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CRYOGENIC HYDROGEN-INDUCED AIR-LIQUEFACTION TECHNOLOGIES FOR COMBINED-CYCLE PROPULSION APPLICATIONS

William J.D. Escher
Transportation and Platforms Division
NASA Headquarters
Washington, DC

ABSTRACT

Extensively utilizing a special advanced airbreathing propulsion archives database, as well as direct contacts with individuals who were active in the field in previous years, a technical assessment of the realization of cryogenic hydrogen-induced air liquefaction technologies in a prospective onboard aerospace vehicle process setting, was performed and documented. This paper derives from, and summarizes this work specifically for an RBCC Workshop audience.

It reviews technical findings relating the status of air-liquefaction technologies, both as singular technical areas, and also as that of a "cluster" of collateral technological facets including: compact lightweight cryogenic heat-exchangers; heat-exchanger atmospheric-constituent fouling alleviation measures; para/ortho-hydrogen shift-conversion catalysts; cryogenic air-compressors and liquid air pumps; hydrogen recycling using slush hydrogen as heat-sink; liquid hydrogen/liquid air rocket-type combustion devices; and technically-related engine concepts.

With the advent of cryogenic liquid hydrogen as an operational aerospace propulsion fuel, roughly in the mid-1950's, propulsion researchers devised a unique propulsion cycle predicated on the unique cryogenic heat-sink qualities of this fuel, the Liquid Air Cycle Engine (LACE). This rocket-like airbreathing engine utilized its liquid hydrogen fuel flow to process atmospheric air, taken aboard the vehicle by a special air inlet, through a compact heat exchanger into its cryogenic liquid form. Using the thus produced liquid air (LAIR) in lieu of tanked liquid oxygen, this engine offered a specific impulse performance level more than double that of a comparable conventional rocket engine.

But, very significantly, this seemingly high level of performance is very substantially below that of an *optimal* hydrogen-fueled airbreathing engine, say a turbojet-cycle engine (which, however, would tend to be much heavier and more complex). The root cause for this shortfall in performance is mainly a technically daunting constraint associated with the basic hydrogen-induced air-liquefaction process: in Basic LACE *much* more than a unity equivalence ratio (stoichiometric) amount of liquid hydrogen is required to liquefy the air, typically a very fuel-rich factor-of-eight more.

Much of the subsequent technology development work in this field was dedicated to various innovative schemes to get around this intrinsic cycle limitation. Discussion of these technical approaches, in fact, provides a basic "theme" for the paper. Several propulsion system concepts, utilizing these advanced technologies (for performance improvement) are described. One of these,

"SuperLACE" was purported to achieve full obviation of this over-richness constraint by synergistically integrating a combination of those technical approaches to be described. SuperLACE was thereby offered as a candidate for integration into the aerospaceplane concepts being considered for advanced U.S. Air Force orbital missions at that time (early 1960's).

INTRODUCTION

This presentation summarizes the findings of a 1986 technology survey of work conducted in the U.S., mostly in the 1960's, related to "aerospaceplane" propulsion concepts of that time-period (Reference 1). This survey focused on numerous technological facets of in-flight/onboard air-cooling and liquefaction processes using liquid hydrogen fuel as the coolant in advanced concept Earth-to-orbit space transport vehicles. The present short paper summarizes this work as a tutorial contribution to the host Rocket-Based Combined-Cycle Workshop (please see Reference 2 or 3 for the fully developed technical paper versions from which the present short-form was developed).

TECHNICAL BACKGROUND

Basic Liquid Air Cycle Engine (Basic LACE)

The simplified schematic diagram of Figure 1 present the essential technical features of the original Liquid Air Cycle Engine, or LACE system, a concept dating to about the late 1950's originiated by researchers at (then) The Marquardt Corporation. It is perhaps instructive to view Basic LACE as a true "airbreathing rocket" since the thrust chamber and turbopump subsystems are quite equivalent to those in used in liquid-rocket propulsion systems. What must now be added, of course, is an air-induction subsystem (inlet) and the cryogenic-hydrogen cooled air-liquefaction heat exchanger, which is required to convert ambient-condition air to its pumpable liquid form. The operation of the cycle can be inferred from the schematic presentation.

Quite important to note, with the two fluids involved (hydrogen and air) in a conventional heat-exchange process, it is not possible to operate Basic LACE at, or even near the normally desired *stoichiometric* (chemically correct) air/fuel ratio of about 34:1 by mass. Consequently, the cycle is operated very fuel-rich, i.e., in a highly overfueled operation. Even so, the sea-level static (SLS) specific impulse -- calculated on propellant flow from the vehicle tankage (the air is not counted) -- is of the order of 1000 seconds, almost triple that of an equivalent hydrogen/oxygen rocket (i.e., same chamber pressure, O/F of 5 - 6, sea-level backpressure).

Since operating the cycle more nearly stoichiometrically would lead to large gains in specific imbulse (the order of 6000 seconds seems technicaly achievable near stoichiometric conditions), a series of follow-on focused efforts were targeted toward "leaning out the cycle", i.e., sharply reduce its inherent fuel-richness. Such derivitive concepts as SuperLACE, NuLACE and ScramLACE ultimately were developed in the course of time, which explains why the modifier "Basic" is appended to the progenitor cycle, LACE. The engineering techniques evolved for this purpose constitute much of the technology development activities of the intervening period, as are sketched out below (and provided in further detail in References 1-3).

A Set of Inter-Related Technologies

With the fundamental cryogenic hydrogen-induced air liquefaction process conducted via a conventional heat exchanger (as shown in Figure 1) as a "technological centerpiece", a set or "cluster" of adjunct technologies and system issues can instructively be considered. These are called out in a technically interrelated fashion in Figure 2. Several of these technical topics are directly associated with the cycle leaning-out strategy described above, e.g., para/ortho hydrogen shift-conversion catalysts, turbine expanders, and cryogenic air compressors. Some of these technologies address heat-exchanger interfaced adjunct devices and processes.

Still others of these technologies relate to operational considerations, for example avoidance of heat-exchanger fouling by atmospheric constituents, notably water vapor/droplet icing. Finally, innovative engine system concepts have been synthesized which encompass novel cycles and operating modes which go well beyond the air-liquefaction process itself (e.g., the family of Air Collection and Enrichment Systems, ACES). Several key items listed in Figure 2 will be touched upon below. It is noted that ACES, while covered in References 1-3, is not included in this shortened version presentation (i.e., of Reference 3).

LIGHTWEIGHT COMPACT CRYOGENIC HEAT EXCHANGERS

Physical Description and Operation

The simplified flow schematic of Figure 3 presents the thermodynamic essence of the compact cryogenic heat exchanger design typically considered for air-liquefaction systems in the 1960's, and relates the principal parameters of interest. A 2-step precooler/condenser configuration is usually considered in which different geometry and materials of construction may be used in each heat exchanger component. The airflow and hydrogen-coolant passages are generally arranged in a counterflow manner. The pressure and, particularly, the temperature profile of the two fluids in the direction of flow are of controlling interest.

The fundamental heat-exchanger stoichiometry problem discussed above (leading, as noted, to a situation of excessive fuel-richness) is directly related to temperature-profile effects. Specifically, a "pinch temperature" heat-transfer limiting condition occurs in the early stages of the air-condensing process, i.e., at the post-precooler "front" of the condenser unit. Here a minimum driving temperature difference between the condensing air and the warming-up hydrogen is to be established (usually of the order of 5 to 10 K), consistent with balancing heat-exchanger surface area requirements (weight, size) with the achievement of overall heat exchanger performance.

Figure 4 reflects the physical design makeup of typically selected heat-exchager matrices, reflecting here both plate/fin and tube-in-shell configurations; the latter configuration was mainly focused upon in this work. Both bare-tube and finned-tube arrangements were investigated in test heat exchangers such as that layed out flow-wise as shown in Figure 5. Aluminum alloy and stainless steel thin-walled, small diameter tubes were focused upon in the early work conducted for the U.S. Air Force by The Marquardt Corporation (now Kaiser Marquardt) and Garrett AiResearch (now encompassed by Allied Signal). Small hydrogen passages were dictated by the need to achieve high specific surface areas (square inches per cubic inches). Tube diameters of one-eighth inches (about 3 mm) with wall thicknesses of 0.1 to 0.3 mm (i.e., as thin as four mils -- 0.004 in) were employed in this exploratory testing work.

Early Subscale Experimental Test Hardware

Such small-scale heat exchanger modules of the type just described were operationally tested in a cryogenic environment both as components (left-hand sketch of Figure 6) and as integrated air-liquefaction subsystems, sometimes connected with air/hydrogen combustors (right-had sketch) at Marquardt's Saugas field laboratory facility inSouthern California. The heat-exchanger sections constructed by AiResearch were encased in sealed vacuum-insulated ducting, within which the hydrogen and airflow streams were controlled as diagrammed.

When such tests were conducted using ambient air, containing water vapor, rather than dry facility-supplied air, icing problems were met. In some cases the heat-exchange surfaces became sufficiently fouled with ice, sometimes in a matter of minutes or so, to terminate the test run. Thus, atmospheric-constituent (argon and carbon dioxide were alos potential foulants) antifouling measures became, and remain today, a subject of high interest, but not one to be further discussed here. Suffice it to say that numerous alleviation approaches have been proposed, and several successfully tested.

This small-scale experimental research and demonstration effort culminated with hot-fire operation for several minutes duration of the Basic Lace engine using a square 4 x 4 in cooled combustor. Of possible interest to the reader is the 20-minute film report covering this work presented by Marquardt researchers before the Institute of Aeronautical Sciences in 1961 (Reference 4).

INCREASING THE REFRIGERATIVE EFFECT OF HYDROGEN AS COOLANT

Hydrogen Turbine Expanders and Cryogenic Air Compressors

One approach for enhancing hydrogen's refrigerative effect is to extract enthalpy from the hydrogen by causing it to perform work, e.g., by flowing it through a turbine expander. At the cost of a measuarble pressure drop, the temperature level of the hydrogen can be significantly reduced, thus allowing it to liquefy more air than otherwise. A distinct advantage of the turbine-expander approach is the resulting shaftpower which can be used productively to drive pumps, compressors and other auxiliary devices.

One device which might be so-driven is a cryogenic air compressor as used in both air-liquefaction based systems, but also in systems referred to as "cryojets", in which air is cooled but not liquefied. Here, compressing the very cold gaseous air (vs. ambient temperature air) to combustor entrance conditions requires a very much smaller, simpler and lower-power compressor than would otherwise be the case. Also, the characteristic condenser pinch-temperature constraint discussed earlier can be partially obviated and the cycle thus leaned out to some degree.

Cryogenic air compression can also assist directly in air-liquefaction dependent concepts. In effect, more air can be liquefied once it is compressed because, both the condensing temperature is raised and the latent heat of condensation is reduced. Archival study references reveal that significant attention was given to this approach in which, usually, a hydrogen turbine expander was used to drive the cryogenic compressor.

Para/Ortho Hydrogen Shift Conversion Process (Use of Catalysts)

Continuing to pursue the paper's basic theme of "leaning out the cycle" for performance gains, another leading approach, borrowing from basic cryogenic engineering practice, is the incorporation of para-/ortho-hydrogen shift conversion catalysts into the air/hydrogen heat-exchange process. For this, an elementary understanding of the equilibrium makeup of hydrogen with respect to its two naturally occuring forms. These are discriminated in terms of the diatomic molecule's atomic nuclei spin orientation: *para*-hydrogen, where the spin directions are opposite one another, and *ortho*-hydrogen, where they are in the same direction, or have the same clockwise/counterclockwise sense. Of the two, the presence of ortho-hydrogen, the "higher energy" form is favored by increasing hydrogen bulk temperature. The para/ortho split for equilibrium hydrogen is shown in Figure 7. Note that at, and above room temperature, the hydrogen is three-fourths ortho-form, the remainder being para-form (this is referred to as "normal" hydrogen).

Conversely, para-form hydrogen is the dominant low-temperature form; liquid hydrogen (at equilibrium) is essentialy all para-hydrogen. In the commercial production of liquid hydrogen, the normal-composition ambient temperature feedstock (75/25 ortho-para ratio) is purposely shifted, by catalytic means, to all para-hydrogen during the refrigeration process. Since the ortho-to-para shift is exothermic, this shift requires additional refrigeration energy to be provided in addition to the installation of shift-conversion catalyst in the "coldbox". If this shift reaction were not done, and normal-composition hydrogen were to be produced, it would rapidly (over several hours) spontaneously convert itself to para hydrogen, releasing sufficient heat to boil off the liquid which would then, most likely, be lost as vented gas.

Now, given that liquid hydrogen is delivered as para-hydrogen, and that it is to be productively warmed up in the heat-exchange process with air, an opportunity arises to produce a matching endothermic effect by causing some of the para-hydrogen to convert to the ortho form. The amount would be limited by the equilibrium content as a function of temperature (Figure 7). But this, again, requires a para/ortho shift-conversion catalyst in view of the overly "slow kinetics" of the non-catalyzed self-equilibration process. Quantitatively, the potential refrigerative effect here is about half-again that gained in converting liquid hydrogen to gaseous form at the boiling temperature (i.e., extracting the latent heat of vaporization).

Achieving this shift conversion in a flightweight cryogenic heat exchanger entails added weight (catalyst and support) and otherwise complicates the design. Nevertheless, numerous systems studies have shown that the ortho/para- conversion approach is a desirable way of augmenting hydrogen's refrigeration capability. Consequently, fairly extensive experimental and design investigations have been pursued on this process over the years (e.g., as reported in Reference 1). For example, the platinum-family metal, ruthenium, as deposited on a refractory substrate, has been shown to be a leading candidate for this application.

<u>Subcooled Hydrogen and Liquid/Solid Hydrogen Mixtures (Slush Hydrogen, SLH2)</u>

In Figure 8, density and enthalpy-difference ratios are presented for saturated (i.e., normal boiling-point, NBP) and subcooled hydrogenat its triple point of 13 K, where a liquid/solid mixture can be formed. This presentation relates to the potential use of so-called slush hydrogen (SLH2). This is of interest to propulsion engineers from at least two standpoints: at the engine level, for performance enhancement of air-liquefaction-involved operating modes via the process of *hydrogen recycling* (to be covered subsequently), and at the aerospace vehicle systems level, for vehicle propellant mass-fraction improvements via fuel-densification effects. Taken together, the benefits of using slush hydrogen, in lieu of NBP liquid hydrogen as conventionally done, ramify into the potential for marked reduction of vehicle takeoff-condition weight and vehicle physical size.

In summary, as can be inferred from Figure 8, slush hydrogen provides for about a 15-percent (factor of 1.15) increase in fuel density and about a 20-percent increase in low-temperature heat sink. The fact that this added potential source of cooling is below the NBP liquid hydrogen temperature range is the key to obtaining recycling benefits which, for certain engine types operating modes can amount to the doubling of engine specific impulse through the resulting cycle leaning-out process of recycling (see later Figure 10).

LESS THAN FULL-AIRFLOW LIQUEFACTION BASED PROPULSION SYSTEMS

Several Distinct Technical Design Approaches Have Been Pursued

Yet another design approach for pursuing cycle lean-out strategies, this time one involving overall engine design considerations, effectively increase the refrigerative effect of the hydrogen by reducing the relative amount of air to be refrigerated to the point of liquefaction. This can be achieved in a multiplicity of ways by selecting other than 100-percent of the engine airflow to be liquefied, the remaining air then being cooled but not liquefied, or not cooled at all. Numerous design variations exist in this particular pursuit, including the following examples, taken here generically, with several specific engine types being noted:

(l) the cryojet family of engines, such as versions of "SuperLACE" and "PACE" (Precooled Air Cycle Engine), is one in which *none*, or only a small fraction, of the processed air is liquefied. The rest of the air is maximally cooled, and thereby densified, providing for much more compact, lighter weight, and lower-power-demand air-compression devices than conventionally required in, say, turbojet engines (see the above discussion of cryogenic air compressors). The net result is somewhat increased performance than typically achieved intrue air-liquefaction systems in a lighter-weight engine than a conventional airbreathing system.

(2) Split-airflow engines have been conceptualized which fractionally divide the airflow into both a liquefied and a non-cooled airstream, the liquefied air being produced by cryogenic hydrogen heat exchange, pumped to pressure, and burned with hydrogen, under either fuel-rich or stoichio-metric conditions, depending on the design. See later Figure 9 for a simplified schematic of the RamLACE engine concept which is based on this approach. This, in turn, provides the means of compressing the non-cooled airstream, following which, the remainder of the hydrogen is injected and burned in the compressed airflow. Examples include the Liquid Air Turbo-Accelerator (LATA) and the RamLACE/ ScramLACE family of concepts. The former uses a conventional mechanical compressor, the latter an air-augmented rocket type "jet compressor", which operates basically as an ejector .

(3) Precooled and/or Intercooled Turboaccelerators are basically conventional turbojet/ turbofan-based engines which use their limited available quantities of combustion hydrogen to cool the airstream somewhat, increasing its density to achieve advantages similar to those of cryojet systems. However, near-saturation cold-air conditions are not approached as they are in cryojets. In being compressed, the somewhat denser air allows for modest reductions in compressor hardware size and power extraction requirements, at the expense of the weight and airflow pressure-drop of the required heat exchanger.

(4) Hydrogen Expander, Regenerative Hydrogen Air Turborocket, Air Turbo Exchanger, and other such proposed engine types, are technically related to the above turbomachinery based systems, but they differ mainly through heat addition to the hydrogen from combustion processes, sometimes in addition to the heating provided by high-speed flight intake air (see, for example, the hydrogen-expander engine discussion in Reference 1). Larger quantities of compressor shaftwork can be extracted through subsequent turbine-expansion with such hydrogen heating, following which, the hydrogen is burned in the engine. These systems are not, however, usually viewed as "air liquefaction related" systems.

An Exemplary Split Airflow Combined-Cycle Engine Concept: RamLACE

One of the numerous cycle lean-out strategies, namely the second item in the above listing, involves a splitting of the engine-induced airflow into two or more streams, and liquefying only one of them. This approach is reflected in the RamLACE family of engines represented in Figure 9 in a simplified schematic. RamLACE was derived from the non-liquefaction Ejector Ramjet engine concept by researchers at Marquardt, sometime after the press of the original aerospaceplane predevelopment work subsided. This type of combined-cycle engine, while centering on the ramjet for operation in the Mach 3 to 8 flight-speed range, utilized an internal set of liquid rocket units ("primary rockets") which -- in effect -- were air-augmented in an ejector-like configuration. The resulting internal *jet compression* of the "secondary" air stream provides the opportunity to afterburn it in the ramjet combustor, and expand the combustion products through the nozzle, producing significantly more thrust than that of the rockets alone. At ramjet takeover the rocket unit would be turned off and ramburner operation continued. Thus was created a simple, lightweight bimodal supersonic/hypersonic engine not requiring any mechanical compression hardware, other than a set of compact, low-power-requirement propellants pumps. The Ejector Ramjet had reached a subscale ground-test status by the late 1960s, but RamLACE, though extensively addressed in conceptual design and application studies, is not known to have achieved such an experimental stage.

RamLACE as the Air-Liquefaction Variant of the Ejector Ramjet Engine

Whereas the Ejector Ramjet used conventional tanked bipropellants, e.g., hydrogen and oxygen, RamLACE uses liquid air (LAIR) directly processed through the now-familiar hydrogen-cooled heat exchanger and thus needs no tanked oxidizer. Nevertheless a fuel-richness problem remains, although it is considerably ameliorated since, typically, only about one-third of the air flowing through the engine must be liquefied, namely, that used in the primary rockets. It turns out that cycle- dictates require a *stoichiometric* primary rocket operation, so that the excess (over stoichio- metric) hydrogen is fed to the afterburner, which thereby operates considerably fuel-rich. At an overall engine fuel/air equivalence ratio of around 4 (half of Basic LACE's), the sea-level static specific impulse is about 1400 seconds, and this increases markedly with flight speed, according to the build-up of ram-pressure in the inlet diffuser. This marks the onset of high- performance ramjet-mode effects prior to the termination of the ejector (air liquefaction) mode, it being still required to achieve the required level of vehicle thrust, prior to full ramjet-mode takeover.

TECHNOLOGICALLY RELATED PROPULSION SYSTEMS CONCEPTS

Recycled RamLACE/ScramLACE

Recalling earlier Figure 8 which characterized the density and enthalpy nature of slush hydrogen, *hydrogen recycle operation* is yet another performance improvement avenue in the pursuit of the cycle leaning-out strategy. It is is reflected in the *Recycled ScramLACE* engine concept represented in Figure 10; this is basically a scramjet-capable variant of RamLACE, covered in the previous paragraphs. Note that the vehicle hydrogen tank is brought into the picture, and that the heat exchanger is now equipped with a hydrogen-return line positioned in between the condenser and the precooler. In this arrangement, the amount of cryogenic hydrogen available for liquefying the air is substantially greater than that immediately to be consumed in the engine. The cycle is accordingly leaned out. The recycled hydrogen is returned as warmed up gaseous hydrogen which is to be *reliquefied* within the hydrogen tank. The fuel that is initially tanked *must* be slush hydrogen, or at least subcooled liquid; recycle cannot be performed with NBP hydrogen since there is no usable heat sink in the tanked fuel. Unacceptable boil-off effects would be encountered. Typically, as mentioned earlier, a 50/50 slush mixture is used at the triple point temperature (13 K, 25 R).

In operation, the amount of *liquid* hydrogen (ideally, slush is *not* removed from the tank) which is passed through the temperature-pinch-limited condenser can be well in excess of that passing into the engine's combustors, distinctly not the case in non-recycled air liquefaction engines. This means a larger quantity of air can be liquefied than otherwise, and the cycle thus made less fuel-rich -- the basic performance objective. The recycled hydrogen, now somewhat warmed up, but still a cryogenic fluid, is returned to the tank. In certain designs a turbine expander is placed in this return line, providing cooling and power extraction, as previously covered. The recycled hydrogen is then reliquefied by indirect (via a heat exchanger) and direct contact (i.e., hydrogen injection into the tanked fuel) with the remaining subcooled tanked hydrogen. This, in turn, adds heat to the tanked fuel, melting the solid hydrogen and in a relatively brief period, raising the bulk temperature toward NBP conditions (20 K, 36 R).

This recycling process is obviously constrained by finite stored-enthalpy considerations, hence it is operating-time limited. Accordingly, an assigned *recycle rate* is established for the air-liquefaction dependent ejector-mode operation such that the remaining tanked hydrogen just approaches NBP conditions, as the engine is to be shifted to ramjet mode where air liquefaction ceases. Thereafter, the non-liquefaction modes to follow, in this case ramjet and scramjet operation, continue in conventional fashion insofar as the fuel supply is concerned.

The recycle rate is taken to be the fraction (stated as a percent) of the total hydrogen flow entering the heat exchanger which is returned to the tank. The range of practical interest is about 25 to 50 percent, 0 denoting a non-recycled case. Hydrogen recycle operation, for realistic recycle ratios can, at best, *about double* the specific impulse of an equivalent non-recycle engine. For example the previously stated 1400 seconds for RamLACE would rise to about 2700 seconds in an optimal Recycled RamLACE engine. However, the heat exchanger condenser would now be larger, hence significantly heavier, to handle the augmented flows. The added fuel-circuit hardware required for recycling and reliquefaction adds weight and complexity as well. The most significant challenge, perhaps, is the proposition of producing, sevicing and maintaining slush hydrogen in the vehicle propellant tank, and then providing a practical heat-exchange means for using this additional low-temperature heat-sink to cool and completely reliquefy the recycled warmed-up gaseous hydrogen.

SUPERLACE: SYNERGISTICALLY INTEGRATING SEVERAL CYCLE LEANING-OUT OPTIONS

Multiple-Process Makeup and Operation of a Representative SuperLACE Concept

Once again, proceeding from Basic LACE, the various technologies discussed so far were, by and large, integrated into a class of propulsion systems generically referred to as *SuperLACE*, one example being reflected in Figure 11. This involves as many as three of the cycle-lean-out strategies cited earlier, plus a fourth one not yet discussed: use of a LAIR regenerator/boileras a pre-precooler in the heat exchanger train. All four are integrated in this particular engine concept as reflected in the simplified flow schematic of Figure 11. Starting with the vehicle fuel supply, it can be seen that slush hydrogen is initally tanked to provide for recycle operation, as just described. Secondly, as covered earlier, the pressurized and warmed-up recycle hydrogen is passed through a turbine expander for cooling and shaftpower generation (e.g., as needed to drive the various turbopumps).

Thirdly, a para/ortho shift conversion catalyst is incorporated into the cryogenic heat exchanger. It is shown here as an external unit located flow-wise between two portions of the condenser. Actual design practice would likely be otherwise; for example it has been suggested that the fairly bulky and heavy catalyst be placed in the air-header sections *throughout both* the condenser and the precooler elements to continuously catalyze the endothermic para/ortho shift, as the hydrogen progressively warms up.

Returning to the fourth avenue named above, the LAIR regenerator/boiler adds a non-hydrogen heat exchanger at the front end of the regular precooler. This uses high-pressure LAIR as coolant for initial cooling of the warm-to-hot air extracted from the inlet diffuser. This provides the double advantage of warming up the engine's oxidizer stream (thermodynamic advantage) while gasifying the LAIR (practical combustor design advantage), on the one hand, and providing augmented precooling of the air, reducing the cooling load of the hydrogen-cooled heat exchanger, on the other.

The SuperLACE features described here mainly apply to the initial acceleration mode for an engine which usually offers high-speed ramjet (but not necesarily scramjet-mode) operating capability. This system can be integrated with the Air Collection and Enrichment Systems (ACES). This distinctly complementary approach is described in References 1-3, but not in the present paper. Such a SuperLACE/ACES combination concept will be next described. Since the various cycle lean-out techniques (i.e., the four described) operate independently, their effects are productively compounded. Proponents of SuperLACE claimed near stoichiometric operating possibilities resulting in, as will be seen, specific impulse levels of that of an advanced hydrogen-burning turbojet cycle, ca. 6000 seconds at sea level static conditions.

<u>SuperLACE/ACES for Single Stage to Orbit Applications (as proposed in the early 1960's)</u>

As suggested in the previous discussion, the two advanced air-liquefaction based concepts covered earlier, SuperLACE and ACES, were combined into a single, integrated Earth-to-orbit propulsion system: *SuperLACE/ACES.* Its performance characteristics are presented in the specific impulse vs. flight speed plot of Figure 15, one which clearly reflects the principle of *multimode operation* in a single-stage-to-orbit system. A reference hydrogen/oxygen rocket specific impulse level is provided (dashed line at bottom of the plot). Also, Basic LACE is reflected over its maximally-assigned speed range of 0 to Mach 8. This is about 1000 seconds at sea-level static conditions, dropping off to half that at its upper speed limit. This is largely a consequence of the very large ram-drag force component sustained in a hypersonic inlet that must completely "stop" the airflow in order to liquefy it statically.

The two near-vertically running lines labeled "Hyperjet" refer to operating mode transitions in a convertible rocket/ramjet concept by this name created by Marquardt, sometimes alluded to as an inlet valved-off ramjet. This serves as a low chamber- pressure rocket from static conditions up to ramjet takeover speeds of about Mach 2. Here the inlet valve is open and the unit operates as a ramjet. Either hydrogen/oxygen or hydrogen/LAIR (i.e., Basic LACE) initial rocket operation can be considered (the two lines on the left). The descending line between Mach 4 and 8 marked "ACES"(as well as "Hyperjet") is simply what was anticipated as performance of a hydrogen-fueled subsonic combustion ramjet system. Ground testing of such a subscale, flightweight hydrogen-cooled ramjet engine was ultimately carried out by Marquardt for the Air Force ca. 1968.

High-Speed Operation - The hatched triangular area in the Mach 8 to 16 speed range marked "growth" represents a potential scramjet-mode extension of speed-limited ramjet operation. It should be noted that, at the time this SuperLACE/ACES approach was being considered (early-1960's), scramjet (*supersonic*-combustion ramjet) operation was only being analytically investigated by the propulsion research community. Hence it was not sufficiently mature, as a working propulsion choice, for assimilation into propulsion system concepts being readied for near-term development. It therefore was viewed, as alluded to here, as a "growth" performance enhancement measure.

Above Mach 8 then, ignoring this "growth" area for the moment, ACES involved rocket operation on LEA/Hydrogen using the Hyperjet (with inlet closed). The dashed line just below the oxygen/hydrogen rocket line reflects the slightly lower rocket performance predicted with the nitrogen-diluted oxidizer to be used (LEA). However, since oxygen "tanking up" takes place at supersonic/hypersonic flight speed and high altitude conditions, rather than on the ground at zero speed, a much higher *equivalent* specific impulse value can be calculated, as shown in the elevated curve ranging from about 1500 down to 1000 seconds. In effect, this is the payoff of ACES as related in terms of engine performance trends.

SuperLACE Operation - This leaves only the "low speed" operation of SuperLACE to be covered. It is as described in the previous chart, i.e., a design involving the compounding of several cycle- leaning-out measures. The objective was to approach stoichiometric operation, thereby achieving much higher specific impulse levels than are available from Basic LACE. As displayed here, in the pre-ramjet flight-speed range of Mach 0 to 3-4, this engine cycle (or set of cycles) is stated to provide 5500 to 6500 seconds of specific impulse statically, ranging down to 4500 seconds at ramjet takeover. As pointed out earlier, this is the level of performance which, from today's perspective, can be estimated for an optimal near-stoichiometric turbojet engine operating on hydrogen fuel. To the extent that SuperLACE is a credible concept, this same level of performance is (perhaps, better, *was*) seen to be provided by a relatively simple (no major rotating parts), lightweight engine.

FURTHER CONSIDERATION OF RAMLACE/SCRAMLACE

Some few years following the demise of aerospaceplane, new alternative air liquefaction based propulsion system concepts arose, still using much of the same technology which evolved through the earlier research and predevelopment activities previously described. Now, however, with much more analytical and testing background being available, the salient importance of the hyper- sonic hydrogen-fueled ramjet, including both sub- and supersonic-combustion variants, became a dominant factor in the design- selection process. The dual-mode or convertible ramjet/scramjet concept was born (and tested). Since this provided telling performance advantages, most of these intermediate-period alternative concepts focused on achieving maximum-performance ramjet/scramjet mode capability, as well as striving for minimal complexity and lightweight construction. Along with their non-liquefaction family members (e.g., Ejector Ramjet, Ejector Scramjet), such concepts as RamLACE and ScramLACE were proposed and explored analytically and at the conceptual design level. These concepts were introduced earlier in Figures 9 and 10. This conceptual design work was performed mostly by Marquardt and its contractor associates for the Air Force and later for NASA).

In Figure 13's representation of these engine types, it is shown how such propulsion systems, departing from the progenitor Basic LACE concept largely by incorporating various cycle-leaning-out strategies, have led to several high-performance ramjet-centered engine types which are comparatively simple and lightweight. As a direct consequence of their air-liquefaction related operation, these concepts can also achieve high *initial* levels of performance without recourse to large, heavy rotating machinery. RamLACE and its recycled (slush hydrogen) variant are shown here, but this applies equally well to the ScramLACE (scramjet capable) family of concepts.

In some cases this class of engine integrates a fan-supercharging subsystem which somewhat improves initial performance and operability, but mainly is proposed to provide a competent vehicle end-of-mission subsonic loiter and powered landing capability at very high levels of specific impulse. Although limited in thrust and speed range, the hydrogen-fueled high bypass ratio turbofan cycle involved can achieve specific impulse levels of the order of 30,000 sec. This ramifies favorably to a low loiter/landing fuel mass requirement.

SUMMARY AND CONCLUDING REMARKS

Summarizing this brief report of a survey of cryogenic hydrogen-induced air-liquefaction technologies as developed in the U.S. several decades ago, and which are evidently of renewed interest today, the following key observations can be offered in conclusion:

- Work began with the Basic LACE concept originated in the mid-1950s, which became the progenitor of numerous air-liquefaction related technologies, leading aspects of which have been discussed in this paper.

- Air liquefaction related concepts proliferated, many reaching the predevelopment hardware stage, in direct response to the technically ambitious goals of the original aerospaceplane program, of which the U.S. Air Force was the leading sponsor.

- A fundamental technological edict quickly emerged, one which was actively pursued through several different design strategies at the time, as a direct consequence of the inherent fuel-richness of the Basic LACE concept: *Lean out the cycle.*

- SuperLACE/ACES, perhaps, represented a culmination of advanced propulsion thinking of this era; SuperLACE combining a multiplicity of cycle-lean-out measures, and ACES extending "airbreathing" operation beyond the then-perceived ramjet flight-speed limit (Mach 8) all the way to orbital speed (recall scramjet, as a prospective means to thus extend airbreathing flight speeds, was then just on the technological horizon).

- Subsequently, in the mid-1960's, the development and demonstration in flight-hardware of hydrogen-fueled ramjet ground-test engines led to the Ejector Ramjet family of engine concepts. The air-liquefaction based variant was the RamLACE engine. Further research efforts on extending high-speed airbreathing operation beyond Mach 6-8 flight speeds led to a strong focus on the potential of supersonic combustion ramjet (*scramjet*) mode operation of a combined-cycle engine. Again, the air-liquefaction variant of the resulting Ejector Scramjet concept was the ScramLACE concept.

Renewed interest has been evidenced internationally, over the past five years or so, toward once again capitalizing on many of these same cryogenic hydrogen air-liquefaction technologies; this thrust may be particularly significant today, now that air-liquefaction basic process-enabling *liquid hydrogen* has been universally adopted as the staple fuel for rocket-powered space-vehicle systems (see Reference 5 for an authoritative technohistorical treatment of this specific subject). Liquid hydrogen fuel is now also under serious consideration for proposed hypersonic airbreathing-powered vehicles which may well be powered by combined-cycle engines of the type considered in this presentation.

REFERENCES

1. Escher, W.J.D. and Doughty, D.L., "Assessment of Cryogenic Hydrogen-Induced Air-Liquefaction Technologies", Astronautics Corporation of America final report under SAIC Subcontract No. 15-860020-82, under U.S. Air Force Prime Contract No. F33615-84-C-0100, September 1986 (limited/restricted distribution)

2. Escher, W.J.D., "Cryogenic Hydrogen-Induced Air-Liquefaction Technologies," NASA Heaquarters paper presented at the NATO Advisory Group for Aerospace Research and Development (AGARD) 75th Symposium of the Propulsion and Energetics Panel on Hypersonic Combined Cycle Propulsion. 28 May - 1 June 1990, Madrid, Spain

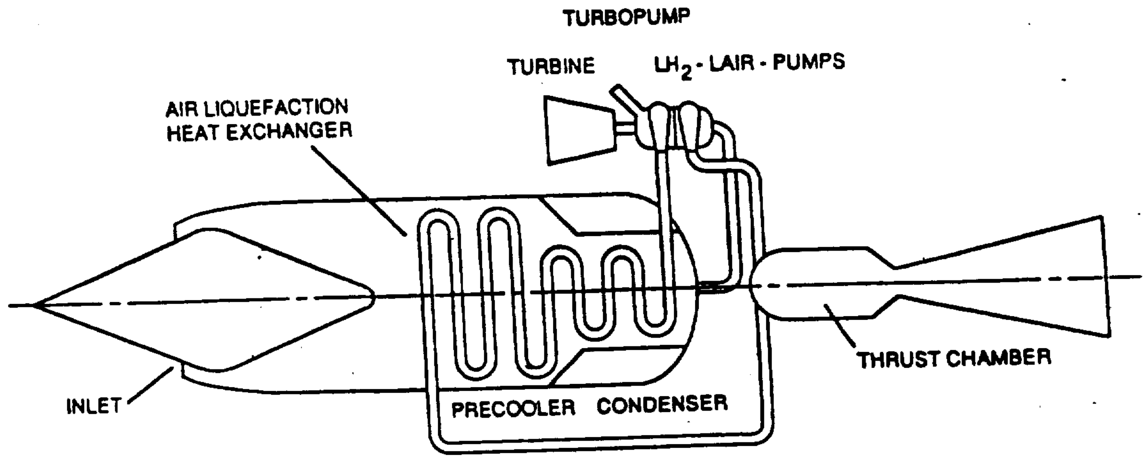
3. Escher, W.J.D., "Cryogenic Hydrogen-Induced Air-Liquefaction Technologies," NASA Heaquarters paper presented at the 1990 JANNAF Propulsion Meeting, 2-4 October, Anaheim, California

4. Anon., "Liquid Air Cycle Engine, film report by The Marquardt Corporation presented at the annual meeting of the Institute for Aeronautical Sciences, 1961

5. Sloop, J.L., "Liquid Hydrogen as an Aerospace Fuel 1945-1949," NASA SP-4404, 1978

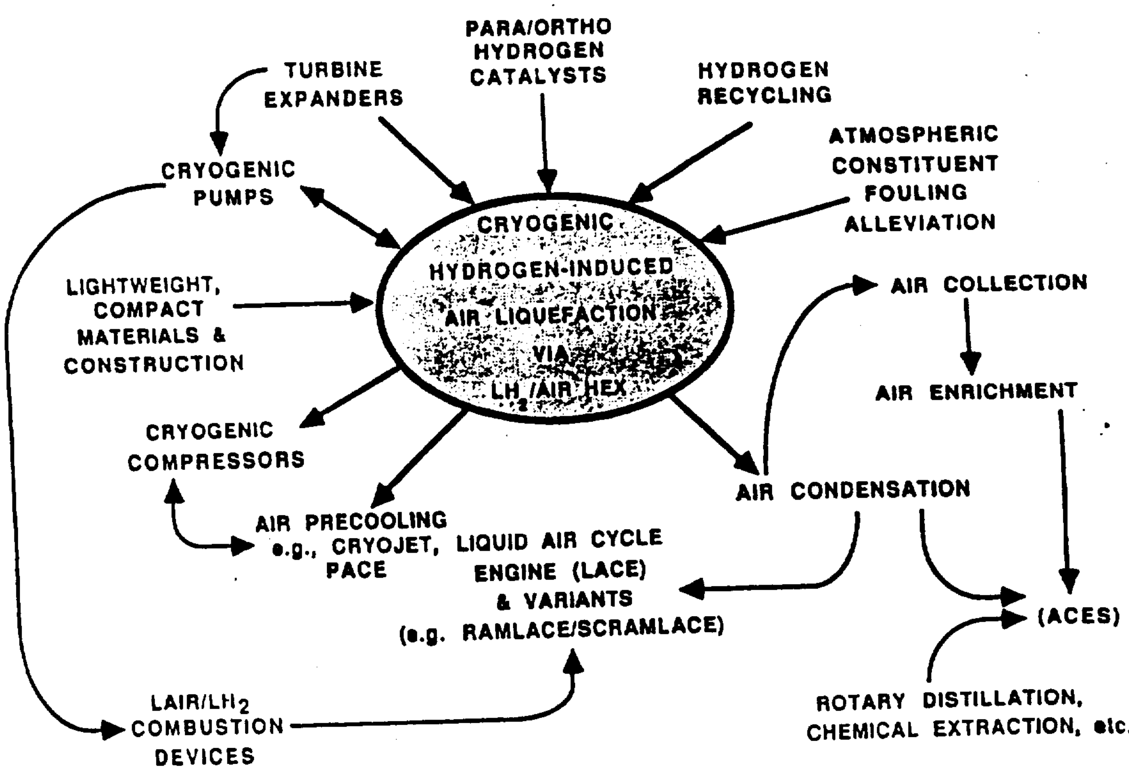
<u>Author's note</u>: Reference 3 is a rewritten, somewhat references-expanded version of Reference 2. Reference 2 is basically a summary of the work reported in Reference 1. Finally, the present paper is a shortened version of Reference 3.

BASIC *LACE* (LIQUID AIR CYCLE ENGINE)



Basic LACE I_s = 1000 lbf/lbm/sec
ϕ = 8

CRYOGENIC HYDROGEN-INDUCED AIR LIQUEFACTION: AN INTERRELATED *CLUSTER* OF DIVERSE TECHNOLOGIES



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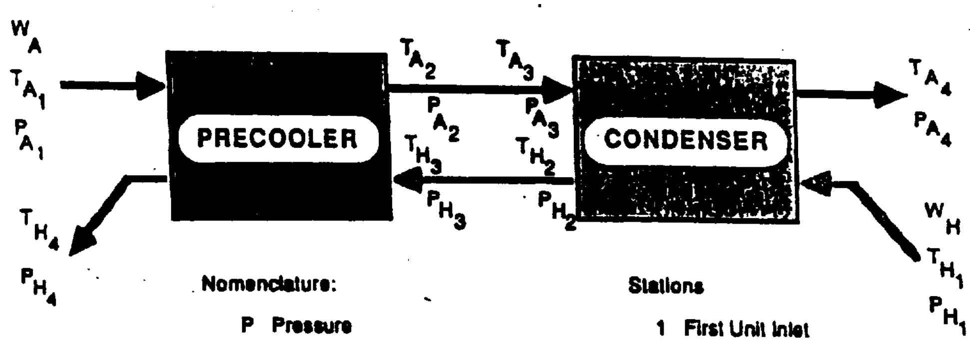
HEAT EXCHANGER SCHEMATIC & KEY NOMENCLATURE



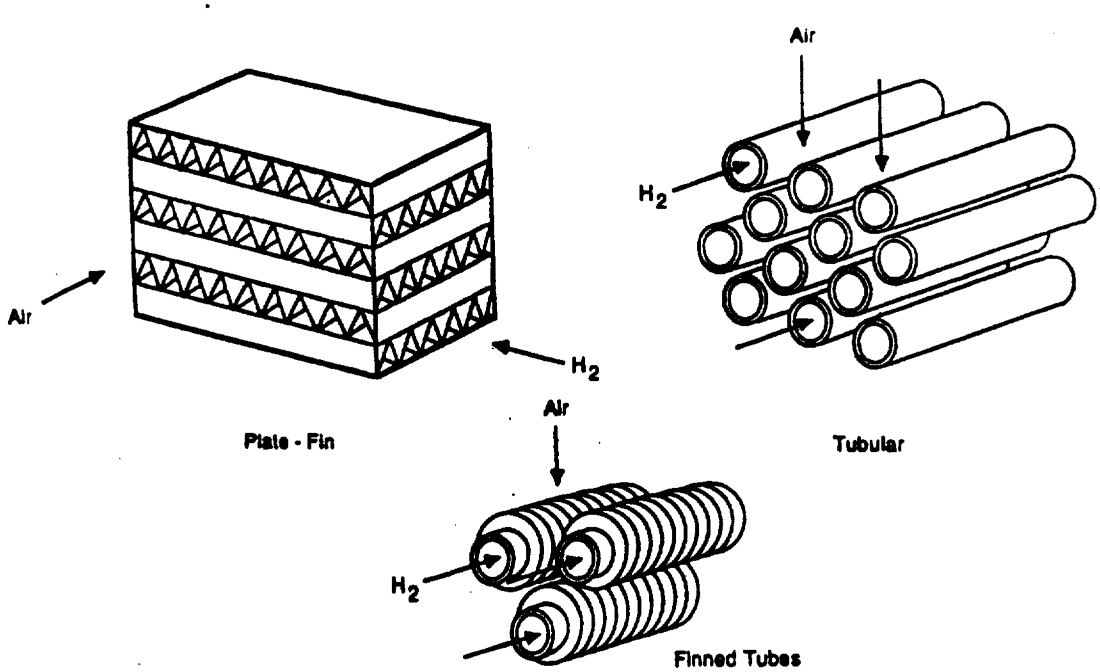
Nomenclature:

- P Pressure
- T Temperature
- W Flow Rate
- A Air
- H Hydrogen

Stations

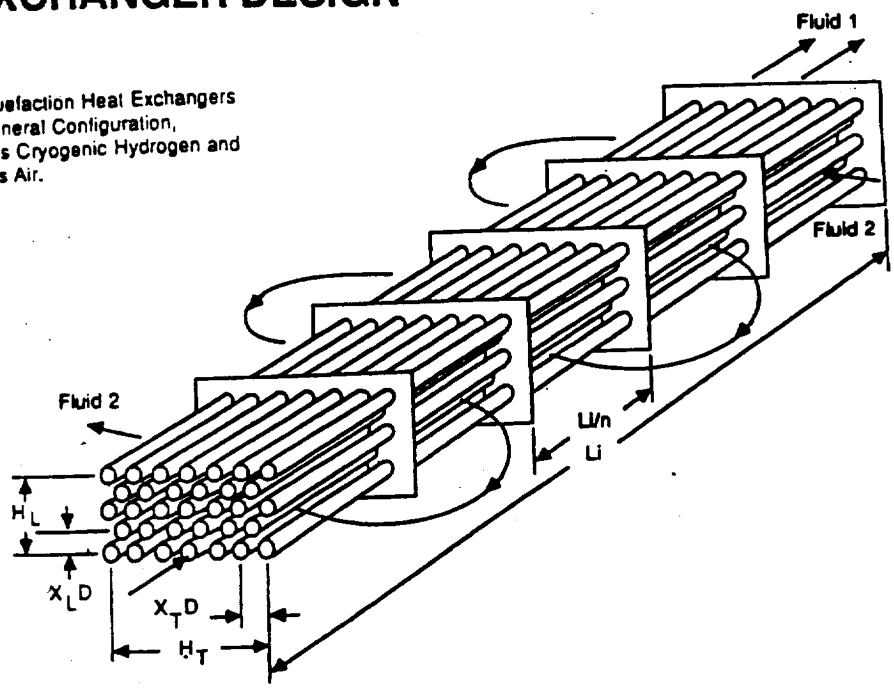
1. First Unit Inlet
2. First Unit Exit
3. Second Unit Inlet
4. Second Unit Exit

TYPICAL HEAT EXCHANGER MATRIX DESIGNS

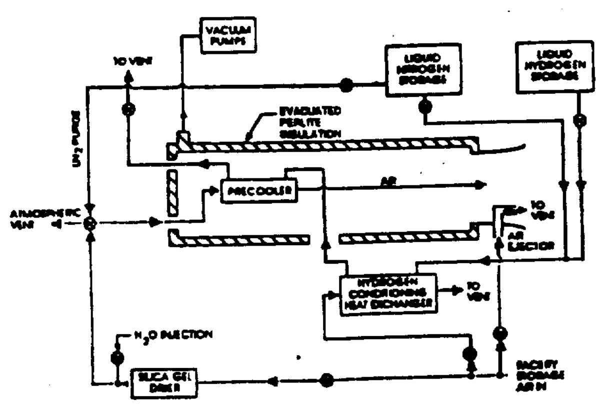


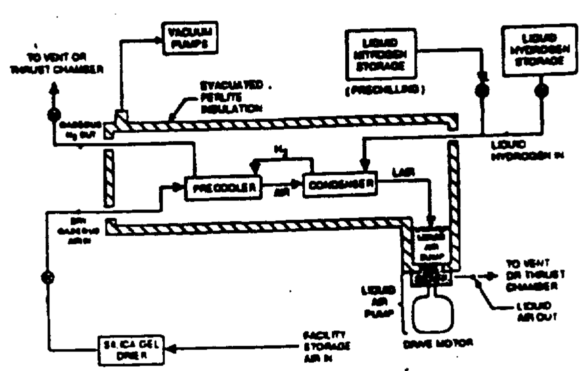
REPRESENTATIVE CROSS-COUNTERFLOW TUBE-IN-SHELL HEAT EXCHANGER DESIGN

Note: In Air Liquefaction Heat Exchangers of this General Configuration, "Fluid 1" is Cryogenic Hydrogen and "Fluid 2" is Air.

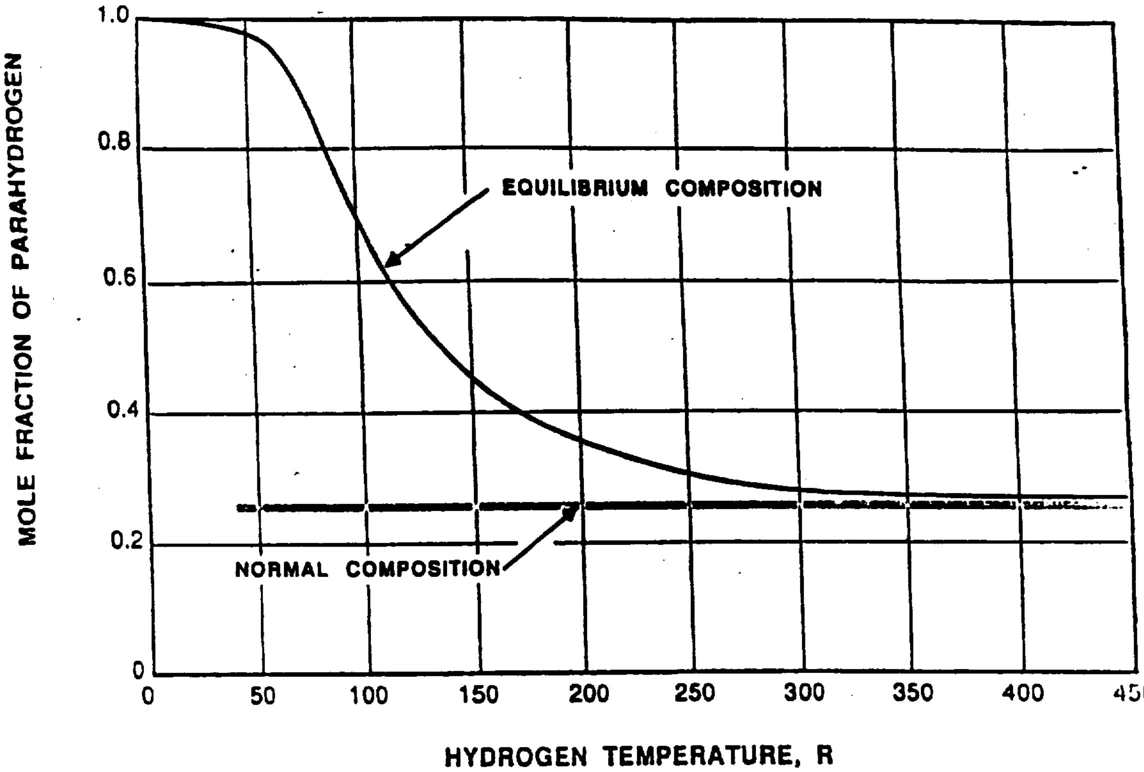


TYPICAL EXPERIMENTAL TEST SET-UPS

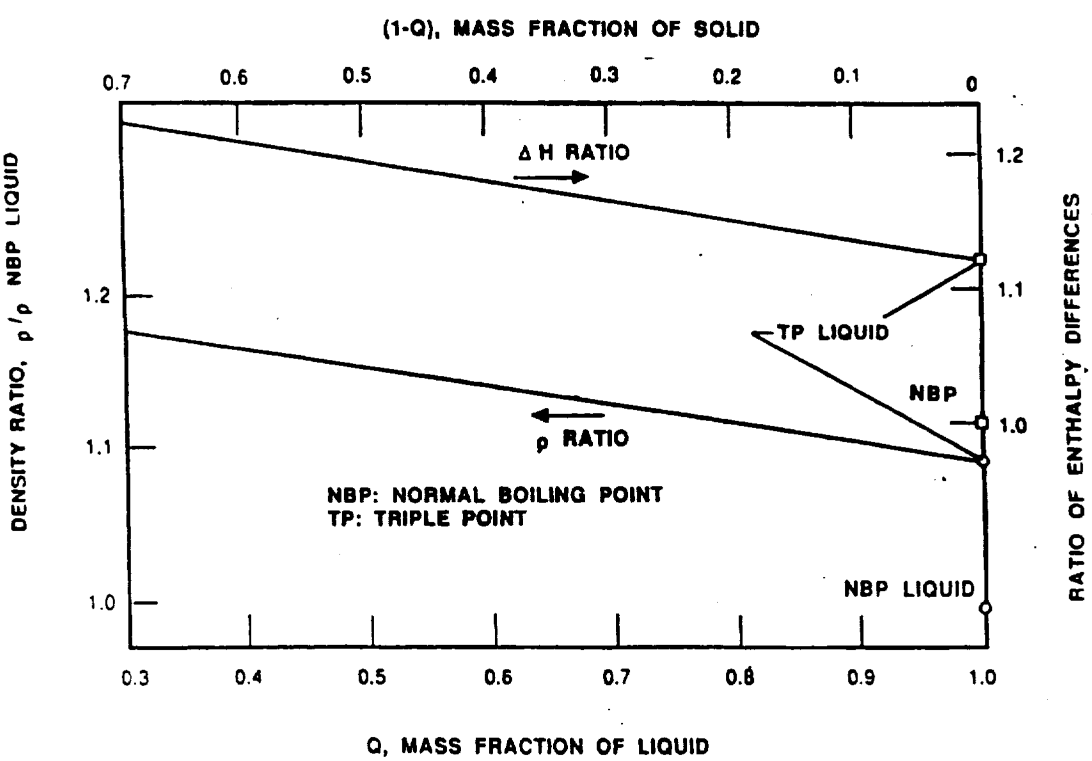




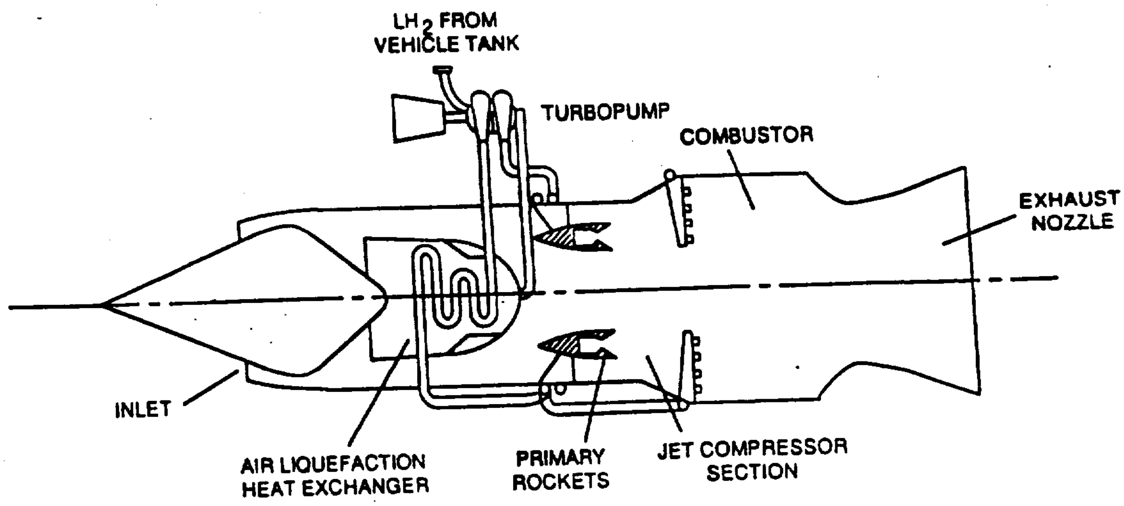
HYDROGEN PARA-FORM CONTENT vs. TEMPERATURE



DENSITY AND ENTHALPY DIFFERENCE RATIOS vs. LIQUID/SOLID CONTENT OF SUBCOOLED LIQUID HYDROGEN

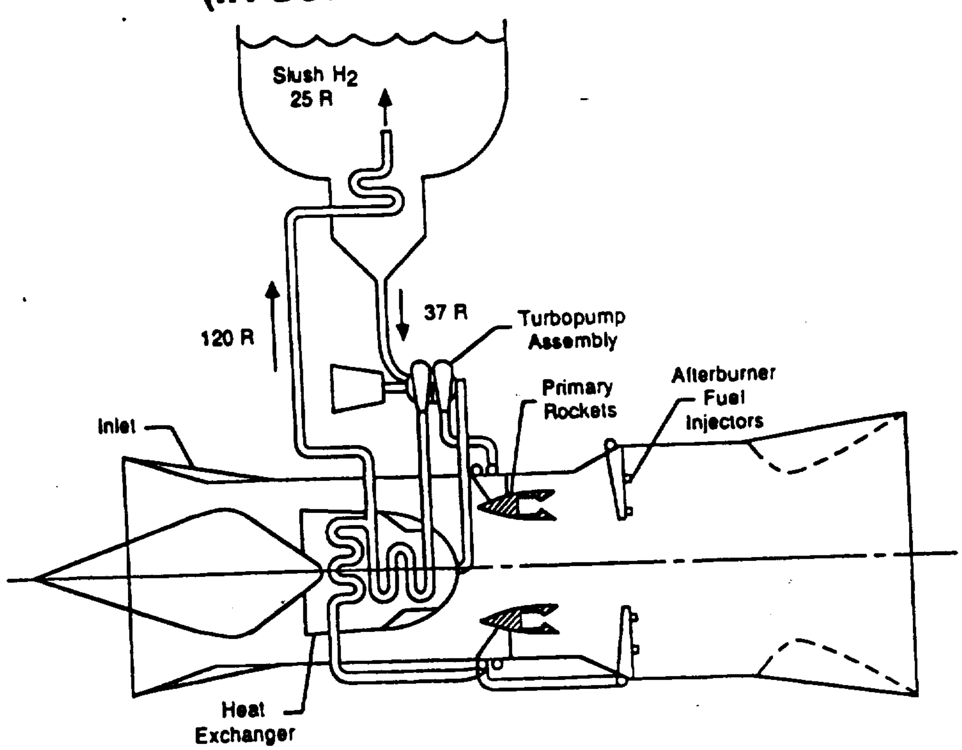


RAMLACE ENGINE

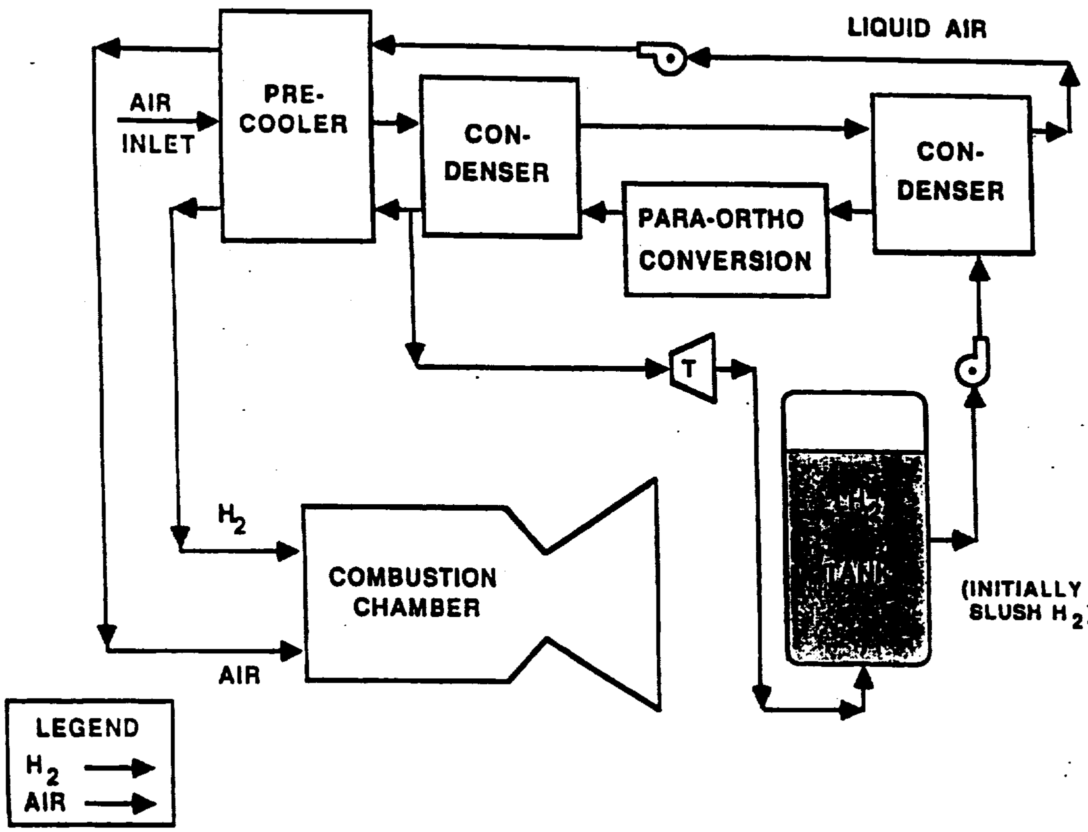


RamLACE I_s = 1400 lbf/lbm/sec
ϕ = 4.5

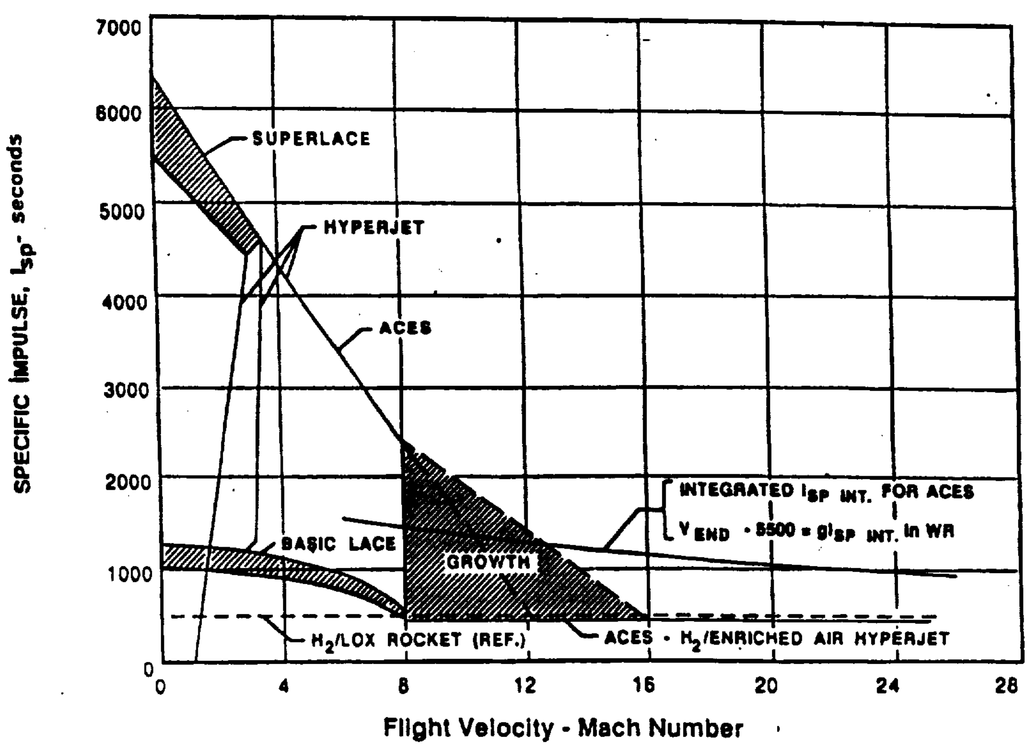
HYDROGEN RECYCLE OPERATION (IN *SCRAMLACE* ENGINE)



REPRESENTATIVE *SUPERLACE* SYSTEM



SUPERLACE/ACES SPECIFIC IMPULSE vs. FLIGHT VELOCITY



PROGRESSIVE "LEANING OUT" TRENDS:
BASIC LACE/RAMLACE/RECYCLED RAMLACE