https://ntrs.nasa.gov/search.jsp?R=19990062726 2020-06-18T01:06:01+00:00Z

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686 420

Approval Final Draft – without illustrations (being integrated)

A U.S. HISTORY OF AIRBREATHING/ROCKET COMBINED-CYCLE (RBCC) PROPULSION FOR POWERING FUTURE AEROSPACE TRANSPORTS, WITH A LOOK AHEAD TO THE YEAR 2020

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Abstract

A technohistorical and forward-planning overview of U.S. developments in combined airbreathing/rocket propulsion for advanced aerospace vehicle applications is presented. Such system approaches fall into one of two categories: 1) Combination propulsion systems (separate, non-interacting engines installed), and 2) Combined-Cycle systems. The latter, and main subject, comprises a large family of closely integrated engine types, made up of both airbreathing and rocket derived subsystem hardware. A single vehicle-integrated, multimode engine results, one capable of operating efficiently over a very wide speed and altitude range, atmospherically and in space. While numerous combination propulsion systems have reached operational flight service, combined-cycle propulsion development, initiated ca. 1960, remains at the subscale ground-test engine level of development. However, going beyond combination systems, combined-cycle propulsion potentially offers a compelling set of new and unique capabilities. These capabilities are seen as enabling ones for the evolution of Spaceliner class aerospace transportation systems. The following combined-cycle hypersonic engine developments are reviewed: RENE (rocket engine nozzle ejector), Cryojet and LACE, Ejector Ramjet and its derivatives, the seminal NASA NAS7-377 study, Air Force/Marquardt Hypersonic Ramjet, Air Force/Lockheed-Marquardt Incremental Scramjet flight-test project, NASA/Garrett Hypersonic Research Engine (HRE), National Aero-Space Plane (NASP), all past projects; and such current and planned efforts as the NASA ASTP-ART RBCC project, joint CIAM/NASA DNSCRAM flight test, Hyper-X, Trailblazer, W-Vehicle and Spaceliner 100. Forward planning programmatic incentives, and the estimated timing for an operational Spaceliner powered by combined-cycle engines are discussed.

Orientation to Combined-Cycle Systems as an Emerging *Third Class* of Propulsion

As will be described at the beginning of the next following section, our subject: Airbreathing/ Rocket Combined-Cycle Propulsion Systems, commonly known today as "RBCC" (for rocket-based combined-cycle) systems, is a leading member of the larger generic family: Combined (airbreathing/rocket) Propulsion. This extensive family of aerospace motive-power system (airbreathing/rocket) Propulsion. This extensive family of aerospace motive-power system concepts embraces any and all propulsive means which employ *both* airbreathing and rocket elements; as components, or subsystems or complete systems, e.g., as standalone engines.

In this context, and focusing on the subject of this paper, it is the author's belief that fully-integrated combined-cycle variants of such combined propulsion systems, should fittingly be viewed basically as a new, emerging and special "third class" of engine. As such, this distinct class of system follows in time, and derives technically from the two established classes: (1) Airbreathing (ISOABE's focus) and (2) Rocket propulsion.

Proceeding on this belief, the single-word moniker proposed some time ago (1972[1]): *Synerjet,* denoting a synergistic integration of airbreathing and rocket elements, was informally tendered to the propulsion and spaceflight community. A rationale for this title, which might eventually supplant "RBCC" and like multi-word titles and cryptic acronyms, is presented in the "opening remarks" section ("Introduction – What's in a Name") of the recently published SAE International publication, "The Synerjet Engine," which the author compiled and edited for the Society[2]. Hopefully, this book will be useful to subject-interested members of ISOABE and the airbreathing engine community generally, and also their counterparts in the smaller, traditionally spaceflight and missile oriented rocket propulsion community. Clearly, it will be the interactive contributions from *both* communities which will evolve combined-cycle systems from today's concepts into motive power systems for tomorrow's operational aerospace transportation systems.

Returning to proposed and in-use titles, in this paper, airbreathing/rocket combined-cycle, RBCC , Synerjet, and other propulsion system terminologies, are used completely interchangeably. This is in the spirit of letting the involved technical people, and the larger discipline communities they represent, develop and use nomenclature over time that works best for them.

Introduction and Historical Background

Combined Propulsion - An Airbreathing/Rocket Propulsion Partnership: Two Basic Types

Combination Propulsion Systems -- Where the airbreathing and rocket propulsion elements, usually as standalone *engines,* are separately installed on the vehicle and do not physically or functionally interact with one another, the overall installation is referred to as a combination propulsion system. An historical example, as illustrated here (Figure 1) is the U.S. developed and operationally deployed (ca. early-1960s) Bomarc IM-99 interceptor missile. Here a liquid-propellant (later, solid-propellant) rocket propulsion system was operated for initial vertical launch, and climbout to ramjet takeover speed and altitude conditions. The twin ramjet engines were then started and the missile further accelerated to a supersonic cruise-out condition, in the speed range of Mach 2.5, and powered to the aircraft target intercept point. The modern solid-rocket boosted turbojet- and ramjet-powered cruise missiles, deployed around the world, are extant examples of combination propulsion systems. A later-developed crewed aircraft application will be described subsequently.

Combined-Cycle Propulsion Systems -- In contrast to the combination propulsion system design approach, where the airbreathing and rocket elements are closely integrated as true *subsystems* into a single engine, this powerplant type is known as a combined-cycle system. Here, the airbreathing and rocket elements are each specially tailored to best physically and functionally interact to provide several distinct high-performance operating modes. This provides a lighter weight, more versatile motive power system than the combination system format, while uniquely offering new operating capabilities. To be discussed, the air-augmented rocket (AAR) or ejector mode is a key example, as used for the initial phase of flight. It provides significantly higher specific impulse performance than the equivalent-technology conventional rocket engine, and higher thrust/weight ratios than conventional turbomachine-centered airbreathing engines

A classical artist concept rendering of a *Spaceliner* class vehicle system powered by combined-cycle engines is pictured in Figure 2. The engine type used here is the Supercharged Ejector Scramjet. Such propulsion systems are today popularly known as rocket-based combined-cycle (RBCC), or in a word, *Synerjet* engines, of which there is a large family of specific types. As noted earlier, this latter title denotes a synergistic integration of the specific airbreathing and rocket constituent elements making up the complete integrated engine.

Combination Propulsion Systems Have Reached Flight Operations Status -- The U.S. Air Force/Lockheed specially modified F-104 "Starfighter" *astronaut trainer* (designated the NF-104A) was an operational example of combined propulsion, and specifically a *combination* propulsion system (Figure 3). Its propulsion complement consisted of the standard General Electric J-79 afterburning turbojet airbreathing engine to which was separately added a Rocketdyne AR-2 series bipropellant rocket engine. Its H2O2 powered turbopump unit is illustrated in Figure 4. It provided high-pressure supplies of this oxidizer and regular aircraft JP-4 fuel to the aft-mounted rocket thrust chamber.

The two propulsive elements were operated both in parallel and serially, propelling this special-mission aircraft to record altitudes of as high as 37 km (122,000 ft), well above the substantial atmosphere where airbreathing propulsion could be sustained. The basic mission was to provide exoatmospheric flight experience for astronauts in training. During the rocket-propelled zoom maneuver shown here, a 3-axis attitude control reaction control system (RCS), using small hydrogen peroxide monopropellant rocket units in the nose (pitch/yaw) and at the wing tips (roll), was engaged by the pilot through the peak altitude point, and then used to orient the aircraft for a "mild reentry" into the atmosphere, where the jet engine was once again operated.

The operational practicability of such a combined propulsion system, of a type also used in certain military combat aircraft in the U.S. and the U.K. for "superperformance" maneuvering, was routinely demonstrated. The NF-104A aircraft, once landed, could be reserviced with jet fuel and hydrogen peroxide and turned around for reflight within one hour by a small crew of regular enlisted service personnel.

Combined-Cycle (RBCC) Engine Status -- While not yet achieving operational flight status, as shown in Figure 5, a hydrogen peroxide/jet-fuel powered combined-cycle subscale ground-test engines was successfully tested in earlier Air Force/ Marquardt and joint Maquardt/Aerojet exploratory development programs. Testing of the Ejector Ramjet (ERJ) engine is reviewed later in the paper. Higher energy cryogenic propellants (hydrogen and oxygen, in high-pressure gaseous form) have also been tested in the ERJ, as is noted.

Several NASA X-Vehicle flight demonstration programs are currently underway which are predicated on RBCC (Synerjet) Propulsion, using both storable and cryogenic propellants. Leading examples are the *Spaceliner 100* TSTO and the *Trailblazer* SSTO flight demonstrator concepts, respectively. These systems, presently at the initial development stage, are pictured later in this paper.

The Air-Augmented Rocket (AAR) -- Starting Point for Synerjet Evolution

Rocket Engine Nozzle Ejector (RENE) -- While aspects of the integration of the rocket, into basically an airbreathing engine concept, go back in time to as early as the 1950s under various titles: ram-rocket, ducted rocket, etc., a variant of significant interest evolved through work performed by a group at the Martin Company's Denver facility about 1960[3]. This was titled the rocket engine nozzle ejector *(RENE)* propulsion systems. It was initially considered as a ballistic missile performance improvement avenue, but quickly became of interest to the space launch vehicle community, for its potential for increasing orbital payload fractions.

The RENE concept was based strictly on the air-augmented rocket propulsion performance gains achievable through the momentum transfer and combustion heat-release process, created by mixing the supersonic exhaust flow of the rocket with a ducted air supply. A controlled airflow was provided through a simple, fixed-geometry inlet/mixing-duct arrangement. Unlike the earlier ram-rocket concept, the airflow was limited to the order of double to triple, the fuel-rich rocket exhaust mass flow. An all-supersonic, fully mixed-flow at the exit of the divergent augmenter duct specified, was presumed in this case.

Based on promising analytical results achieved by the Martin Denver researchers, a set of preliminary experimental verification tests was sponsored by the Air Force's Rocket Propulsion Laboratory (AFRPL), and conducted at the Arnold Engineering Development Center (AEDC)[4]. In support of this effort, NASA Langley tested a monopropellant hydrogen peroxide AAR thrust chamber operated ejector device as reported in 1962[5]. These tests involved single primary rocket units, requiring extensive duct mixing lengths. While these long mixers were acceptable for research purposes, they were impractical for "real" vehicle-integrated applications from an implied excess installed weight and volume standpoint.

The engineering solution to shortening mixing-duct lengths, to those practical for real vehicle applications, was to go to a *multiplicity* of primary rocket units. This is illustrated in the cutaway artist concept renderings shown here (Figures 6 and 7), where, in one case, a multiple rocket engine installation is reflected in powering the boost stage of a large multi-stage launch vehicle (Figure 6). Follow-on RENE testing at AEDC utilized the 12-rocket cluster shown in Figure 8 and 9[6]. It was specially developed by the NASA Marshall Space Flight Center (MSFC) for the Air Force/Martin RENE test program[7]. The rocket units used were 2250 N (500 lbf) thrust liquid oxygen/kerosene propellant, water-cooled units previously developed by the MSFC Test Laboratory. Here they were used for a variety of special subscale, all-rocket powered engine/vehicle testing purposes, all relating to NASA's Saturn vehicle series, then under development under the Apollo Program.

Further On the Origins of Combined-Cycle Hypersonic (Synerjet) Propulsion

Early U.S. Aerospaceplane Pursuits Yielded Numerous Innovative Engine Types -- As early as the late 1950s a number of advanced "beyond rocket" airbreathing-capable propulsion systems were being explored in the U.S. and elsewhere. Multi-company studies of an early "aerospaceplane," in many design variants which utilized these propulsion systems, were supported by the U.S. Air Force. Innovative propulsion system designs arose and interest in hypersonic ramjet propulsion intensified. The potential of the new-on-the-scene partial-diffusion, or supersonic combustion ramjet *(scramjet)* became of especial interest, as a way of extending the upper-speed range for high specific impulse airbreathing operation. The full-diffusion subsonic combustion ramjet reached a practical upper-speed limitation of Mach 6 to 8, where thermal and structural hardware design problems increased exponentially with higher flight speeds. Initial exploratory research projects were undertaken in support of many of these new and, sometimes, quite novel propulsion approaches, such as those next described.

Cryogenic Liquid Hydrogen Practicability Led to Innovative Engine Types -- With the advent of practical applications of *cryogenic* hydrogen fuel, beginning in the mid-1950s (see John Sloop's recounting for this interesting story[8]), with its unsurpassed performance and cooling characteristics (vis-à-vis regular liquid hydrocarbons), a set of new concepts were soon forthcoming. This included "deeply cooled" *cryojet* and liquid air cycle engine (LACE) system concepts. The latter, whose basic cycle layout is displayed in Figure 10, was demonstrated in small-scale component and system ground test rigs, such as that shown in Figure 11. Hardware testing was pursued by The Marquardt Corporation, and others, under Air Force sponsorship. The special compact cryogenic heat-exchanger elements used in much of this research and demonstration work were fabricated by Garrett AiResearch. The Basic LACE (Figure 10), as literally, an airbreathing rocket propulsion system, was an early member of the Synerjet family.

This technology, which is still being pursued today (e.g., in Japan; e.g.[9]), was subsequently assimilated into further developed Synerjet engine concepts, those with higher performance and wider speed-range capabilities, such as the RamLACE and ScramLACE engines. These engine types, derived from the basic Ejector Ramjet engine format, to be covered subsequently. The RamLACE (Figure 12) and a *recycled* variant of the ScramLACE engine (Figure 13) are shown here in simplified schematic diagrams.

The latter recycled engine types required the use of *slush hydrogen* (SLH2) as a tanked low-temperature heat sink. Slush hydrogen is a triple-point temperature (13K, rather than NBP 20K) mixture of liquid and solid hydrogen. This is used to reliquefy the returned warmed-up hydrogen, while itself being converted to normal boiling point (NDP) hydrogen, without posing a rapid in-tank hydrogen boil-off problem. Recycling can lead to a near-doubling of ejector mode specific impulse. But this performance advantage must be weighed against the collateral operational complications, such as those posed by the need for embracing difficult-to-maintain, albeit somewhat denser (by ~15%) SLH2 fuel. (See the author's NATO AGAARD survey paper covering many of these technologies and systems[10].)

Increased Wide Speed-Range Performance and Operability: Forte of the Synerjet Engine

Engine Specific Impulse Trends in Multimode Operation: Takeoff to Landing -- For projected highly reusable Spaceliner class vehicles providing Earth-to-orbit transportation services for passengers and high-value cargo, the Synerjet engine is characteristically operated in several progressive operating modes, from takeoff to post-entry flyback and landing. The notional chart of Figure 14 depicts typical trends resulting in specific impulse performance (note the logarithmic ordinant values). The relative boldness of the trend lines attempts to suggest the concomitant *specific thrust* characteristics: the heavier the line, the greater the thrust-per-unit-size (installed weight, frontal area, etc.) of the engines.

One can note here several "straight" airbreathing modes, e.g., ramjet/scramjet, fan; and the rocket mode used for final acceleration to the staging point, or to orbit insertion in the case of SSTO systems. In addition, the important air-augmented rocket (ejector) mode is seen to be prominent for powering the initial ascent phase. This is a *mixed* airbreathing/rocket mode, one unique to the Synerjet approach, as discussed earlier. A second such mixed mode, but one not depicted here, can be descriptively referred to as the oxidizer-augmented scramjet mode. This might be employed to maintain thrust-level adequacy in the transition from highest-speed airbreathing operation in scramjet mode to the in-space rocket mode. End-of mission loiter and powered landing would be conducted in ultra-high Isp fan mode, in fan-supercharged Synerjet variants.

Increased Equivalent Effective Specific Impulse (I*) Yields Higher Payload Fractions (than with equivalent all-rocket propulsion) -- The set of bar charts of Figure 15 presents published study results for five different Synerjet engines powering an SSTO vehicle system of the "extensively axisymmetric type," as illustrated earlier in Figure 2[11]. These payload results reflect the imposition of each of two "technology levels," by date of estimated availability. The 1995 technology availability dates (TADs) are easily the applicable values today; the source study was performed in the mid-1980s, hence the posting of the less-favorable 1985 values.

Payloads delivered to a 170 km (100 n mi) circular polar orbit by a 230 metric ton (500 klbm) gross takeoff weight (GTOW) Synerjet-powered vehicle are called out in both absolute terms, and in terms of payload fractions (percent of GTOW) for the five RBCC engine types named. Whereas all-rocket SSTO systems, as studied today (none have flown), have payload fractions of but 1 to 2 percent, the range of 4 to 8 percent is shown here to be potentially available with Synerjet propulsion. This suggests that, for a given payload mass, the GTOW can now be reduced by several factors. This contributes directly to reduced mission-cycle recurring costs.

Alternatively, this amplified payload potential can be traded for increased system robustness toward achieving aircraft-like dependability. With a substantially increased vehicle structural fraction required allowance, due to the Synerjet's decreased propellant consumption, as compared to all-rocket systems, factors of safety can be increased, and backup components and subsystems installed as needed for increased reliability, and mission intact-abort capabilities. This is judged a most important consideration for the designer to act upon.

Advent of the Ejector Ramjet (ERJ) Engine: Progenitor of Leading Synerjet Propulsion Systems

Limitations of RENE and Similar Air-Augmented Rocket (AAR) Concepts -- The AEDC direct-connect RENE test series verified predictions of measurable increases in thrust and specific impulse levels from equivalent rocket levels, over a range of simulated flight speeds and altitudes approximating a suitable launch vehicle trajectory. But now several inherent limitations of this "simple air-augmentation" approach became increasingly evident. A primary one of these was the unpromising low-speed performance achievable in the takeoff and subsonic flight regimes. Even a *negative augmentation* problem was revealed here. This serious shortcoming was seen as inherent in the simultaneous mixing and combustion (SMC) cycle used. The conventionally fuel-rich rocket exhaust immediately burned with the atmospheric oxygen intake during the mixing process, adding heat at less than the optimal operating cycle condition. This seriously attenuated the air-augmentation performance benefit potentially available. Also, characteristic of these "add-on" designs, there was no straight-airbreathing ramjet mode to transition to once the vehicle was "at speed."

Boeing's Study of Simple Air-Augmentation of a Rocket-powered Launch Vehicle -- A definitive, while modestly-scoped study undertaken by Boeing under NASA MSFC sponsorship, in effect, examined the RENE (and like AAR system) schemes. The approach was used for powering a hypothetical *Saturn 5* class launch vehicle in which the five F-1 engines – now air-augmented -- were retained for first-stage propulsion[12]. The results were *negative;* payload was lost rather than gained. This was a consequence of the basic propulsion limitations noted above, but now compounded by the added weight of the mixing duct and the installed-engine vehicle aerodynamic drag generated in flying the increased dynamic pressure "depressed" ballistic ascent path used.

The Ejector Ramjet Engine -- Meanwhile, under Air Force Aero Propulsion Laboratory sponsorship, The Marquardt Corporation was definitively exploring the ramjet-mode capable Ejector Ramjet (ERJ) concept, through a multiyear analytical, design and experimental effort. The ERJ engine is illustrated in the simplified schematic diagram of Figure 16; note the AAR afterburner, providing ramjet-mode capability. Importantly, the ERJ was predicated, not on the SMC cycle, but rather the diffusion and afterburning (DAB) ejector-mode cycle. This specified a *non* fuel-rich rocket, with fuel heat-release *following* rocket exhaust/air mixing, followed, in turn, by subsonic diffusion to a typical ramburner elevated-pressure entrance condition (Mach ~0.25). A convergent/divergent nozzle provided a supersonic exhaust flow. Now low-speed positive augmentation was assured, and an uncompromised ramjet mode was made available beyond Mach 3, for its high specific impulse performance extension contribution.

ERJ subscale "boilerplate" engines of the half-meter (18-inch) diameter size were extensively tested at Marquardt. Both hydrogen/oxygen and hydrogen-peroxide/JP-4 propellants were tested in four different engine builds from 1964 to 1968. Several of these test engines are presented in the set of test hardware illustrations of Figures 17-20; see e.g.,[13].

The 1967 NASA Sponsored Marquardt/Rocketdyne/Lockheed "Composite Engine Study" (Contract NAS7-377) -- As evident from the foregoing discussion and illustrations, there was a large number of airbreathing/rocket combined-cycle propulsion (RBCC) concepts which had been brought forward by the mid-1960 time period. Many of these were being strongly advocated for progressing beyond the performance and operability limitations of all-rocket launch vehicles. What was needed was a systematic assessment of all these concepts, by way of "sorting out" and definitizing the leading contenders. Were this to be accomplished, a rational and orderly set of technology development and demonstration efforts could then be initiated -- given positive findings.

Such an assessment effort was proposed to NASA in 1965 by a Marquardt-led team involving Rocketdyne Division, whose rocket expertise complemented Marquardt's high-speed airbreathing forte; and the Lockheed California Company. Lockheed was then a leader in exploring the potential of hypersonic acceleration/cruise vehicles and reusable launch vehicles. Contract NAS7-377 was awarded to this team in 1966 (see the study output documentation reference following). This assessment effort was managed out of NASA Headquarters, and extensively technically monitored by a multi-center group of NASA specialists in both airbreathing and rocket propulsion technologies and systems applications. Application emphasis was on fully reusable two-stage horizontal takeoff and landing (HTHL) vehicles, in the 455,000 kg (1 million lbm) GTOW class. The first stage vehicle was to be powered by a range of "composite" airbreathing/rocket engines. The payload-carrying second stage used advanced hydrogen/oxygen rocket propulsion. This vehicle type is illustrated at its staging point in the artist concept rendering of Figure 21.

The study format, illustrated in Figure 22, provided for a progressive screening down of engine concepts, based on technical (rather than cost) criteria. As the concepts under study were reduced from the original 36 "Class 0" engines to 12 "Class 1" types, and finally to 2 ("Class 2" finalists), the analysis and design level of "technical penetration" was able to be progressively increased. The "finalist" engines turned out to be the Supercharged Ejector Ramjet (SERJ) engine, representing nearer-term technologies, and the ScramLACE (SL) engine, reflecting "further out" technologies. This latter category was represented by the combination of the technological hallmarks of air liquefaction and scramjet operation, as featured employed in the SL engine. Comparisons of the payload performance of the Synerjet engines were made, throughout the study, with reference to two non-RBCC "referee" cases: an all-rocket and an all-airbreather TBCC (turbine-based combined-cycle) powered system.

The leading Synerjet systems were found to surpass the all-rocket comparison cases in payload fractions by factors of 2 to 3. They were also found to approximate the all-airbreathing Turboramjet systems' payload performance, ScramLACE being somewhat better, and SERJ trailing the Turboramjet slightly. At the conclusion of the basic study, NASA elected to support an "extension phase" effort, organized to provide further design penetration to a "Class 3" level. This included a set of special studies on points of interest emerging from the basic study. The study plan used for this final phase of the study is shown in Figure 23. All told, a nine-volume final report set resulted[14].

U.S. Air Force/Marquardt Hypersonic Ramjet Engine Exploratory Development (1964-1968) -- The set of aerospaceplane studies cited earlier, as performed by several U.S. airframe companies for the U.S. Air Force in the early 1960s, clearly revealed the very significant system performance and operability contribution of hydrogen-fueled hypersonic ramjet operation over the general flight speed range of Mach 3 to 8. This was the demonstrated case, almost independent of the selected "low speed" mode, be it gas-turbine (as in the Turboramjet), the "deeply cooled" *cryojet* type, or one of the advanced LACE-based system variants under examination at that time, e.g., *SuperLACE*[10].

The hypersonic subsonic-combustion ramjet was also usually called upon in the makeup of those propulsion systems concepts in which a following *scramjet* mode was to be implemented. This led to the convertible or *dual-mode ramjet* approach, later to be investigated experimentally. Also, the air collection and enrichment system (ACES) approach, being examined at the time, required lower-speed ramjet operation to power the vehicle during its supersonic air-collect phase, and then to accelerate the vehicle hypersonically to the point of initiation of the ACES' final rocket mode to orbit. Operation then was on liquefied enriched air (LEA, typically 90% LO2 and 10% LN2.)

In view of the hypersonic ramjet's payoffs as thus evidenced, an intensive multiyear exploratory research and development effort was soon initiated at The Marquardt Corporation (TMC) under contract to the U.S. Air Force Aero Propulsion Laboratory, Wright Patterson Air Force Base. The effort was duly titled The Hypersonic Ramjet program. The technical key to success pivoted on needed advances in lightweight, durable structures, those capable of withstanding the severe hypersonic airflow and combustion thermal-mechanical environment. Hydrogen fuel, and a set of relatively new high-temperature superalloy materials and thermal-protection coatings, provided a firm basis for progress. Intensive component work was performed, exploring these new materials and innovative fabrication schemes were developed. Direct-connect testing of half-meter (~18 inch) diameter flight-type regeneratively-cooled hardware was extensively performed.

Following the construction and testing of several incrementally advanced ramjet combustor/ nozzle assemblies, the effort culminated with the successfully direct-connect tested hydrogen-fueled and cooled test engine shown in Figure 24 in a frontal view. It featured a variable geometry (VG) exit nozzle, and was fabricated of brazed together *Hastelloy-X* D-tubes (cooling passages), with a *Rene 41* square wire-wrapped brazed on outer structure. As called out in the simulated flight speed and altitude chart (Figure 25), this component development rig (CDR) was tested over the full Mach 3 to 8 range, accumulating some 55 run-cycles, and 3 hours of total run time at the noted conditions. Heated hydrogen was both coolant and fuel[15].

Scramjet Hypersonic Engine Ground- and Flight-Test Programs Initiated

Hypersonic Propulsion Facility Ground Testing Efforts of the mid-1960s -- In addition to the Hypersonic Ramjet Program just described, work was carried out on the scramjet-mode capable, dual-mode ramjet approach, as well as on "straight" scramjet experimental hardware. The supersonic combustion -- or *partial-diffusion* -- ramjet mode offered the important advantage of extending hypersonic airbreathing propulsion operation beyond the Mach 6 to 8 limitations of the subsonic-combustion ramjet. In ramjet mode at these speeds, specific impulse performance descends sharply for several reasons, e.g., mounting inlet momentum losses and dissociation of the combustion products. In addition, the high inlet recovery temperature and pressure levels increasingly caused severe heating and structural problems. Scramjet mode' reduced static temperatures and pressures greatly eases all of these limitations, permitting that sought-for extension of airbreathing flight speeds, beyond those of the subsonic combustion ramjet.

Under Air Force Aero Propulsion Laboratory sponsorship, scramjet-related ground-testing was performed on a variety of hardware designs by such organizations as GASL (see below), General

Electric, United Technologies and Marquardt. The U.S. Navy supported scramjet work directed toward fleet-defense missile propulsion applications at the Johns Hopkins University's Applied Physics Laboratory (JHU-APL). In view of characteristic ground facility flight-simulation limitations with respect to scramjet-mode testing, interest in flight testing of subscale hypersonic airbreathing type engines arose at this time. Two flight-test projects subsequently got underway as described next.

Hypersonic Engine Flight Test Projects Under Air Force/NASA Sponsorship -- Based on scramjet engine configurations originated by Dr. Antonio Ferri and his associates, and ground-tested by his firm, General Applied Sciences Laboratory, GASL, an Aero Propulsion Laboratory contract was provided to a Lockheed/GASL/Marquardt team to build and fly the four-engine-module scramjet-powered test vehicle depicted in the artist rendering of Figure 26,and also shown in wind-tunnel model hardware (Figure 27). The liquid hydrogen fueled scramjet modules were to be started following a solid-rocket boost to hypersonic flight conditions. The vehicle was then to accelerate over a measurable speed increment on scramjet-mode power. The project actually achieved an initial boosted unpowered-vehicle test flight. However, it was then terminated for budgetary reasons.

Over the decade: 1965-1975, the National Aeronautics and Space Administration (NASA) conducted its Hypersonic Research Engine (HRE) project, led by the Langley Research Center. This project initially focused on the prospect of flight testing a subscale dual-mode ramjet engine on the rocket-powered X-15 research airplane. Phase 1 feasibility studies were conducted by Garrett AiResearch, General Electric, Marquardt/GASL and United Technologies. Proposals for follow-on hardware development were offered by each of the contractors.

AiResearch won the Phase 2 "build and test" effort with the axisymmetric engine design shown in the following photographs. Two full-scale, but non-propulsive engines were actually flown on the X-15 up to 1968, as reflected in Figures 28 and 29. At that point, the X-15 program was concluded leaving the project without a flight-test vehicle means. Appropriately, the NASA HRE project then continued strictly on a ground-test basis. A series of successful structural and propulsive flight-simulation ground tests were conducted at the Langley and Lewis Centers in 1974, and the project was concluded in 1975. The two engine builds so tested are shown as installed in free-jet test facilities at these two centers, respectively, in Figures 30 and 31. An extensive propulsion database resulted[16].

National Aero-Space Plane (NASP) Program: Vision of Hypersonic Airbreathing Propulsion to Near-Orbital Speeds in a Combination Propulsion System

> "We are going forward with research on a new Orient Express, that could, by the end of the next decade, take off from Dulles Airport and accelerate up to 25 times the speed of sound, attaining low-Earth orbit or flying to Tokyo within two hours."
>
> President Ronald Reagan
> State of the Union Address
> 4 February 1986

The *technopolitical* story of the U.S's National Aero-Space Plane (NASP) program is highly complex (e.g., see Russell J. Hannigan's version, Chapter 6, "NASP: Pushing the Limits"[17]). But any engineering oriented summary would note that this was an extremely technically ambitious undertaking, one begun in 1984 with its Phase 1 "Copper Canyon" set of exploratory studie, conducted under DARPA funding. The project escalated in time and funding levels to a long-sustained Phase 2 in 1986, about the time of the presidential citation. Phase 2 was an extensive-technologies focused development and maturation effort. The U.S. Department of Defense (DoD; several agencies) and NASA jointly supported some five major prime contractors, and a host of subcontractors and other participants in this work, as well as conducting in-house government laboratory work.

An intended Phase 3 "build and fly" effort, scheduled to begin in 1994, with an initial crewed orbital flight targeted for mid-1999, never materialized. Instead, the Phase 2 program was first extended, and then ramped down in its level of effort, and eventually terminated in 1995. Two proposed subscale hypersonic propulsion flight test effort, referred to as "Hyflite" and "HyStp" were momentarily considered. These efforts, technically not unlike the mid-1960s' incremental scramjet flight test project described earlier, were also never fully initiated.

Over $ 2 billion of government funding, and some $ 700 million of industrial company contributions, were outlayed over the decade in which the NASP program was pursued.

The program focused on a large-scale hypersonic airbreathing powered research vehicle concept designated the X-30 (similar vehicle designs are pictured in Figures 32 and 33). The X-30 was not intended to be a direct prototype of an operational system (such concepts were dubbed "NDVs" -- NASP derived vehicles, but only employed for study purposes. It was a large lifting-body configured vehicle, in its finally defined format: ~60 m long and having a GTOW of around

200 tonnes. Powered by an airbreathing/rocket combination propulsion system made up of a special low-speed propulsion system plus a dual-mode ramjet and a separate "helper" rocket, the X-30 was predicated on extremely high Mach number scramjet-mode operation. With considerable optimism, it was to accelerate in hypersonic airbreathing operation to near orbiting speed.

Despite NASP's programmatic shortfalls, substantial technological advancements were systemmatically generated in the conduct of the program. These covered a broad range of technologies, such as a host of advanced material systems which were vigorously researched, much of which bears centrally on today's engineering challenges of achieving advanced aerospace transportation systems.

Current and Projected U.S. Airbreathing/Rocket Combined-Cycle (Synerjet) Propulsion System Developments

NASA's Advanced Space Transportation Program (ASTP) Currently Supports RBCC Propulsion Exploratory Research

The ASTP Advanced Reusable Technologies (ART) Project's RBCC Multi-Contractor Exploratory Development Effort -- An Advanced Reusable Technologies (ART) effort was mounted under NASA's Advanced Space Transportation Program (ASTP) which was established in the mid-1990s. Under a mid-1996 NASA Research Announcement (NRA) contracting initiative valued at about $ 25 million, a number of contracts were awarded by the Marshall Space Flight Center to propulsion industry and university organizations toward conducting exploratory research efforts on RBCC subscale ground-test engines. Several engine rigs have since been fabricated and tested under simulated flight conditions. Two of these research engines are shown in Figures 34 and 35[18].

Much of the ART contractor testing was conducted at GASL's modern research facilities in Ronkonkoma, New York. There, a unique facility has been established which permits simulated flight speed and altitude conditions to be acceleration-trajectory varied during a given engine run. The GASL Flight Acceleration Simulation Test (FAST) facility, developed under ART support, represents a significant and unique advancement in high-speed ground testing technology[19].

In view of the strong emphasis given to very high-speed airbreathing propulsion research in the NASP program, the ART effort focused on the less-explored, but still critical "low speed" operation of RBCC engines. Characteristically, this revolves around the ejector (air-augmented rocket) mode. However, ramjet and scramjet testing is also within the purview of the ART project, including mode-transition demonstrations. A unique project technical area is the requirement for in-space rocket-mode analysis and tests. In this case the engine flowpath is typically physically closed off upstream of the primary-rocket station, and the rockets restarted, at optimal in-space rocket performance operating conditions, e.g., mixture ratio, chamber pressure. Rocket exhaust expansion within the downstream engine combustor/nozzle flowpath is intended to effect high nozzle area-ratio rocket-mode operation. Attaining maximal specific impulse in rocket mode, which can stretch over a large flight-speed regime on the way to orbit insertion, is quite important to the achievement of high overall vehicle performance across the full mission ascent path.

An important aspect of the ART- RBCC effort was the conceptual design, early on, of a set of "Vision Vehicles" to which the several proposed engine types, in their full-scale flight-design guises, were to be integrated. This using-vehicle design work was performed by a number of airframe companies under subcontracts from the propulsion contractors. The results provided a preliminary end-use systems framework to assist in assessing propulsion system characteristics, which could subsequently guide full-scale engine design requirements identification.

Next Step: Build and Test Larger Ground-Facility and Flight Test Prototypical Synerjet Engines -- The proposed next step in the NASA ART project line of progression is to proceed to a set of flight-type engines of somewhat larger size, and different construction, than are currently being ground tested (see Figures 34 and 35). These are typically heavy-wall, "heat sink" constructed units with flowpath dimensions of the order of 20 to 30 centimeters. Actively-cooled, lightweight structural designs are now needed, those perhaps, to some degree, emulating the Hypersonic Ramjet and Hypersonic Research Engine hardware units reviewed earlier. Also, the challenge of building and integrating self-cooled hot-firing primary rocket units must be carefully and fully addressed in this next step. To date, only heavy-walled water-cooled thrust chambers were employed, as was done in the RENE and Ejector Ramjet testing of the mid-1960s as described earlier.

Following successful sea-level static, direct-connect and free-jet ground testing to the limits of simulated flight conditions and model size capabilities of available facilities, experimental flight testing will then be in order. Accordingly, the next round of ground-test engines should strive to be more or less prototypical of the flight units to follow, to achieve net program economies and to shorten the overall schedule. Two basic kinds of propulsion flight tests have been considered, as noted next -- and both types have been demonstrated in past projects, as planned, but not always as completed, as we have seen.

Two Types of Flight-test Projects -- The first type would be of the "carried passenger" experiment type: a research engine transported over the specified flight test regime by a separately powered vehicle. The planned X-15-carried HRE project, described earlier, is an (unfulfilled) example. The Russian hypersonic ramjet flight-test project, described below, is a current example. The second type would be an RBCC *self-powered* test vehicle, operating over a designated part of the eventual flight trajectory, as was intended in the solid-rocket boosted Incremental Scramjet project noted earlier, and in the Hyper-X project, also to be described below. The ultimate development in this direction would be a Synerjet-powered technology demonstrator, capable of *standalone* and perhaps even fully reusable operation. NASA's recently inaugurated *Future X* program might host this approach (however, the initial flight vehicle selected, dubbed the X-37, is an all-rocket based system).

A Contemporary Hypersonic Propulsion Flight Test Program, Conducted on an International Bilateral Cooperative Basis -- Originated by Russia's Central Institute of Aviation Motors (CIAM), three flight tests of a liquid hydrogen fueled, axisymmetric dual-mode ramjet/scramjet ("DMSCRAM") have now been made under, in progression, domestic, Russian/French and Russian/American cooperative sponsorship. The latest flight, conducted in February 1998, is reflected in Figures 36 and 37. The test engine was carried through its Mach 3 to 6+ flight test condition, mounted at the nose of a highly modified SA-5 missile. The DMSCRAM test engine operated up to a peak speed of Mach 6.4 providing telemetered propulsion data. The test hardware was recovered for post-flight inspection, with data analysis still underway[20].

Hyper-X and Trailblazer -- U.S. Synerjet Related Flight Test Projects Presently Underway

The NASA *Hyper-X* Project Conducted by an Industry Team Technically Managed by the Langley and Dryden Flight Research Centers -- The 4-meter long *Hyper-X* hypersonic test vehicle is of the typical lifting-body configuration, one equipped with an underslung two-dimensional (2D) dual-mode ramjet/scramjet engine. It will be carried to its Mach 7 and 10 hypersonic flight-test conditions by a modified *Pegasus* first-stage vehicle, following an air-launch from a B-52 aircraft. The overall flight systems is shown in this artist rendering of Figure 38. The tightly packed, highly instrumented X-43A flight unit is pictured in the captioned insert[21].

Once released from its solid-rocket booster, the test vehicle's engine will be operated on gaseous hydrogen fuel for up to about 10 seconds duration, followed by hypersonic aerodynamic maneuvering tests. Both propulsion and aerodynamic parameters are to be extensively monitored. The numerous test measurements aboard will be telemetered to ground stations; the vehicle, to be launched out over the Pacific Ocean, is not to be recovered.

Prior to first flight, a full-scale sector of the complete Hyper-X flowpath, from "tip to tail," will be ground tested in Langley's 8-Foot (2.4 m) high-temperature tunnel under Mach 7 free-jet conditions. Hyper-X is illustrative of the "separately boosted" research engine flight-testing approach discussed earlier.

The *Trailblazer* RBCC Self-Powered Demonstrator is Being Developed by the Glenn (formerly, Lewis) Research Center -- Presented in Figure 39 is the NASA Glenn (formerly Lewis) Research Center *Trailblazer* RBCC-powered research and technology demonstration flight vehicle. This "Bantam class" vehicle, equipped with three highly-integrated Synerjet engine modules mounted on its axisymmetric vehicle body, is to be vertically launched and is entirely self-powered. Cryogenic hydrogen and oxygen are its propellants. Following its multimode ejector and airbreathing mode powered acceleration ascent flight, which concludes with in-space rocket mode operation, the vehicle reenters the atmosphere and is to be recovered in an unpowered glide-in horizontal landing. While not yet given a full program go-ahead, Trailblazer is an apt illustration of the *self-powered* reusable technology demonstrator vehicle approach[22].

A "Bantam" Class Orbital Payload Delivery System -- The "W Vehicle" concept, so named because, in its original planning framework, it preceded (alphabetically) the larger-scale "X" and "Y" vehicles then under consideration, is depicted in its overall flight sequence in Figure 40, derived from NASA/Industry studies in 1995 (as published in 1997[23]. It is a self-powered reusable TSTO system concept, one based on the storable non-toxic propellant combination: hydrogen peroxide and kerosene, such as used in the NF-104A system. Post-entry, both stages are soft-landed using parachutes and momentary retro-thrusting at touchdown.

NASA's Highly Reusable Space Transportation System (HRST) Study Developed Many Combined-Propulsion/Vehicle System Concepts Toward Sharp Increases in Affordability

HRST Study Origins, Goals and Approaches -- Initiated by NASA shortly after the completion of its 1993 "Access to Space" study, and the follow-on initiation of its Reusable Launch Vehicle (RLV) initiative with industry, NASA's HRST study examined next-generation space transportation possibilities, i.e., those beyond contemporary all-rocket RLV candidates. Its aim was to explore a variety of engineering paths to a further order of magnitude reduction in Earth-to-orbit transportation recurring costs. This "affordability" goal was ambitiously set at ~$200-400/kg-payload ($100-200 /lbm-payload), *two* orders of magnitude below today's ELV/Shuttle costs. This cost target was then a full order of magnitude below that established for the all-rocket RLV operational systems, possibly to become available in the first decade of the 21st Century, e.g., with *VentureStar*™[24] or other all-rocket designs which may come about.

The findings of this special study were reported out at the end of 1997. An article in the March 1998 issue of *Aerospace America* (AIAA) provided a general summary[25]. As noted here, HRST adopted a Grand Strategy of capitalizing on technologies for "side-stepping the ideal rocket equation," with emphasis on non-staged (SSTO) vehicle system concepts. Combined airbreathing/rocket propulsion played a major role in the study's successful realization of this strategy's payoff objectives. Both combination and combined-cycle propulsion systems now joined highly-advanced all-rocket systems (with thrust/weights as high as 183:1), providing motive-power advancements for some 20 different study vehicle concepts. Also, the striking energetics advantages of launch-assist systems, e.g., subsonic catapults using, for example, electromagnetic thrust and levitation means (an approach dubbed "Maglifter"), entered the scene, significantly relaxing the flight propulsion challenges by saving the significant quantities of propellant otherwise used initially in a conventional unassisted launch.

Illustrations of HRST-class Systems: A "generic" RBCC-powered vehicle concept, representative of several of the HRST systems examined, which utilized horizontal takeoff and landing (HTHL) operation, is presented in Figure 41. Figure 42 shows a vertical takeoff and landing (VTVL) vehicle, similar to that shown at the beginning of the presentation (see Figure 2). It used Supercharged Ejector Scramjet (SESJ) propulsion, which provides the ultra-high-Isp fan mode for final post-entry descent-phase subsonic loiter and vertical let-down.

Most recently, NASA's TSTO "SpaceLiner 100" concept, illustrated in Figure 43 uses a *Maglifter* launch assist system to a high-subsonic release speed, significantly easing the requirements placed on its twin hydrocarbon-fueled ERJ propulsion complement. These engines operate in ramjet mode to Mach 6 (no scramjet mode). While, the first two systems utilize their built-in high-bypass ratio turbofan capabilities for the final descent and landing phase of the mission profile, Spaceliner 100, as configured here, is to perform a horizontal glide-in landing.

An important wrap-up phase of the HRST study was the detailed assessment work carried out on the finalist vehicle/propulsion concepts by four NASA in-house HRST Integration task teams, focusiing on: System Concept Definition, Operations Assessment, Cost Assessment, and Technology Assessment. Their in-depth reports have been recently released, generally substantiating earlier findings. Airbreathing/rocket combined-cycle propulsion was further underscored as a key enabler for future affordable, dependable space transportation[26,27].

A Look Ahead to the Year 2020 Toward the Advent of True Spaceliner Systems

"One Cannot Predict the Future . . ." -- At best, our tracking through of the *technohistory* of the airbreathing/rocket combined-cycle propulsion system approach to date, as done in this paper, can only provide some measure of informed insight as to what the next several decades *may* bring about. Still, since one cannot predict the future in any definitive way, projecting those things to be developed and deployed over these next two decades must be seen as basic speculation. And, if done from an advocacy stance, as here, probably having an optimistic slant. Nonetheless, here is expressed *one* view.

In closing, if there is to be a distinctive "standalone" airbreathing/rocket combined-cycle propulsion future, and the appearance in operating guise, of new-capability vehicle systems based on this class of powerplant, what is the sense of timing for it? When will we actually have flight-certified commercial and/or military RBCC-powered aerospace transportation systems in revenue or defense-related service? Dauntingly, the title of this paper offers a look-ahead to the Year 2020 with respect to an answer to these questions on timing. Right, but first a somewhat sobering admonition from an authority on *looking futureward:*

> Sir Arthur C. Clarke, of science-fiction and science-fact fame, reminds us in his book *Profiles of the Future:* "It is impossible to predict the future and all attempts to do so in any detail appear ludicrous with a very few years."

Spaceliner IOC by 2020? – Hopefully, avoiding the "any detail" level trap, the author herein expresses his view that Synerjet powered Spaceliner systems will very likely enter full operational service by 2020. Given as much as a *decade* for full-scale development and initial type production (such a nominal schedule has been long published[2, p. 86]), were all of the exploratory and advanced developments required for adequately statusing the involved technologies to be accomplished in the 2000-2010 period – the full ten years immediately ahead of us – a 2020 initial operational capability (IOC) seems entirely plausible.

As cited earlier[18], the NASA ASTP-ART RBCC project already constitutes a credible start in this process. But, obviously, this start must be followed up with an expanded ground- and flight-test program, just as discussed earlier in the paper. Hyper X, Trailblazer, *Future X* (its X-37, the all-rocket initial system is underway), along with the completed and ongoing RLV efforts with the DC-X, X-34 and X-33 technology flight demonstrators, are all "directionally correct" for leading into a 21st Century first decade decisive predevelopment progress. So, there are the beginnings of both programmatic momentum, and recognition of sufficient time, to fly Spaceliner operationally in 2020 – perhaps, even a few years earlier. Interestingly, NASA's present roadmap for advanced Earth-to-orbit transportation currently shows the entry point of hypersonic airbreathing systems to be 2015.

Still, all-in-all, a credible understanding of this potential new-system availability date is of high importance to those who today are concerned with the practicable longevity of America's Space Shuttle, and the possible replacement or supplementation roles of its in-development Evolved Expendable Launch Vehicles (EELVs). Expectations here are related below.

Is There a Programmatic Will to Do So? -- But what serious program and supporting budgetary plans, those visible today, would support a 2020 IOC for a Spaceliner class system? Clearly, we are here contemplating a very major commitment of R&D funding, as well as a very large investment in production and deployment infrastructure means. Fielding a true operational Spaceliner will likely cost several times that of the most expensive of the World's aircraft developments. "The (Boeing) 777, which rolled out several years ago, is estimated to have cost at least $ 5 billion to develop[28]." No such estimate for Spaceliner will be tendered here!

But there is strong evidence afoot that there exists a *programmatic will* nationally, and perhaps internationally, to bring all this about. In the U.S., as just mentioned, serious consideration is being given to the question: What will replace the Shuttle, and when? With a prudently selected set of hardware (and software) upgrades, detailed studies show that this dependable – but *very* expensive – venerable space transportation system can serve effectively until 2020, and even beyond. Nevertheless, the year-by-year high costs involved act as a "forcing function" of considerable magnitude, for seeking a suitable operationally superior changeout transportation system. Spaceliner, with its implied timing, would seem a viable candidate.

NASA's Pillar III Goals -- More directly, a strong resolve by the U.S. for achieving Spaceliner operating economies by 2020 (but literally, 2023) has been documented by NASA in its 1998 published "Pillar 3 – Goal 9" objectives[29]: "Reduce the payload cost to low-Earth orbit by an order of magnitude, from $ 10,000 to $ 1,000 per pound within 10 years, and by an additional order of magnitude within 25 years" (i.e., to $ ~100/lbm-payload or $ ~200/kg by ~2020). Important to note, these estimates are mission *recurring costs,* which equate to those of the HRST study[25,26]. They do *not* include the amortization of development costs or the system procurements costs involved. Nor are they "prices," higher numbers actually to be paid, which would include profits and other per-flight mark-ups, insurance, etc.

To repeat the subject-pertinent basic HRST study findings, generally confirmed by its follow-on NASA task forces assessments, as paraphrased earlier in the paper: "Airbreathing/rocket combined-cycle propulsion was underscored as a key enabler." This is here inferred to mean Spaceliner, with its enabling Synerjet powerplants.

Acknowledgments

This advanced space transportation overview paper was prepared by Science Applications International Corporation (SAIC) as supported under NASA Contract NAS8-99060, "Space Transportation Systems Technology," issued to SAIC Huntsville Operations by the George C. Marshall Space Flight Center. The opinions and projections expressed in this paper are, however, those of the author, and not necessarily those of NASA or SAIC.

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