed emulation of the larger aviation experience.

Addressing our second concern, the fact that this particular engine project was foreshortened at its exploratory development stage -- it was terminated in 1970 for reasons expressed in the paper -- does not reflect despairingly on its basic propulsion system technical approach, per se. Rather, those negative programmatic factors leading to this termination, related to top-priority war-fighting materiel needs which taxed available budgets, a lack of established requirements for a Mach 4.5 combat aircraft capability, and the less-forward-looking status and direction of military aviation developments, in general, at that time. This perception of the positive nature of the engine's technical attributes, is supported by the ongoing combined-cycle propulsion technology effort being pursued today by NASA and industry, as well as those further comments to follow.

Turning all this around to a positive orientation, it will be noted that the SERJ engine had its origins in advanced highly-reusable launch vehicle application studies of the mid-1960s. Example SERJ-powered two-stage-to-orbit (TSTO) reusable vehicle systems were shown to as much as triple the "payload throw" of equivalent-technology all-rocket counterpart systems. Assessments of SSTO systems powered by scramjet-capable variants of SERJ, in the late-1980s, confirmed orbital payload fractions of 4- to 8-percent, approaching that of the *Concorde.* These promising findings suggest that combined-cycle propulsion can lead to marked reductions of vehicle takeoff weights, engine thrust levels, and a general sequence of vehicle subsystem downsizing gains. This should all lead to favorable mission-application operational flexibility and accompanying life-cycle economics.

With "aircraft like" being today's advanced spaceflight *watchword,* and with combined-cycle propulsion systems fast approaching advanced-development and flight-demonstration status, the technical and programmatic information provided in this case-history paper seems to us highly relevant. We submit that "The SERJ Story" related here should be of considerable interest to those participating in today's advanced space-transportation and propulsion planning and development activities.

INTRODUCTION

On Airbreathing and Rocket Propulsion, and a Synthesis of the Two

Taking a *technohistorical* perspective, aerospace propulsion systems fall into two major classes: 1) airbreathing propulsion and 2) rocket propulsion. To date, airbreathing propulsion has exclusively served the large, long-existing aviation community. Rocket propulsion, comprising both liquid- and solid-propellant types, have been the propulsive mainstay of all spaceflight endeavors so far.

But today, those involved with advancing the field of space transportation systems are facing unprecedented challenges such as those exemplified by NASA's *Spaceliner 100* technological initiative goals. These challenges ask for no less than today's aircraft-like levels of flight safety and operating dependability, and full "ticket price" affordability. A leading engineering response in addressing these revolutionary goals is to integrate airbreathing propulsion's high specific impulse performance and operating agility, with the demonstrated strengths of the rocket -- notably, high thrust/weights and the ability to operate in the space environment.

To illustrate the technical potential and development status of this "new" class of aerospace motive power systems, a 1960s case history is presented that covers a specific engine type: the Supercharged Ejector Ramjet (SERJ) powerplant. SERJ was initially considered under a 1965 NASA assessment for reusable space transportation system applications (under Contract NAS7-377, see Reference 1). But, with the onset of full-scale development of the all-rocket powered Space Shuttle, which still dominates the U.S. launch vehicle stage, national support for combined-cycle propulsion for launch vehicle applications abruptly vanished. The SERJ engine initiative was then redirected by a new Marquardt-led industry team, to military high-performance aircraft applications. U.S. Air Force and U.S. Navy support then took this engine project into exploratory development status -- prior to the termination of SERJ activities in 1970, as to be noted.

The fact that this particular airbreathing/rocket combined-cycle engine became a serious candidate for aircraft service denotes a promising message "from the past" to today's Spaceliner planners and technology developers. This message is that combined-cycle systems may well be the demonstrated propulsive means for achieving the stated ambitions for tomorrow's aircraft-like Spaceliner-class transportation systems. To this end, "The SERJ Story", presented here, offers a distinct set of "lessons to be learned" for today's advanced spaceflight-systems involved researchers.

Combined Airbreathing/Rocket Propulsion Systems: An Airbreathing/Rocket Partnership for Expanded System Capabilities

Combined airbreathing/rocket propulsion systems are of two basic kinds:
1) *combination* propulsion systems and 2) *combined-cycle* propulsion systems. These

two classes, and several subclasses of the combined-cycle type, are defined in Table 1 and further discussed below.

Combination Propulsion Systems -- If the airbreathing and rocket propulsion elements, usually as standalone *engines,* are separately installed on the vehicle and generally do not physically or functionally interact with one another, the overall installation is referred to as a combination propulsion system. Today's solid-rocket boosted turbojet- and ramjet-powered cruise missiles are extant examples of combination propulsion systems. An earlier crewed aircraft application, the NF-104A "astronaut trainer", will be described subsequently.

Combined-Cycle Propulsion Systems -- In contrast to the combination propulsion system design approach, an alternative powerplant type where the airbreathing and rocket elements are closely integrated as constituent *subsystems* into a single engine, is known as a combined-cycle propulsion system. Here, the airbreathing and rocket elements are each specially tailored such that they optimally interact, both physically and functionally. This synthesis approach provides several distinct engine operating modes to match engine thrust demands and flight conditions. Thus is gained a single, lighter weight, more versatile motive power system than that using the combination system format, one which uniquely offers important new operating capabilities.

The combined-cycle engine type covered in this paper is the Supercharged Ejector Ramjet, *SERJ.* Having both a fan-supercharging *turbine* element, and an internal *rocket* subsystem, this engine comprises design features of both TBCC and RBCC engine types (see Table 1). SERJ is thus an exemplary *Synerjet* engine, of which there is an extended family of specific types. This latter title denotes a synergistic integration of the specific airbreathing and rocket constituent elements making up the complete integrated engine.

BACKGROUND FOR THE SERJ AIRCRAFT ENGINE (1962-67)

Origins of the Supercharged Ejector Ramjet (SERJ) Engine

A Starting Snapshot in Time -- Fully integrated airbreathing/rocket propulsion systems were under assessment by advanced space transportation systems planners in the mid-1960s, just as the original Space Shuttle conceptual design and planning studies were being completed, on a more serious level. An exemplary study was conducted for NASA by a team of Marquardt, Rocketdyne and Lockheed under Contract NAS7-377: "A Study of Composite Propulsion Systems for Advanced Launch Vehicle Applications." Reference 1a&b is the final report series; the paper of Reference 2 summarizes this study effort. This study, begun in 1965, was completed in 1967. A leading example of the large combined-cycle engine family, which was mission-assessed, and documented at the detailed conceptual design level, is the Supercharged Ejector Ramjet (SERJ) engine, pictured in Figure 1 and to be further described below.

A Shift from Space Transportation to Combined-Cycle Powered Military Aircraft -- In 1967, for reasons to be noted, there occurred a significant "shifting of gears" in the programmatic direction being pursued by the Marquardt research team. This was a shift in the engine's applications focus from that of reusable space transports to military combat aircraft. The NAS7-377 study had focused on hydrogen/oxygen and hydrogen/liquid-air combined-cycle engines in the 250 klbf-thrust range. These large engines were fitted to the one million lbm gross takeoff weight, two-stage-to-orbit (TSTO) vehicle designs evolved in the study by the Lockheed-California Company (Figures 2). The new high-performance aircraft application would see a much smaller engine, and a shift to storable propellants.

Despite expectations otherwise, it soon became apparent to the NAS7-377 study team participants, and particularly to its organizer and leader, The Marquardt Corporation, that, with the onset of NASA's Space Shuttle full-scale development, there was to be *no* government sponsored follow-on to this study. A side exception was the subject-related Ames Research Center's contract with the Lockheed team members for a follow-on assessment entitled, "A Study of Advanced Airbreathing Launch Vehicles with Cruise Capability" (its final report is Reference 3). In the main, prospective advanced development work, targeted toward large launch vehicle combined-cycle propulsion systems, was *not* to be further supported by NASA in the, then, foreseeable future. As the NAS7-377 industry team disbanded, Marquardt followed through proactively in the manner next described.

In early 1967, this sharp systems application "course change" to military aircraft usage was then taken by the company in direct response to this termination of support by NASA, following the completion of the NAS7-377 main study effort (the study's "extension phase" was still underway). As noted above, rather than continuing to consider large reusable launch vehicles, the strategy was to apply the promising combined-cycle propulsion approach, with its technological underpinnings now fairly well established, to advanced military aircraft applications. Applying the SERJ engine to military combat aircraft was specifically recommended to Marquardt top management, as early as mid-1966 by Richard Foster, a special consultant to General J.B. Montgomery, the company's new president. Acceptance of this recommendation paved the way for the company's new SERJ initiative to follow.

<u>Marquardt's Forte: Hydrocarbon-Fueled Ramjet Engines</u> -- Marquardt's prior-years bread-and-butter production program was the RJ-43, 28-inch diameter JP-fueled ramjet engine. A pair of RJ-43s powered the rocket-boosted Boeing *Bomarc* IM-99 interceptor cruise missile, a supersonic aircraft-like machine capable of near Mach 3 flight speeds (Figure 3). The company had also participated in designing, building and operating other ramjet-powered experimental vehicles capable of Mach 3 to 4+ flight speeds, on regular JP-type liquid hydrocarbon aircraft fuels.

By the mid-1960s, these prior ramjet engine developments culminated in a higher-speed, higher-altitude, limited-production variant of the RJ-43 engine designated: XRJ-43MA-20S-4. This JP-7 fueled engine powered the Mach 3.2 *D-21* air-launched, unmanned reconnaissance aircraft developed by Lockheed's advanced development organization, the *Skunk Works* (Reference 4). This vehicle was flown for some 21 test and operational missions from 1966 to 1971 (Reference 5). It is pictured in Figure 4 mounted on its special M-21 supersonic carrier/launch aircraft. However, the bulk of the D-21 flights were launched subsonically from special B-52 bomber aircraft, using a solid propellant rocket to boost the vehicle from its air-launch conditions to the designated supersonic ramjet takeover speed. The Marquardt engine performed well in this program, setting new speed, altitude and flight-duration records.

The Ejector Ramjet Engine, the Forebearer of SERJ

Origins of the Ejector Ramjet (ERJ) Engine -- The inherent capabilities-limiting design issue with the ramjet engine is its lack of static and low-speed operating capability. What can one devise, in further developing the engine, to provide takeoff thrust, and to accelerate up to ramjet takeover speed? Installing an internal set of liquid-propellant rocket elements was a favored design response, and Marquardt's Ejector Ramjet engine concept was a promising mechanization of this approach. The ERJ would be the forerunner of the SERJ fan-supercharged variant, the subject of this paper. The added fan system mainly provided subsonic cruise and maneuvering power at very low fuel-consumption levels. It also enhanced the engine's high-thrust initial acceleration operation, generally increasing its overall operability.

Exploratory Testing of ERJ Elements -- During 1962 and 1963, under Air Force exploratory research sponsorship, Marquardt performed experimental studies of ERJ engine-oriented jet mixing, diffusion and combustion processes, the key to high ejector (jet compressor) mode effectiveness (Figure 5). Experimental data correlations for various primary-jet/mixer geometries were attained, while predicted cycle performance levels were achieved. Preliminary design studies of full-scale, flight-type Ejector Ramjets, and other related engine types such as RamLACE (Reference 6), indicated that acceptable performance, and size and weight characteristics could be achieved for operational applications. These applications included tactical and strategic aircraft and missiles, and, somewhat later, reusable space launchers (e.g., as presented in Reference 7). With these preparatory steps achieved, a move to full-engine testing was next in order, a step agreed to by the Air Force sponsorship at the Aero Propulsion Laboratory.

ERJ Subscale Ground-test Engine Builds Tested -- The performance characteristics of the ERJ engine concept were then experimentally demonstrated by Marquardt in a series of subscale engine tests performed from 1964 through 1967. This series of tests was conducted under Air Force contracts, as a continuing key element of the multifaceted Air Force/Marquardt *Advanced Ramjet Concepts (ARC)* program. The performance and operating characteristics of a 16-inch diameter non-flight-type, hydrogen-air jet compressor/combustor equipped ERJ operating over a simulated takeoff and acceleration flight profile, were now initially documented (Figure 6, Reference 8).

Subsequent testing, utilizing an improved 18-inch diameter engine, was accomplished using both hydrogen/oxygen and JP-4/ hydrogen-peroxide bipropellant rocket-driven jet compressors (Figures 7,8 & 9, References 9 & 10, respectively). The afterburner and ramjet-mode fuel was gaseous hydrogen and JP-4 liquid hydrocarbon, respectively. Multimode system operation was shown to be entirely feasible by these tests and critical performance goals were achieved at sea level static conditions (sls) and at (simulated) transonic and supersonic flight conditions. Smooth, readily controllable transitions between the low-speed ejector mode and high-speed ramjet operation were routinely accomplished. As anticipated by the engine designers, the ramjet mode performance levels were not compromised by the upstream presence of the ERJ's internal rocket thrust-chamber set. Correspondingly, the constituent *ramburner* was demonstrated to ably serve as the ejector mode afterburner.

DEVELOPMENT OF THE SUPERCHARGED EJECTOR RAMJET HIGH PERFORMANCE AIRCRAFT ENGINE (1967-70)

Evolving the SERJ Engine from Reusable Space Transportation to High Performance Military Aircraft Service

A Non-Cryogenic Reduced-Scale SERJ Aircraft Engine -- Returning to Marquardt's new-initiative decision to move from the large reusable launch vehicle application arena to high-performance aircraft systems, the key question was: Which combined-cycle engine type should be selected to power a Mach 4-5 high-performance aircraft, one that would capitalize on Marquardt's operational ramjet engine know-how?

The Supercharged Ejector Ramjet (SERJ), a detailed study phase finalist out of the NAS7-377 study, was the clear choice. Portrayed in the cutaway engine layout drawing of Figure 1 is the large hydrogen/oxygen 203 klbf-thrust (sls) SERJ engine design developed in the NAS7-377 study extension phase (Reference 1b). This hydrogen-cooled engine was designed to operate over a Mach 0-8 speed range. Rocketdyne's dual-concentric annular-bell rocket subsystem design was incorporated. High-speed fan disposition was accomplished by a pivoting tip-turbine driven fan, powered by a pair of remote turbojet-type gas generators. As shown, the fan unit was "swung up" into a protective housing. This compartment was then closed over and pressurized to protect the fan element and the fan-drive units from the thermally hostile inlet-diffuser environment at hypersonic flight conditions.

An Order-of-Magnitude Scale-down and a Change of Propellants -- Departing from this large launch vehicle engine design, the "high performance military aircraft engine" version of SERJ was scaled down ten-fold to a nominal 25 klbf-thrust at sea level static operating conditions. A top ramjet mode operating speed of Mach 5 was nominally selected. Cryogenic hydrogen/oxygen propellants were considered unsuitable logistically and operationally for military aircraft service. Accordingly, a switch was made to JP fuel and an aircraft flight-proven storable, JP-compatible oxidizer, hydrogen peroxide, H_2O_2. The top flight speed rating was mindful of JP-fuel cooling limits, which were technically more restrictive than those of hydrogen fuel.

Hydrogen Peroxide: Oxidizer and Monopropellant of Interest -- "Peroxide" had been used extensively in various aircraft rocket systems, including several reaching production status and then being deployed in military flight service. These aircraft-rocket units were applied either as sole propulsion, as in the German *World War 2* Me-163 *Komet* interceptor, or later as an added "superperformance" rocket unit in certain jet-engine powered combat aircraft. An operational example of the latter included variants of the U.K. BAe *Buccaneer* shipboard attack aircraft. Later, such a turbojet + liquid-rocket combination propulsion system was successfully used in the limited edition U.S. Air Force NF-104A "Astronaut Trainer" aircraft (Figure 10), next discussed.

The Impressive NF-104A Astronaut Trainer Aircraft -- Operating out of the Edwards AFB Test Pilots School in the mid 1960s, an extensively modified afterburning-turbojet-powered fighter aircraft, was employed for special Air Force spaceflight-training missions. This USAF/Lockheed NF-104A aircraft was fitted with a Rocketdyne AR-2 hydrogen peroxide/jet-fuel rocket engine, one developed earlier for military superperformance applications. This tail-mounted engine was installed just above the aircraft's standard General Electric J-79 turbojet engine exit nozzle. As an "astronaut trainer," this aircraft was capable of being routinely piloted through a rocket-assisted transonic punch-through, followed by a rocket-enabled steep-climb, high-altitude zoom maneuver into the fringes of the space environment, to altitudes of ~120 kft. A set of nose and wing-tip mounted monopropellant hydrogen peroxide rocket reaction-control units provided the aircraft three-axis attitude control, required during the low dynamic pressures experienced during this maneuver (as low as 5 PSF). Post-entry flyback to base was on turbojet power.

From an operational practicability point of view, it was learned that the NF-104A aircraft, once landed, could be routinely turned around for reflight by a small enlisted-man ground crew, with full propellants reservicing, all within one hour's time. This field-proven level of operability testified to the practicability of this choice of fuel and oxidizer for a projected SERJ-powered military tactical aircraft.

SERJ Initial Documentation Developed -- As early as November 1966, just a month or so after the NAS7-377 main study final report had been published, and while the study's extension phase was getting underway under Bruce Flornes' leadership, the company's initial SERJ aircraft engine technical specification was developed under Joe Bendot's direction. A spirited marketing brochure, "SERJ, A Forward Leap" came off the press (Reference 11). Its foreword, attributed to J.D. Wethe, Marquardt's Executive Vice President, is worth citing to indicate the marketing "tone" adopted by the SERJ Team:

> Military aircraft designers have long desired a powerplant giving them an ability to take off and climb like a rocket, cruise efficiently at high Mach numbers like a ramjet, and fly subsonically and loiter like a high bypass ratio fan.
>
> Now, this combined capability is in sight . . . the *Supercharged Ejector Ramjet* offers all three in a single propulsion system.

With this engine technical and marketing documentation in hand, government and airframe-company technical marketing contacts could now commence.

SERJ: Building on the Ejector Ramjet Experience -- As noted earlier, from an engineering standpoint, the SERJ initiative built heavily on Marquardt's ongoing Air Force sponsored Advanced Ramjet Concepts (ARC) program, and particularly its multiyear Ejector Ramjet (ERJ) subscale ground test effort. The program's series of several subscale experimental boilerplate ERJ engine builds, covered earlier, could be viewed as approximating SERJ *without* the fan supercharging feature. This test series had just shifted from hydrogen/oxygen propellants to JP-4/H_2O_2. A Marquardt built 8-unit cluster of rocket thrust chambers was used in this year-1967 test series (Figure 8 & 9, Reference 10). Likewise, the engine's afterburner/ramburner unit fuel shifted from gaseous hydrogen to JP-4 liquid hydrocarbon fuel. Now successfully engine-tested, these same propellants were convincingly the right choice for the SERJ aircraft engine.

Formation of the SERJ Industry Team

The SERJ Industry Team Forms Up -- Marquardt could competently build and test such small water-cooled heavy-weight rocket thrust chamber assemblies, as were used in these boilerplate test engines. But, to credibly respond to the challenge of full-scale, flight-type primary rocket subsystems, Marquardt saw the need to acquire a recognized member of the liquid rocket industrial community as a team mate. Aerojet was known to have just successfully completed an applicable hot-firing rocket test program for the Air Force's Rocket Propulsion Laboratory. This test series used 98% concentration H_2O_2

oxidizer (SERJ selected the more commonly used 90% type), and an experimental "Alumizine" fuel. Testing had been conducted at a very high 3000 psia chamber pressure (Reference12). Marquardt contacted Aerojet to explore a prospective partnering arrangement for SERJ.

Robert J. Kuntz, P.E., Aerojet's project engineer for this effort, provisionally accepted Marquardt's invitation (tendered by the lead author) to join the "SERJ Team." Here, the "provision" was the necessary joint-company upper management agreement to this teaming arrangement. An acceptable inter-company agreement was quickly penned by Escher and Kuntz and signed off by both companies. The expanded SERJ Team was in business.

Aerojet subsequently contributed mightily to both technical program progress, and to an intensive marketing effort, conducted mainly with the Air Force and the Navy over the next several years. Exploratory research funds for the SERJ project were soon forthcoming from both of the military services. A full-scale flight engine advanced development program was soon in planning. A comprehensive text-plus-graphics presentation document was promptly prepared. This presentation covered these development plans, the engine's ongoing experimental status, and a set of tactical aircraft application studies covering both Air Force and Navy missions of interest (Reference 13).

<u>Ejector Ramjet Design Study Evolves a Pre-Prototype Engine Design</u> -- In mid-1967, a nine-month study program was initiated at Marquardt under an Air Force study contract to critically detail the design features and to evaluate the technological makeup of a storable-propellant Ejector Ramjet engine. This required a specific engine design for a representative aircraft, to be exercised in a set of tactical mission applications. A swing-wing, high-performance Mach 4-plus combat aircraft was selected. It was outfitted with two 23 klbf-thrust ERJ engines, plus a single lower-thrust turbojet "helper" engine. The turbojet was sized to provide the aircraft low fuel-consumption subsonic cruise capability, otherwise unavailable from the ERJs (due to its ejector mode's excessive propellant consumption). In the SERJ engine, fan-mode operation provides this important subsonic operating capability, at even lower fuel-consumption rates than that

of a separate turbojet -- now no longer needed.

Aerojet assisted Marquardt in this study under subcontract. The final report (Reference 14) presents the resulting full-scale flight-type Ejector Ramjet preliminary design. This was then evolved into a pre-prototype engine design, with top-level fabrication drawings being produced. The study also provided an assessment of technology requirements to be met prior to the initiation of full-scale engine development. This Air Force contracted flight-hardware focused ERJ work contributed directly to advancing the parallel company-sponsored SERJ design work. In turn, it benefited from the ongoing SERJ efforts, e.g., those contributing to the development of Aerojet's unique primary rocket design, to be described below.

Allison Division Joins the Team -- The makeup of the SERJ team soon expanded to cover the supercharging fan subsystem as well. Allison Division of General Motors (now, Rolls Royce Allison) became the subcontracted fan subsystem Team member. Allison engineers provided detailed designs of advanced high-bypass ratio turbofan hardware for full-scale SERJ engines. Subsequently, a significant milestone was achieved in Allison's experimental demonstration of the aerodynamic feasibility of the fan-windmilling approach for high-speed "fan disposition," when the engine was in its ramjet mode. Earlier, Marquardt had broadly assessed "fan integration" aspects of the SERJ engine under a Navy study contract, with the Curtiss-Wright Corporation providing technical support under subcontract (Reference 15). [See also later-issued Reference 16 which addresses the broader issues of "fan integration" aspects in the design of hypersonic combined-cycle propulsion systems for space-transportation applications.]

SERJ Full-Scale Flight Engine Designs Developed

SERJ Engine Designs and Performance Initially Documented -- The initial engine configuration fully documented by Marquardt, prior to the formation of the multi-company team just referred to, was designated Model MA176-XCA, using the traditional company ("Marquardt Aircraft") numbering system. This "C" Engine type was more or less directly derived from the large, cryogenic launch vehicle SERJ engine depicted in Figure 9, with the scale-down and propellants changes discussed earlier. A cluster of fifty regeneratively-cooled (by the water-like hydrogen peroxide) bipropellant, turbopump-fed H_2O_2/JP-4 stoichiometric rocket thrust chambers, comprised the rocket subsystem. The high-speed fan disposition method selected comprised a forward and downward folding of the tip-turbine driven fan unit, similar to that shown previously in the large launch vehicle engine (Figure 1). This engine was designed for Mach 5 service and featured an all fuel-cooled mixer/combustor flowpath ducting and nozzle arrangement. It was sized to provide 25 klbf-thrust at sea-level static (sls) conditions. A preliminary engine installation and performance bulletin for this engine was issued in March 1967 (Reference 17).

On further examination of this design, the "C" Engine was seen to have three critical technical-challenge areas which might lead to untenable technical and programmatic risks. These were: 1) the cluster of small high-temperature rocket thrust chambers, 2) the folding-fan high-speed disposition approach, and 3) the regeneratively-cooled flowpath, which encompassed the added complexity of a fuel-cooled, high surface-area variable-geometry nozzle. Further, the initially designated Mach 5 flight-speed condition was now seen as "pushing the fuel-cooling limit." A new engine design was now in order, as represented in the C-to-E engine "transition" situation expressed in Figure 11.

<u>Evolution of the SERJ-176E Series Engines</u> -- As Aerojet, and then, Allison technical support became available, technical design means for alleviating each of these critical engine subsystem areas were worked. Alternatives were explored to reduce the technical risks and to arrive at a more practical engine design, one compatible with lower costs and an accelerated development schedule. Well-focused design efforts in each of the three areas soon yielded a set of superior design responses toward meeting these objectives. The resulting changes were incorporated in the new "E" engine, now designated by the more conventional descriptive call out: *SERJ-176E*. It was upwards sized to 32 klbf-thrust (sls), while its maximum design speed was reduced to a somewhat more thermally relaxed, Mach 4.5 rating.

The design of the "E" Engine's three critical subsystem areas departed significantly from those of the "C" engine: 1) a low-temperature, high-pressure *monopropellant* hydrogen peroxide based primary rocket subsystem was evolved by Aerojet, guided by Marquardt's engine performance staff; 2) *fan windmilling* of a fixed-location fan rotor/stator assembly became the fan-disposition approach of choice (as later partially validated by Allison's tests); and 3) the outer flowpath section of the engine's large mixer/combustor flowpath was now an *air-cooled* hot structure design, with just the centerbody and variable exit nozzle components regeneratively fuel-cooled -- now at the reduced temperatures allowed by the shift to the lower Mach 4.5 top speed.

The milestone SERJ-176E-1 engine design soon came off Bill Hammill's drawing board. It is pictured in the cutaway artist concept rendering by Leo Skubic in Figure 12. A new, expanded SERJ engine installation and performance brochure was published in June 1967 (Reference 18). In time, the "E" Engine series was to be further developed by the SERJ Team, led by Joe Bendot, under joint Air Force and Navy sponsorship, in the 15-month exploratory development phase effort of 1969-70. The final engine design, then achieved, was designated the E-4 series, a configuration in which the fan-drive gas generator was located more conventionally on the engine's centerline immediately aft of the fan.

Mach 4.5, Half Again as Fast as the Fastest -- A word about SERJ's ultimately selected Mach 4.5 top-speed choice: this was "half again as fast" as the recently demonstrated Lockheed A-12 (with its F-12, M-21 and SR-71 variants) and North American B-70, with their Mach 3 speed capability. Mach 4.5 was selected as a reasonable upper limit for sustained, repeatable ramjet mode operation. The governing design criteria were those relating to materials and structures operating limits and -- particularly -- the perceived need for active cooling of major components using JP fuel, with its long-term gumming and coking upper-temperature limits. An aircraft *capable* of flying at Mach 4.5 was strictly a presumption at this time.

A Successful Subscale SERJ Ground-test Engine Test Series

Successful SERJ Subscale Engine Ground Testing -- A successful joint Marquardt/Aerojet company-sponsored SERJ subscale engine test program was conducted in the spring of 1968. Modified ERJ hardware from the Air Force sponsored testing (e.g., as covered in Reference 8) was used with permission. A new rocket subsystem unit was added, as described below. Fan subsystem hardware was not physically present in this engine. Rather, a simulated fan pressure-rise was provided by direct-connect airflow means, as explained below. The full-scale engine *reference basis* for this subscale test series was the new SERJ-176E-1 engine design. The basic purpose of this test series was to validate this engine's published (Reference 18) performance over the Mach 0 - 3 portion of its larger operating envelope. This effort was conducted by the two companies under their discretionary independent research and development (IR&D) programs.

<u>Aerojet's Monopropellant Rocket Unit</u> -- As noted above, the new hardware item was the rocket subsystem. In accordance with the "E" engine design, Aerojet designed and fabricated a 36-nozzle high-pressure *monopropellant* hydrogen peroxide operated primary rocket unit. This innovation over the previous clustered, stoichiometric bipropellant thrust chamber arrangement, as depicted in the "C" engine design, greatly relaxed the innate technical design challenges in this subsystem corner, with only a small sacrifice of ejector mode specific impulse performance. This, stoichiometric-bipropellant to monopropellant "left-to-right" trade on engine performance, is reflected in Figure 13. The implied capability to sustain acceptable engine-level specific impulse levels, as a shift is made from a high specific impulse "hot rocket" (~250 sec) to a low specific impulse "cold rocket" (~100 sec), may not be intuitively obvious, even to an experienced propulsion engineer. A brief explanation follows.

<u>Oxygen Addition in a "Staged Combustion" Arrangement</u> -- The technical basis for the process sequence illustrated in Figure 13 lies in the fact that the monopropellant hydrogen peroxide decomposition products consist of over 40-percent *oxygen*, the remainder being superheated steam, all at a temperature of about 1350 F. The resulting supersonically injected oxygen, once mixed with the entrained air, very significantly "enrichens" the oxygen content of the induced air stream, being processed through the engine, during its ejector mode. The fuel flow to the afterburner can then be markedly increased in effecting full-power stoichiometric combustion. Performance-wise, the resulting "staged combustion" process essentially makes up for the reduced

internal specific impulse of the monopropellant rocket unit. The result is only a small reduction in engine specific impulse, the order of 5-percent. This small performance loss is readily compensated for by the shortened flowpath mixer, with its significant savings in engine weight. This was the payoff of installing a much larger number of supersonic nozzles in the rocket subsystem, now practical with its simple, uncooled construction.

At the full-scale design level, a 300-nozzle monopropellant primary rocket subsystem, designed for 4000-psi chamber pressure, was engineered by Aerojet and "installed" in the full-scale designs of the *SERJ-176E* series engines now coming off Marquardt's drawing boards. This vital unit now became a much simpler single-fluid system, operating at uncooled-material temperature levels throughout, without ignition or combustion problems. Also, as noted, the rocket exhaust/airflow mixing duct now became much shorter, reducing engine weight and length. This innovative design represented a major stride forward in rocket subsystem practicability. The E-1 engine design, pictured in cutaway detail in the artist rendering presented in Figure 12, shows the five thrust chamber rings, each having a multiplicity of supersonic nozzles (in blue). The single-fluid, self-driven (via a local catalyst bed) hydrogen peroxide turbopump is shown mounted below, and external to the flowpath (in black). A separate, hydraulically-driven hydrogen peroxide boost pump, and an afterburner JP-fuel turbopump were also incorporated (but are not shown here).

<u>Experimental Subscale Verification of SERJ-176 Engine Performance Estimates</u> -- The SERJ joint IR&D test engine is pictured in Figure 14 on the test stand at Marquardt's Saugus, California remote research facility. A simplified flowpath schematic sketch is provided in Figure 15. Under the direction of Marquardt's senior ERJ test engineer, Kenneth Stroup, in April 1968 some eleven SERJ engine tests were conducted totaling 26 minutes of run time. A condensed test log appears as Table 2. Most of these runs were made at the sea-level static test condition, as noted, with several at simulated Mach 1.9 and 3.0 flight-speed, and matching-altitude, inlet (but not exit) temperature and pressure conditions.

<u>Fan Pressure Rise Simulated by Direct-Connect Airflow Control</u> -- As indicated earlier,

this joint company IR&D test effort used a direct-connect controlled high-pressure air supply to *simulate* a range of engine fan pressure ratios from 1.0 (no fan) to 2.0 (1.5 being nominal). While supercharged ejector mode testing was emphasized in the test series, as noted in the test log, transitions to the fan-ramjet and ramjet operating modes were successfully demonstrated as well. A view of the engine's variable-geometry translating-plug nozzle exit nozzle during testing is shown in Figure 18. The overall test program description and results are reported in Reference 19, Marquardt's IR&D final project report, and summarized in a test-series briefing brochure (Reference 20). Aerojet's development of the 36-nozzle monopropellant rocket subsystem is covered in their IR&D report (Reference 21). In general, the full-scale "E" engine predicted levels of performance, documented in Reference 18, were experimentally validated over the Mach 0-3 range tested.

A proposed follow-on test phase, based on this proven engine hardware set, but now featuring a "real" tip-turbine driven fan hardware unit, was laid out in a bid for Air Force/Navy sponsorship (Figure 16). A vendor-offered subscale tip-turbine driven, single-stage fan unit was identified and found to be available at an acceptable cost and delivery schedule (see Figure17). However, the sponsoring military services elected to support *other* SERJ-related work, rather than extending subscale engine testing as proposed. This then-selected effort focused on *full-scale* component exploratory development and testing, and engine conceptual-level design studies, to be covered later. The proposed *physical*-fan (rather than its simulation) integration step and its testing effort, using the otherwise upgraded subscale SERJ ground-test engine, was put on indefinite hold.

An Intensive SERJ Government/Airframe-Industry Marketing Campaign

<u>SERJ Government Marketing Campaign Intensified</u> -- By late 1968, impressive progress was being made by the SERJ industry team, under combined government and company sponsorship, both at the engine systems level and in each of the key subsystem areas: fan, rocket, and ramjet. An expanded marketing campaign was now underway, in a concerted move to increase the level of customer funding support. This was strongly supported by senior company officials and certain noted outside company

consultants. These contacts followed up those initiated in late 1967. This "SERJ message" was carried to numerous DoD and NASA offices, those that were understood to be in any way potentially influential in advancing the SERJ development cause. This included several "using commands," e.g., the Air Force's front-line SAC, TAC and ADC organizations of that day. Each of these organizations were briefed along the lines of their mission interests. This notable "marketing campaign" was documented in an extended set of visit reports (e.g., Reference 22 covers the numerous marketing contacts made in the fall of 1967).

Contacts were also broadened and intensified with the leading aircraft companies involved in tactical military aircraft development, namely: Convair, Douglas, Grumman, Lockheed, McDonnell, North American, and Northrop. A number of follow-up actions resulted, as will be related.

<u>A SERJ High Speed Commercial Transport Application?</u> -- While the application focus of the SERJ Team was clearly on military tactical and strategic advanced aircraft, the thought arose that -- in a longer-term horizon view -- commercial passenger aircraft of the "beyond SST" kind, might someday fly at Mach 4.5 (rather than Mach 2, as today). This prospect was considered of some interest to those involved in long-range aeronautical systems planning, e.g., certain of our NASA contacts. This higher speed regime clearly called for ramjet propulsion, and the SERJ, as a ramjet-centered engine, might be the logical way to power such a high-speed commercial transport aircraft. A limited-distribution, future-scenario setting type document was prepared on this subject (Reference 23). In it, the makeup and operation of a SERJ-powered Mach 4.2 commercial transport aircraft was speculatively described, as experienced by imagined flight-crew members in training. The document also included informative factual background material for those not conversant with the SERJ prospect.

<u>An Air Force/Navy SERJ Exploratory Development Phase Is Entered Upon</u> -- In 1969, the expanded 15-month exploratory development effort mentioned above, focusing on full-scale engine components and designs, got underway under cooperative Air Force and Navy sponsorship. Such a *joint* service sponsorship arrangement was unusual, if not remarkable. It reflected the services' advanced planning organization's strong

interest in the potential of this new engine. This major effort, conducted by Marquardt, Aerojet, Allison and several subcontractors, generated an extensive final report series in mid-1970 (Reference 24).

This SERJ component work included a subscale fan windmilling test series (Allison), and an advanced hydrogen peroxide decomposition catalyst-bed performance and durability demonstration (Aerojet). Allison windmilled an existing experimental fan unit under those *aerodynamic,* but not thermal (the airflow was not heated) conditions simulating those in the inlet diffuser at the fan interface for Mach 4.5 flight. It was determined that the pressure drop experienced was acceptably low, particularly with an "open" stator row position. There was no tendency for the fan to "run away," rotational speed-wise. Aerojet's high-pressure hydrogen peroxide testing of a compact, modular arrangement of their unique full-scale catalyst pack design demonstrated 100-percent decomposition efficiencies and met extended durability goals.

Several efforts were undertaken within Marquardt. These covered: an innovative variable-geometry exit nozzle sequence of design, analysis and cold-flow aerodynamic performance testing; a unique high turndown-ratio afterburner fuel injection/flameholder unit proof-of-concept test effort; a "hydrocarbon fuel heat sink/cooling definition" effort, the development of a SERJ performance computer program, and the design of a set of advanced "E-series" SERJ engines. These engine depictions utilized the Aerojet and Allison designed rocket and turbofan subsystems, respectively. It turned out that this engine design work was to be productively integrated with an important military aircraft systems study, then underway.

Airframe Company Interests In SERJ Begin to Surface

Comparative Propulsion System (COPS) Study -- The evolution of the several further evolved "E" Series SERJ engines was guided by a special military tactical aircraft systems study of that day (then highly classified; reference not available). This systems-level, mission-specific assessment, was being conducted by McDonnell Aircraft under joint Air Force and Navy sponsorship. Along with speed-comparable Turboramjet and Turbofanramjet engine designs, provided by General Electric and

Pratt & Whitney (under proprietary cover), the SERJ E-series engines were competitively assessed in this Comparative Propulsion Systems (COPS) study. With regard to SERJ's competitive position, with respect to the more conventional TRJ and TFRJ engines, the COPS effort concluded that SERJ ranked fairly evenly with its compatriots. This was true for both the advanced interceptor (Air Force) and deck-launched interceptor (Navy) missions examined -- even without the engine's being called upon to exercise its ejector-mode prowess.

SERJ Briefing for Kelly Johnson at the Skunk Works -- In the process of meeting with Lockheed personnel on the NF-104A aircraft, and in general contractor liaison activities, the SERJ Team was invited to brief Clarence L. (Kelly) Johnson, director of the company's famed Skunk Works organization, *aka* Advanced Development Projects. But his time-availability had been foreshortened by prior commitments just at briefing time. Thankfully, there were few interruptions to roil the accelerated pace of the briefing, and it finished on time. Retrospectively, as evidenced in the types of later aircraft which subsequently appeared out of the Skunk Works, it was "stealth," and not "speed" which was then of leading interest to this unique development organization (one comprehensively described in Reference 4 & 25). From what is known today, SERJ was never to be followed up by the Skunk Works.

Use of the X-15 for Airbreathing Propulsion Testing -- Marquardt, along with several other propulsion companies, had reflected interest in using the flight-proven X-15 rocket-powered research airplane to flight-test airbreathing-capable propulsion systems of various types. The mode of testing generally considered was to use this unique aircraft for subscale "captive/carry" type engine testing. Marquardt's assessment for the NASA Flight Research Center (now the Dryden Flight Research Center) of the X-15 and several other research aircraft, as a potential flight-test bed for a variety of air-augmented rocket type propulsion systems, exemplified this interest. Reference 26 is the final report for this early combined-cycle propulsion flight-demonstration study.

The X-15/SERJ Proposal -- In 1967, X-15 project engineers from North American Aviation met with members of the SERJ team to discuss the use of the X-15 in a quite different combined airframe/propulsion testing mode. This went well beyond the size-limited captive/carry approaches studied earlier -- and the original basis of the NASA hypersonic research engine (HRE) project. Their idea was to fully *re-engine* the airplane -- actually replacing its LR-99 rocket engine with a full-scale SERJ engine. This replacement sequence was to start with the simpler ERJ and then move on to the fan-equipped SERJ engine. A heavy-weight development engine would be followed by a flight-weight engineering prototype. Retaining the B-52-carried aircraft launching approach, once in ramjet mode at Mach ~4.5, the SERJ-powered X-15 would now be uniquely capable of a short-duration (~10 minutes) *cruise operation.* This presently unavailable operating capability was believed to have significant flight-research opportunity payoffs, e.g., steady-state thermal protection system testing, and having advanced high-temperature materials now operate under near-hypersonic "real atmosphere" exposure conditions. The SERJ-powered X-15 prospect was subsequently examined in some engineering detail by Marquardt under a Navy contract (Reference 27).

North American prepared a detailed model of the SERJ-powered X-15 (see Figure 19). Marquardt enthusiastically developed an advocacy brochure draft (Reference 28 and Figure 20). This document included an artist's rendering of the vehicle in full ramjet-mode flight (presented in Figure 21). But the timing of this proposal was decidedly not propitious: a long-pending X-15 program termination decision had now been finalized. This decision was announced following X-15 Flight No. 199 (which, incidentally, carried the second of the two HRE-replica modules to be flown). The remaining two airplanes were soon off to the museums in Dayton and Washington. Marquardt's X-15/SERJ brochure never got beyond the indicated "Preliminary Copy -- Not for Distribution" stage (Figure 20).

The SERJ Exploratory Development Phase Peaks Out;
Termination of the Project (1970)

<u>SERJ Exploratory Development Effort Concluded in 1970</u> -- But now, in these trying days of the languishing war in Southeast Asia, the end was in sight for the SERJ effort itself. War-fighting demands for funds were ravenous. On the official DoD front, with regard to advanced-product development propositions like SERJ, there was a distinct lack of decision-level management interest. More significant, there was a complete

absence of visible funding means to provide the country with an innovative, high-speed aircraft powerplant. The pivotal problem was that no one in authority would step forward and issue a firm "Requirements Document" for a Mach 4.5 engine. This was despite a universally positive response from the many Air Force and Navy senior representatives exposed to the "SERJ Story." Without such an authoritative "statement of need," further funding for the SERJ industrial team was no longer a reasonable prospect.

It became evident to the involved company leaders that the SERJ initiative had thus begun to "stall out" in early-1970. A few months earlier, under Joe Bendot's technical direction, a detailed engine performance document had just been issued on the SERJ-176E-4A version (Reference 29). Thrust was now elevated to 52 klbf (sls). This was soon followed by the multi-volume exploratory development phase final report series cited earlier (Reference 24).

The Navy's "Proposed Technical Approach" -- The Navy came the closest in terms of official government advocacy statements, with its September 1968 issuance of a Proposed Technical Approach (PTA) document (Reference 30). It was directed to the support of the "Supercharged Ejector Ramjet (SERJ) Engine for High Supersonic Speed Aircraft" (Reference 30). While its issuance helped on the local Navy offices' advocacy front, it could only induce minimal further funding, namely that for the 15-month SERJ exploratory development effort concluding in 1970.

The Project Terminated -- Consequently, as its last set of contract final reports were submitted (Reference 24), the SERJ Team disbanded for lack of further funding support. Several sporadic attempts were made over the years to follow, to somehow restart the SERJ activity, or certain technical aspects of it. For example, Aerojet campaigned, under their "SPATE" (for Superperformance Afterburning Turbine Engines) initiative, for the integration of their rocket subsystem into the afterburner section of existing turbine engine types. Engine thrust could be as much as doubled that way. These "latter day" activities sometimes involved yet other companies. For example, even as late as 1989, Rocketdyne released a limited distribution text-plus-graphics advocacy document on SERJ (Reference 31). But, such efforts were to be of no further program-restoration avail. The SERJ high-performance aircraft engine initiative was over.

Scheming a Multi-Corporate Product Development Approach for SERJ -- The competing turbine based-cycle (TBCC) engines, namely the Turboramjet and Turbofanramjet concepts, were being supported by the established aircraft engine companies, notably General Electric and Pratt & Whitney. These large "monolithic" companies seemingly required no external teaming arrangements to supply such future engine types. Their established "one company does all" current businesses were routinely conducted, with individual lines of company developed and service-backed gas-turbine engine products, those being offered to the entire aircraft industry.

But the SERJ Team had been formed as a *multi-company* venture, with Marquardt, Aerojet and Allison being the original team members. The strategic question then posed was, given that the SERJ engine had been entered as a competitor to the TRJ and TFRJ, could its implied multi-corporate development organization effectively compete with the "monolithic majors." The credibility of this unconventional teaming arrangement was held in some doubt in the eyes of the military service decision makers, a potential problem for the SERJ Team were the country to get serious about developing a Mach 4.5 high-performance aircraft engine,

While this issue was somewhat of an academic question, in view of the arrested exploratory development status met with by SERJ (but, nor were the TRJ/TFRJ rival engines actively pursued into development), a certain amount of effort was devoted to addressing it at that time. An internally circulated graphics-plus-short-text draft document was prepared for the SERJ Team management to contemplate: "Organizing for the Systems Engineering Function in a Multi-Corporate Product Development " (Reference 32). As one would suspect, this presentation responded *positively* to the issue of the competency of the multi-corporate engine development approach. Interestingly, this positive stance has been more than confirmed by events years-later in the aircraft engine business, e.g., CFM International (two teamed companies), International Aero Engines (five teamed companies) -- these and other multi-company businesses, are all building and selling aircraft engines along with the continuing monolithic majors.

Retrospectively, A SERJ Patent Issues -- Probably stimulated by Aerojet's submission of a patent application for its unique monopropellant primary rocket subsystem design (Reference 33), Marquardt elected to gain U.S. patent protection for the SERJ engine in late 1971. The lead author, now departed from Marquardt, was tasked by the company to author that patent application. It was filed in February 1972 and issued in May 1974 as United States Patent 3,812,672, "Supercharged Ejector Ramjet Aircraft Engine" (Reference 34). It was in the pursuit of depicting the SERJ engine to fit patent description requirements, that a set of engine-control block diagrams, one for each operating mode, was documented for the first time. These operating-mode diagrams will be found in the paper of Reference 35, as well as in the cited patent (which expired in 1991).

CONCLUDING REMARKS

This paper has briefed a unique case-history recollection of how -- a third of a century ago -- a specific combined-cycle airbreathing/rocket engine concept, the Supercharged Ejector Ramjet (SERJ), evolved from its initial NASA-studied reusable space transportation status into a potential powerplant for high-performance military aircraft. These hypothetical aircraft, perceived as being capable of exceptional all-around combat agility, were rated at flight speeds of Mach 4.5, some 50-percent higher than the fastest planes flying then (and now).

These aircraft, and this engine never materialized. The SERJ aircraft engine exploratory development, initiated under joint Air Force and Navy sponsorship, was terminated at the onset of its full-scale engine design and prototypical component testing stage. But, even though this was a foreshortened development experience, there are believed to be significant "lessons *to be* learned," for today's advanced aerospace systems planners and decision makers, deriving from "The SERJ Story." Seven programmatically oriented ones of these lessons have been recited in the appendix section of the paper. The concomitant technical aspects of this engine's development have been covered in the main body of the paper.

Today's emerging interest in high-performance aerospace propulsion systems is seen now to be returning to the advanced *space transportation* application arena, rather than to that of high-performance aircraft. In fact, a primary subject of interest is attaining *aircraft-like* space transports. And the basic goals are clear, as stated for NASA's ongoing *Spaceliner 100* technology development initiative. Aircraft levels of flight safety and affordability are paramount. *Beyond-rocket propulsion* systems are likely to be mandated by these most challenging goals. Combined-cycle propulsion is here seen to be the leading candidate motive-power system approach.

With the SERJ engine being viewed as broadly representative of the combined-cycle propulsion class of motive power systems, the following concluding thoughts are offered: [reference to the nomenclature covered in earlier Table 1 may be helpful.]

1 Combined-cycle propulsion systems have been demonstrated as being technically compatible with the established engineering protocols and operational disciplines governing the development of advanced aviation systems. It should follow that this "practicability" rating should extend to *aircraft-like* space transportation systems as well.

2 In planning advanced space transportation applications, those going "beyond rockets," it will be increasingly recognized that the combined-cycle approach integrates the high specific impulse and operational agility contribution of airbreathing propulsion, with the established strengths of rocket propulsion: high thrust/weights, ability to operate in the space environment. Studies and experimentation efforts, conducted over the past three decades, confirm that a *synergistic compatibility* exists here (see Reference 36).

3 Today's CCP *dichotomy* recognizes two prominent combined-cycle propulsion subclasses: RBCC and TBCC systems (with articulate advocates for each). This quasi-competitive duality seems to fall short of what is ultimately required for the achievement of true aircraft-like systems. If so, this dichotomy should now be "productively defocused" and its leading "R" and

"T" elements constructively merged, as in the subject SERJ engine (see the following paragraph). With this in mind, further systems synthesis and subsystem integration steps are in order, to arrive at an optimal propulsion system for tomorrow's Spaceliner class vehicles.

As clearly demonstrated in SERJ, the *rocket* subsystem is entirely compatible with the *turbofan* subsystem -- these leading RBCC and TBCC elements demonstrably can be integrated within the overall engine design. In SERJ, for example, both subsystems "feed" the afterburner subsystem from takeoff into supersonic flight, after which -- as both the rocket and fan are deactivated -- it becomes the ramburner, providing acceleration into the hypersonic regime in ramjet mode. In further developed Synerjet engine types (e.g., the Supercharged Ejector Scramjet), the important airbreathing-extending *scramjet* mode can then productively follow, with the mission-pivotal in-space rocket mode completing the ascent to orbit. Ramjet and fan modes can handle the post-entry return to base, providing extended loiter and powered landings.

4 It follows that there is now a clear-cut advanced-propulsion development pathway, one in many ways trailblazed for us by the SERJ experience. This pathway leads toward the acquisition of further-developed *Synerjet* motive power systems, those which may be fully capable of meeting the propulsion engineering challenges underscored by today's Spaceliner-class transportation system goals.

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39 Escher, W.J.D., Conference Meeting Report (3 versions: Highlights, Summary Briefs, Full Reviews) -- AIAA 9th International Space Planes and Hypersonics Systems and Technologies, 1-4 November 1999, Norfolk, Virginia

APPENDIX -- Lessons to be Learned from "The SERJ Story"

The foregoing text and graphics information spell out what might be called "The SERJ Story." While all this may be of some interest to those who track aerospace development histories, today's active propulsion system researcher will more likely ask, "What are the specific lessons learned"? What can be distilled out of this specific engine development experience? How is it applicable to meeting today's engineering challenges? In this final section, an attempt to respond to such understandable queries is made. These remarks are, however, limited to *programmatically* oriented observations and suggestions. The many technical subjects addressed earlier, relating to the SERJ developments which may also be instructive, are embodied in the foregoing text, and are not revisited here.

The format to be used is simple: "SS" stands for (the) "SERJ Story" (as related above), and "LtbL" signifies "Lessons *to be* Learned." The "to be" heeds the practical observation that, generally speaking, we are talking about a learning process which has yet to happen.

1-SS Technically and programmatically, the company-team sponsored SERJ high-performance aircraft project (1967-70) built directly on the previously accomplished and ongoing Government-sponsored Ejector Ramjet efforts (1962-67). More generally, the SERJ Team members also productively utilized the considerable knowledge base then available in ramjet, rocket and gas turbine propulsion work derived in earlier years. The SERJ effort definitely did not "start from scratch."

LtbL <u>Payoffs of Mining the Archives</u> -- Any ongoing or new combined-cycle propulsion (CCP) initiative should maximally capitalize upon past *and* present related R&D efforts, those having been supported mainly by Government funding streams over the years. The resulting knowledge-base archives represent a very large national sunk investment, one which prospectively should be actively "mined" by today's performing organizations. [Note is made of NASA's under-development Combined-Cycle Propulsion Database (CCPD) which is directed to serving just this "retaining experience" purpose (Reference 37)]

2-SS While the SERJ effort was initiated and ultimately led by The Marquardt Corporation at that time, the broad-ranging technical makeup of this combined-cycle engine required an *inter-company outreach,* one leading to the formation of the SERJ industry Team of Marquardt, Aerojet and Allison.

LtbL <u>Need for Inter-Organizational Teams</u> -- By the nature of its diverse technical makeup, being based on a wide range of airbreathing and rocket propulsion technologies and development expertise, future CCP enterprises will likely call for a similar multi-corporate industrial organization arrangement. Similarly involved Government organizations, which may sponsor CCP R&D, and ultimately be a customer for associated flight service equipment, may also profit through the engagement of inter-organizational activities, such as forming project teams within various branches of the government. The SERJ Team's inter-organizational guideline document (Reference 32) might be a pertinent reference for today's industry and government representatives.

3-SS With its mid-1960s origins in NASA's advanced CCP-powered reusable launch vehicle application arena, which foundered with the onset of the Space Shuttle development program, the SERJ engine approach was strongly (and promptly) redirected to military high-performance aircraft applications. This led to a shift in customer focus from NASA, to the U.S. Air Force and U.S. Navy.

LtbL Broadening the Transportation Service Base Beyond ETO Deliveries-- The present CCP focus on Earth-to-LEO *commercial* transportation future possibilities might productively be extended to other "highest speed" transportation markets. Examples might include *transglobal* passenger and high-value cargo delivery, and beyond-LEO transportation missions, e.g., those supporting lunar bases (a proposition addressed in Reference 38). Also non-commercial, unique civil and military transportation service possibilities should be continuously explored. Success in broadening that ultimate customer base, one eventually to procure operational CCP-powered flight systems, will lead to increased, more stable development and eventual revenue streams, as well as assuring early and complete "customer buy-in."

4-SS Marquardt's traditional long-standing customer supporting pre-SERJ Ejector Ramjet developments was the U.S. Air Force's Aero Propulsion Laboratory in Dayton, Ohio (now AFRL-WPAFB). But, the SERJ initiative immediately expanded its Government customer liaison base to many other Air Force organizations, and added those of the Navy, as well as keeping NASA informed of progress. Consequently, a unique joint Air Force/Navy "paying constituency" was thereby established, one which supported SERJ up to entering (but never completing) its exploratory development stage.

LtbL Expanding the Participating Government Entities -- CCP developing industrial organizations, teamed with corresponding systems-level (airframe) companies, should probably not confine their technical and programmatic liaison activities to that with a single Government organization, even one that has provided past support. Rather, a broad-ranging set of future product communication and industry/government business interfaces needs to be established and serviced to ensure adequate and stable lines of funding. For instance, an exemplary set of U.S. Government organizations, one which should presumably have a dedicated interest in the future potential of Transglobal/Spaceflight transportation services, would be the combination: NASA + DoD + FAA.

5-SS Early information communications on advanced propulsion system developments, those centering on the SERJ engine, were continually related to the full set of airframe companies, those which were in the tactical military aircraft business (the count at that time: seven companies). Marketing brochures and presentations, plus SERJ engine installation and performance documents, supported this active liaison. While the response-time opportunity was brief, several of these companies positively responded to this technical marketing effort, e.g., North American's X-15/SERJ proposal.

LtbL Early and Full Involvement of Vehicle Systems Houses is Mandatory -- While the number of large airframe companies in the U.S. is now down to some three companies, today's CCP development organizations must establish strong two-way technical and programmatic ties with the "majors." For one thing, the establishment of a vehicle-level of system cognizance is technically necessary for CCP systems to be properly engineered. For another, the sole avenue to the ultimate paying customer is the vehicle-*plus*-engines "big picture." Even the most optimal of engines does not constitute a transportation system.

6-SS SERJ was primarily held to be a military tactical aircraft engine candidate, one competing with the established TRJ and TFRJ system concepts from the major aircraft engine companies. It was therefore only appropriate to deal with interested and, hopefully to be supportively involved, components of the Department of Defense as customers -- appropriate offices of the U.S. Air Force and the U.S. Navy, as was done.

LtbL While Carefully Heeding the Military, Go for the Commercial Carriers! -- In contrast to strict adherence to military needs, it is expected that tomorrow's commercial Spaceflight services will ultimately be provided by the carriers industry; tomorrow's counterparts of the airlines and the express-package services of today. [Some consider that Airbus, Boeing and Lockheed Martin will provide these services; not likely -- their business interest will be in *selling and servicing* the needed transportation vehicles.] While these future Spaceflight carrier organizations have yet to be established, it is likely they will evolve from today's airline and air-express businesses. Keep in mind the transglobal highest-speed prospect which may someday *directly impact* the future transport airplane arena. It may not be too early for CCP propulsion and vehicle systems companies, working together, to begin a capabilities-information advocacy dialogue with advanced planners in the leading air carrier companies. Their associated advocacy/lobbying groups, such as the Air Transport Association (ATA) should be involved.

7-SS As stated above, the SERJ Team worked with the U.S. Defense community, and not the much larger constituency relating to commercial Spaceflight and Transglobal transportation services, prospects just now appearing on the forward-planning screens of the emerging CCP systems development community, e.g., space tourism, orbital research parks.

LtbL Today's *World Airplanes* Presage Tomorrow's Global Spaceliners -- While U.S. (and other nation) defense interests may be well served by certain CCP-powered transportation systems, the commercial transportation markets are likely to be the dominant, business-sustaining ones. This is emphatically a *global* business proposition. No new commercial transport airplane developed over the past several decades is aligned with *only* U.S. domestic service (or that of any other *one* country). Large and small commercial transport aircraft are all World Airplanes. These observations underscore the clear prospect for a markets-governing *international* constituency as the *main avenue* leading to advanced transportation system sales and service, such as those being contemplated here in the long-range view.

In this respect, it turns out that combined airbreathing/rocket propulsion systems, and a diversity of vehicle types to be powered by such systems, are high on the priority list of leading-nation aerospace R&D agendas (e.g., see the conference summary of Reference 39). It follows that cooperative R&D activities with such potential overseas partners should be seriously contemplated by both industry and Government organizations of the United States, in consonance with those of other nations. These potential R&D alliances could provide a *multinational* set of strong science and engineering know-how and development capabilities for these new engines and vehicles. In addition, it is probable that only *international partnerships* will be able to provide the very large level of financial, facility and skilled-worker resources required to do this ultimate job. Such partnerships will also ensure a fully expanded roster of future customers for these revolutionary products and services.

Figure Captions

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Figure No.	Caption
Cover.	Advanced SERJ-Powered Navy Tactical Aircraft Scene Depicting On-the Deck High-Speed Flight and Vertical "Salvo" Launch Capabilities (Artist: L.J. Skubic)
1.	SERJ Engine Sized at 200 klbf-thrust (sls), Hydrogen/Oxygen Propellants, for Reusable Launch Vehicle Service (NAS7-377)
2.	SERJ-Powered TSTO Earth-to-orbit Reusable Launch Vehicle Concept at Mach 8 Staging Conditions (Lockheed-California Company)
3.	*Bomarc* Rocket/Ramjet Combination Propulsion System Powered Interceptor Missile (IM-99, CIM-10) (The Marquardt Corporation)
4.	Lockheed D-21 Supersonic Reconnaissance Unmanned Aircraft installed on its M-21 Supersonic Launch Platform (Seattle Museum of Flight)
5.	Ejector Ramjet Engine Cycle Exploratory Test Rig at the Marquardt Jet Laboratory
6.	Ejector Ramjet Engine Build #1 (16-inch dia.) at the Marquardt Research Field Laboratory (Hydrogen, Air and Oxygen Propellants) (1964)
7.	Ejector Ramjet Engine Build #2 (18-inch dia.) at the Marquardt Jet Laboratory (Hydrogen/Oxygen Propellants) (1965-66)
8.	Ejector Ramjet Engine Build #3 (18-inch dia.) at the Marquardt Research Field Laboratory (Hydrogen Peroxide/JP-4 Propellants) (1967)
9.	Ejector Ramjet Engine Build #3 Under Test
10.	Lockheed NF-104A Astronaut Trainer Aircraft in Rocket-Powered Zoom Maneuver (Hydrogen Peroxide and JP-4 propellants)
11.	SERJ-176 High-Performance Aircraft Engine Design Features in the Transition from the "C" to the "E" Model Engine (Hydrogen Peroxide/JP-4 Propellants)
12.	The SERJ-176E-1 Engine Cutaway Artist Rendering (Artist: L.J. Skubic)

13. Trade on Engine Specific Impulse (sls), as a Function of Chamber Pressure, in the Shift from SERJ Stoichiometric Bipropellant to Monopropellant Operating Rocket Subsystems

14. SERJ Subscale Joint Marquardt /Aerojet Joint IR&D Engine on the Test Stand at the Marquardt Research Field Laboratory (April 1968)

15. Simplified Schematic Drawing of Subscale SERJ Joint IR&D Engine as Tested Direct-Connect (See Figure 14)

16. Simplified Schematic Drawing of Proposed Advanced Subscale SERJ Engine with a Tip-Turbine Fan Unit, High-Pressure Rocket Unit and Translating-Ring Variable Exit Nozzle Suitable for Freejet Testing (was not developed)

17. Subscale 12-inch dia. Tip-Turbine Single-Stage Fan Unit Applicable to Proposed Subscale SERJ Engine from *Tech Development, Inc.* (See Figure 16)

18. View of SERJ Joint IR&D Subscale Variable-Geometry Exit Nozzle During Engine Operation (See Figures 14 & 15)

19. North American X-15/SERJ Model as displayed by Marquardt's Leo Skubic, Graphics Group Head, and William Escher, SERJ Program Manager

20. Cover of Marquardt's X-15/SERJ Draft Brochure (1968)

21. Artist Rendering of X-15 in Flight Powered by SERJ Engine in Ramjet Mode (Artist: L.J. Skubic)

Table Captions

1. Combined Airbreathing/Rocket Propulsion System Nomenclature

2. SERJ Subscale Joint IR&D Test Project Engine Test Log Summary