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# Airbreathing Space Boosters Using In-Flight Oxidizer Collection

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**A historical review of the development of a propulsion fluid system known as ACES (air collection and enrichment system) is presented. The role of the ACES system is to acquire and store liquid oxygen (LOX) en route to orbit for rocket use beyond the airbreathing envelope. The refrigeration capacity of liquid hydrogen is employed to condense the air and fractional distillation used to extract the oxygen component from the inlet airflow. Earth-to-orbit capability is achieved without carrying LOX from takeoff or relying on scramjets. The development history of the major ACES components is traced and a review of ACES system studies conducted since the 1960s is provided. The payload fractions achievable with ACES are shown to be competitive with scramjet-powered space launch vehicles without relying on airbreathing propulsion beyond the speed of conventional turboramjet engines.**

## Nomenclature

| | |
|---|---|
| $CR$ | = collection ratio, kilogram of oxidizer collected per kilogram hydrogen fuel coolant |
| $GW_{ACES}$ | = gross-takeoff weight of ACES vehicle |
| $GW_{LC}$ | = gross-takeoff weight of LOX-carrying vehicle |
| $g_c$ | = gravitational constant |
| $I_{sp}$ | = specific impulse |
| $I'_{sp}$ | = apparent or effective specific impulse |
| $K$ | = first-stage weight factor of a LOX-carrying vehicle relative to an ACES vehicle, $W_{1LC}/W_1 - 1$ |
| $MR$ | = mass ratio |
| $MR'$ | = apparent or effective mass ratio |
| $O/F$ | = oxidizer-to-fuel ratio |
| $W_{ACES}$ | = weight of ACES equipment |
| $W_F$ | = weight of fuel |
| $W_{FC}$ | = fuel used by ACES during collect |
| $W_{F2}$ | = second-stage fuel weight |
| $W_{LEA}$ | = weight of liquid-enriched air |
| $W_{OR}$ | = second-stage weight in orbit |
| $W_{OX}$ | = weight of second-stage oxidizer |
| $W_1$ | = weight of first-stage structure, propulsion, and fuel of ACES vehicle |
| $W_{1LC}$ | = weight of first-stage structure, propulsion, and fuel of LOX-carrying vehicle |
| $\Delta GW$ | = gross-takeoff weight difference between LOX-carrying vehicle and ACES vehicle, Eq. (15) |
| $\Delta V$ | = boost phase velocity increment |

## Introduction

IN the late 1950s, interest grew in developing fully reusable orbital launch systems. The prospect that nonrecoverable systems would impose immense costs for space operations was as apparent then as now. As is also the case today there was interest in horizontal takeoff and landing, single-stage vehicles, and maximum use of airbreathing propulsion. The weight penalties for single-stage, horizontal takeoff vehicles having no airbreathing propulsion were known to be prohibitive. In that era, very little was yet known about scramjets and their potential for propelling vehicles to orbit.

Only very cursory studies of scramjets' prospects existed before 1960. In an effort to extend the high specific impulse payoff of airbreathing propulsion to flight speeds beyond its actual function, concepts such as an air hoarder were investigated. Such a vehicle would use the refrigerant capacity of the liquid hydrogen fuel to condense and store liquid air for a subsequent rocket mode after airbreathing operation was no longer possible. The limit of airbreathing propulsion was that of the subsonic burning ramjet (i.e., about Mach 8). By about 1959, it was concluded that collecting and storing liquid air would not be effective, the inert weight penalty of the nitrogen constituent being much too high. Just prior to 1960, studies were initiated to investigate air collection approaches in which the nitrogen component was removed and expelled from the vehicle while retaining the oxygen and storing it as a liquid. This concept, known as ACES (air collection and enrichment system), was the subject of an extensive U.S. Air Force-funded vehicle system study and propulsion hardware experimentation from 1960–1967. The ACES concept employed conventional airbreathing propulsion to approximately Mach 8. Figure 1 depicts the weight history of a typical two-stage orbital vehicle using ACES. The vehicle accelerates on airbreathing engines to approximately Mach 5 at 22,860 m (75,000 ft) altitude. Then, during an ensuing cruise phase of about 20–30 min, liquid enriched air (LEA, 90% $O_2$) is collected and stored in the vehicle. Figure 2 shows a functional diagram of the LEA collection system. Typically, 4–6 kg of LEA can be produced for each kilogram of hydrogen fuel needed to liquefy stored air and sustain cruising flight. As Fig. 1 shows, the vehicle weight increases greatly; in this example case the final weight at the end of the collect phase is substantially greater than the takeoff weight. After the LEA is collected, the vehicle accelerates to the maximum speed of the airbreathing propulsion system; in the example of Fig. 1, this is Mach 8. At the end of the airbreathing phase the vehicle has achieved the correct mass ratio to go on to orbit using the collected LEA and the remaining hydrogen in a rocket mode.

The dotted line of Fig. 1 shows the weight history (mass ratio) of a two-stage airbreathing vehicle that would have to carry liquid oxygen (LOX) from takeoff. The process of LEA collection (ACES) permits a vehicle to reach this mass ratio curve at a hypersonic velocity (following along the bold solid

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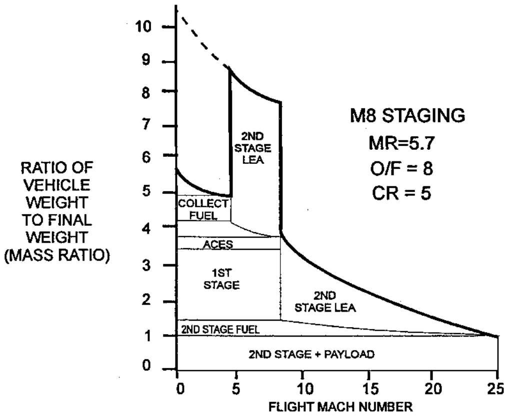


**Fig. 1 ACES vehicle weight history.**

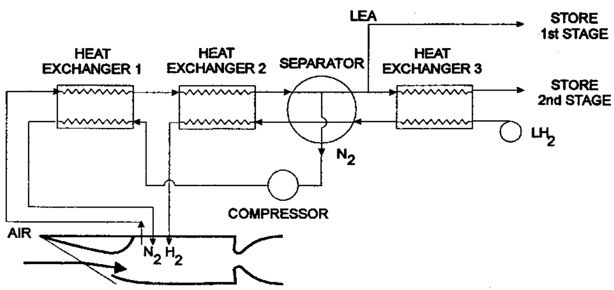


**Fig. 2 ACES schematic.**

line) starting without stored LOX and at a much lower takeoff weight. The takeoff weight of an ACES vehicle is generally approximately half that of a vehicle carrying LOX from takeoff.

The performance advantages of utilizing ACES in two-stage space boost vehicles can be mathematically demonstrated. The first step is to examine the performance of the second-stage rocket propelled vehicle. The performance of this stage is given by

$$\Delta V = g_c I_{sp} \ \ell n \ MR \tag{1}$$

or its alternative form:

$$MR = \exp[\Delta V/(g_c I_{sp})] \tag{2}$$

The mass ratio is expressed as

$$MR = \frac{W_{OR} + W_{F2} + W_{OX}}{W_{OR}} \tag{3}$$

For a rocket oxidizer-to-fuel ratio of the oxidizer and fuel quantities are

$$W_{OX} = W_{OR} \left\{ \frac{\exp[\Delta V/(g_c I_{sp})] - 1}{1 + (1/O/F)} \right\} \tag{4}$$

$$W_{F2} = W_{OR} \left\{ \frac{\exp[\Delta V/(g_c I_{sp})] - 1}{1 + O/F} \right\} \tag{5}$$

During the first-stage collect phase, fuel in the amount $W_{FC}$ is expended to collect and store oxidizer in the amount $W_{OX}$ by the following relation:

$$W_{OX} = CR \cdot W_{FC} \tag{6}$$

Combining Eqs. (4) and (6) gives an expression defining the amount of collect fuel required:

$$W_{FC} = W_{OR} \left\{ \frac{\exp[\Delta V/(g_c I_{sp})] - 1}{CR[1 + (1/O/F)]} \right\} \tag{7}$$

Thus, at takeoff, the total propellant required for the second stage is $W_{F2} + W_{FC}$. An apparent effective mass ratio $MR'$ can be used with Eq. (1) to define an apparent effective specific impulse for the second stage:

$$MR' = \frac{W_{OR} + W_{F2} + W_{FC}}{W_{OR}} \tag{8}$$

$$I'_{sp} = \frac{\Delta V}{g_c \ \ell n(MR')} \tag{9}$$

Equations (5), (7), and (8) can be combined to define $MR'$ from the $\Delta V$ requirement and the actual rocket effective specific impulse:

$$MR' = 1 + \left\{ \frac{\exp[\Delta V/(g_c I_{sp})] - 1}{1 + O/F} \right\} \left( 1 + \frac{O/F}{CR} \right) \tag{10}$$

The following example, for a second stage of 5487 m/s (18,000 ft/s) and a 15% impulse loss due to drag and gravity effects, illustrates how large $I'_{sp}$ can be. Assuming the following values: $\Delta V$ = 5487 m/s, $I_{sp}$ of LEA/$H_2$ rocket = 440 s, $I'_{sp}$ = 0.85 × 440 = 374 s, $O/F$ = 8, and $CR$ = 5.

Equation (10) gives an $MR'$ of 2.00 and Eq. (9) gives an $I'_{sp}$ of 807 s compared to a maximum LOX/$H_2$ rocket $I_{sp}$ of 460 s. The actual mass ratio, from Eq. (2), is 4.464.

The previous treatment of the second-stage performance is relatively accurate because the drag and gravity losses deducted from the rocket specific impulse are small and are known with reasonable certainty for the usual high-speed, high-altitude staging conditions. A question arises that, if such a large advantage to the second stage is seen for ACES, there might be an offsetting penalty imposed on the first stage. Simple mass ratio analysis of the first stage is complicated by the fact that the drag and gravity losses are large and very much driven by the ascent path details. Unlike a conventional launch vehicle that applies all of its propellant directly to increasing velocity, an ACES vehicle pauses for a cruise phase during ascent to use some fuel (collect fuel) for increasing mass ratio instead of velocity.

The following seeks to compare the launch weights of an ACES and a LOX-carrying vehicle and to establish the circumstances in which the ACES vehicle will have a smaller launch weight. Basically, an answer is sought to the question of what weight of ACES equipment plus collect fuel will always give a lighter vehicle than a LOX-carrying approach.

The gross takeoff weights of an ACES vehicle and a LOX-carrying vehicle are, respectively,

$$GW_{ACES} = W_1 + W_{ACES} + W_{OR} + W_{FC} + W_{F2} \tag{11}$$

$$GW_{LC} = (1 + K)W_1 + W_{OR} + W_{FC} + W_{F2} \tag{12}$$

Using Eq. (6) and the definition of $O/F$ as $W_{OX}/W_{F2}$:

$$GW_{ACES} = W_1 + W_{ACES} + W_{OR} + W_{FC} + W_{F2} \tag{13}$$

$$GW_{LC} = (1 + K)W_1 + W_{OR} + W_{OX}[1 + (1/O/F)] \tag{14}$$

Subtracting Eq. (13) from Eq. (14) to define the gross weight difference:

$$\Delta GW = KW_1 - W_{ACES} + W_{OX}[1 - (1/CR)] \tag{15}$$

Table 1 Comparison of first-stage vehicles

| Vehicle no. (Ref. 1) | 5 | 6 | 7 | 8 |
|---|---|---|---|---|
| Propulsion | Air breathing | Air breathing + rocket | ACES | Scramjet |
| First-stage airbreathing velocity, m/s | 2439 | 1829 | 1829 | 2439 |
| Staging velocity, m/s | 2439 | 2896 | 2439 | 2439 |
| Gross takeoff weight, 1000 kg | 522.7 | 604.5 | 420.5 | 481.8 |
| Fuel/propellant used for first-stage acceleration, 1000 kg | 105 | 208.2 | 102.7[a] | 111.4 |
| Mass ratio to staging | 1.25 | 1.53 | 1.32 | 1.3 |
| First-stage $I_{sp}$, s | 1110 | 700 | 888 | 946 |
| $W_{1LC}$, first-stage weight, LOX-carrying vehicle, 1000 kg | 306 | 429 | — | 301 |
| $W_1$, first-stage weight, ACES vehicle, 1000 kg | — | — | 285.9[b] | — |

[a]Excludes LEA collect fuel ($W_{FC}$ = 43.6 K kg).
[b]Excludes LEA collect fuel ($W_{FC}$ = 43.6 K kg) and LEA collection equipment ($W_{ACES}$ = 13.6 K kg).

Data from Ref. 1 are useful in considering the implications of Eq. (15). A summary of the following discussion is found in Table 1. Vehicle 6 (LOX carrying) and 7 (ACES) each has the same maximum airbreathing velocity, 1829 m/s (6000 ft/s). Vehicle 6 reaches 2896 m/s (9500 ft/s) staging velocity with a first-stage mass ratio of 1.525, giving a delivered $I_{sp}$ of 700. Vehicle 7, assuming a rocket *O/F* of 8 and a *CR* value of 5, reaches 2439 m/s (8000 ft/s) staging velocity at a mass ratio of 1.323 and $I_{sp}$ of 888. This result is obtained by estimating the collected LEA to be 217,727 kg (479,000 lb), requiring 43,636 kg (96,000 lb) of fuel as coolant for the collection cycle. This leaves 102,727 kg (226,000 lb) of fuel available in the first stage to reach staging. This vehicle reaches staging velocity at a weight of 426,818 kg (939,000 lb), which is slightly greater than its takeoff weight.

Vehicle 5 is a LOX-carrying vehicle having high-performance capability to its staging velocity of 2439 m/s (8000 ft/s). Vehicle 8, which embodies both a scramjet and a rocket within its upper stage and also stages at 2439 m/s (8000 ft/s), has a first-stage performance similar to vehicle 5. Vehicle 5 has a first-stage mass ratio of 1.251, giving an $I_{sp}$ of 1110 s. Vehicle 8 has a first-stage mass ratio of 1.30, giving an $I_{sp}$ of 946 s. Because these two vehicles employ airbreathing to much higher speeds, they have smaller first-stage mass ratios and are closer overall competitors to the ACES vehicle 7.

For vehicles of roughly identical maximum airbreathing velocity a value of $K$ greater than zero is anticipated, meaning a structural, propulsion, and fuel penalty in the first stage for carrying oxidizer instead of collecting it. Vehicle 6 has a $K$ value of 0.500 relative to vehicle 7. The dominant term in Eq. (15) is $W_{OX}$, the amount of oxidizer to be carried. The ACES equipment weight is relatively small, 3–5% of gross takeoff weight. For vehicles as closely related as vehicles 6 and 7, there is no circumstance by which a LOX-carrying vehicle could weigh as little as an ACES vehicle. In comparing an ACES vehicle to vehicles having significantly greater airbreather velocity, such as 5 and 8, the ACES advantage is diminished, but still remains. Note that if the ACES vehicle (vehicle 7) had the same maximum airbreathing speed capability as vehicle 5, it would have an even smaller takeoff weight.

## Prior Systems Studies

Initial studies of an ACES vehicle considered a single-stage-to-orbit vehicle.[2] The payload goal was 9072 kg (20,000 lb). By 1962, it was concluded that vehicle materials technology and propulsion weight requirements made a single-stage concept all but impossible for technology available in the 1975–1980 period. Study emphasis then turned to two-stage vehicles. These were studied in the 1962–1964 period and were assessed to be considerably less risky. The final vehicle design, designated the 1964 Point Design Vehicle, is shown in Fig. 3. Gross takeoff weight was 317,518 kg (700,000 lb). It delivered a payload of 10,433 kg (23,000 lb) to a 555.6-km (300-n mile) polar orbit. Turboramjet propulsion was used to accelerate the

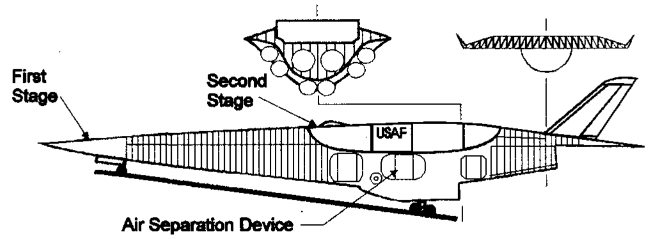


Fig. 3 General Dynamics 1964 Point Design Vehicle.

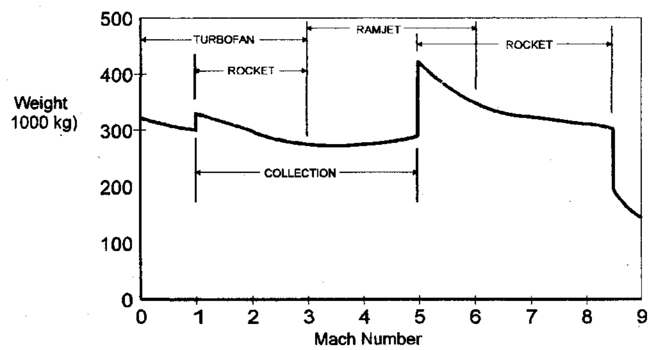


Fig. 4 1964 Point Design Vehicle propulsion modes.

vehicle to the LEA collection point near Mach 5. After the 20–30-min LEA collection phase, the vehicle accelerated to staging using rocket and ramjet thrust. At staging, the second stage ascended to orbit on rocket propulsion using a ballistic path. The weight history and propulsion phases are shown in Fig. 4. Staging was accomplished at Mach 8.6 at 53,645 m (176,000 ft) altitude.

Because the Point Design Vehicle staged hypersonically, optimum solutions to important configuration and material problems could be obtained separately for a hypersonic (Mach 8) vehicle and for a rocket-powered ascent/re-entry vehicle. As examples, the first stage was exclusively a Mach 8 aircraft, and as such it could employ superalloy construction on the underside and titanium on the upper surface. The second-stage configuration requirements were dominated by re-entry heating, thus its blunted shape. Coated refractory metals were used on the underside and superalloy and titanium on the upper surface. The relatively heavy LEA collection equipment only had to be accelerated to the staging velocity. The advantages of a two-stage vehicle are accentuated when the propulsion system or other fixed components are unusually heavy. The 1964 Point Design Vehicle represented the highest state of refinement reached in the vehicle studies. The work is documented in Ref. 2.

A later effort, conducted in 1967, examined propulsion alternatives for two-stage vehicles delivering 18,143.9-kg (40,000-lb) payloads to a low Earth orbit. That study (Ref. 1) was particularly significant because it considered eight different concepts, including ACES, rocket-only concepts, and scramjets, all using common study ground rules. The all-rocket systems had the smallest inert weight, but had the heaviest launch weight (due to stored LOX). The ACES vehicle and the scramjet had the largest inert weight except for an in-flight refueling concept. Scramjet and ACES had the smallest takeoff weight.

## Air Separator Development

During the 1959–1961 period, various air separation concepts were studied for the ACES application. These concepts included cocurrent spray contactors, nitrogen freezeout, centrifugation, chelation, molecular sieves, membranes, fractional distillation, vortex tubes, and chemical reactions. For ACES to be advantageous relative to LOX-carrying orbital vehicle approaches, its equipment weight had to be very small relative to the required mass of stored LOX. By 1961, it was concluded that the chemical reaction and fractional distillation concepts had the best prospects for meeting weight and volume goals for the ACES air separation system.[3]

References 4–6 discuss the chemical-reaction air separation concept. System studies indicated this separation concept to have potential for higher payload performance than the rotary distillation concept.[7] However, due to the extremely high-temperature environment created by the oxygen extraction chemical reaction, it became evident that the chemical air separator would be a much more complex mechanical device than originally anticipated. Thus, the bulk of the air separator development effort was concentrated on developing the fractional distillation air separation concept.

The optimum air separation scheme for the ACES application proved to be a variation of the commercially used double column cryogenic fractional distillation air separation process. Although the principles behind fractional distillation of air are simple, the actual process is somewhat complex. The functional elements of this process include a high-pressure distillation column to effect a preliminary separation, a low-pressure distillation column to provide product streams of the final desired purity, a reboiler–condenser in which the nitrogen-enriched vapor stream from the high-pressure column is condensed against the oxygen-enriched liquid product from the low-pressure column, and subsequently, used as liquid feed for both the high- and low-pressure columns, and a reflux condenser in which hydrogen is used to provide the required refrigerative capacity for the entire process. More detailed discussions of fractional distillation are found through the literature.[4,8–10]

Although the commercial cryogenic fractional air distillation process offers excellent oxygen recovery from the airstream and would make good use of the available refrigerative capacity of hydrogen, weight and volume requirements would be prohibitive for air vehicle applications. An invention by Nau and Campbell[11] solved this dilemma. The flat plates used in conventional 1-*g* distillation become cylinders rotating about their own axes. The liquid travels in crossflow from downcomer to downcomer to the outside of the column, while vapor travels radially inward. As a result of the increased gravitational field, the foam heights in the trays are substantially reduced and vapor velocities can be increased. Thus, the weight and volume occupied by the columns are reduced and the capacity of the process is dramatically increased (see Fig. 5). The reboiler–condenser also would be an extremely heavy, bulky component in 1-*g* use. To obtain desired weight and volume reductions in the reboiler–condenser, it was necessary to minimize resistance to heat transfer on both the boiling and condensing sides. In the rotary air separator, this was accomplished by applying a special porous surface to the boiling and condensing sides. Surface tension drew the condensate into the porous layer and the gravitational forces then drained the condensed liquid from the porous matrix. The weight and volume reductions realized in the reboiler–condenser were a major accomplishment of the 1960s rotary air separator development program. The design of the reboiler–condenser is illustrated in Fig. 6.

The operating requirements for a rotary air separator for the 1964 Point Design Vehicle, along with weight estimates for a flight weight separator, are given in Table 2. Design studies of a full-scale rotary air separator established separator specific weight to be approximately 5 kg per kg per second of airflow. The diameter of the separator, which is dictated by the desired product purity, was approximately 3.05 m (10 ft) and the length of the unit, which is determined by desired throughput capacity, was approximately 6.1 m (20 ft). To demonstrate the functional feasibility and confirm the weight and volume estimates of the cryogenic rotary air separator, several programs were conducted culminating in the design, fabrication, and test of a 45.36-kg/s (100-lb/s) boilerplate rotary air separator. The functional design of the boilerplate air separator is shown in Fig. 7. The arrangement of the various components and the radial dimensions were similar to those of a full-scale unit. The internal components were made of aluminum, but stainless steel was used for all other components to simplify operation of the unit. Photographs of the boilerplate separator and various components are shown in Figs. 8–10.

The predicted performance of the boilerplate separator, along with actual results from seven test runs conducted between July 1965 and April 1966, are presented in Table 3. The boilerplate tests were very successful. Although maximum throughput was not achieved due to limited power availability, the stable operation of the system demonstrated that the operation of a double-column rotary air separator presents no major difficulty. High-pressure tray efficiencies were some-

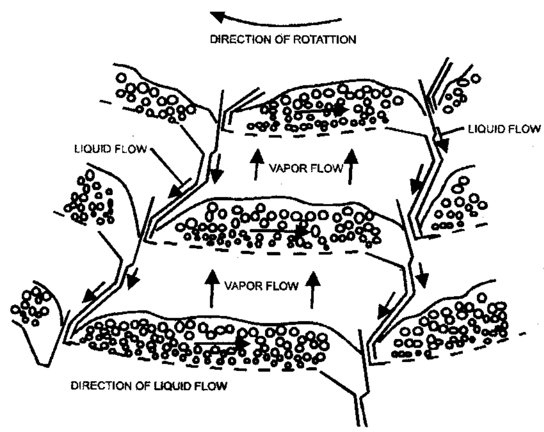


**Fig. 5 Rotary high-*g* air separator trays for ACES.**

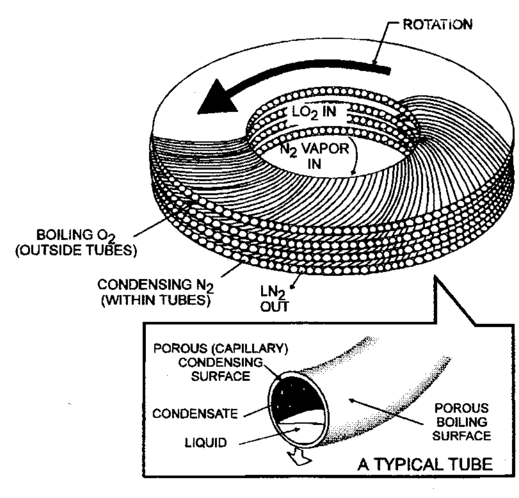


**Fig. 6 Reboiler–condenser for rotary high-*g* air separator.**

Table 2 ACES rotary air separator performance and weight

| Performance | Component weights |
|---|---|
| Throughput, 945 kg/s (2083 lb/s) | Columns, 1225 kg (2700 lb) |
| Inlet pressure, 15.1 atm (222 psia) | Reboiler condenser, 1225 kg (2700 lb) |
| Outlet pressure, 3.8 atm (56 psia) | Other, 1860 kg (4100 lb) |
| Waste purity, wt% $N_2$, 98 | Total, 4310 kg (9500 lb) |
| Product purity, wt% $O_2$, 90 | |

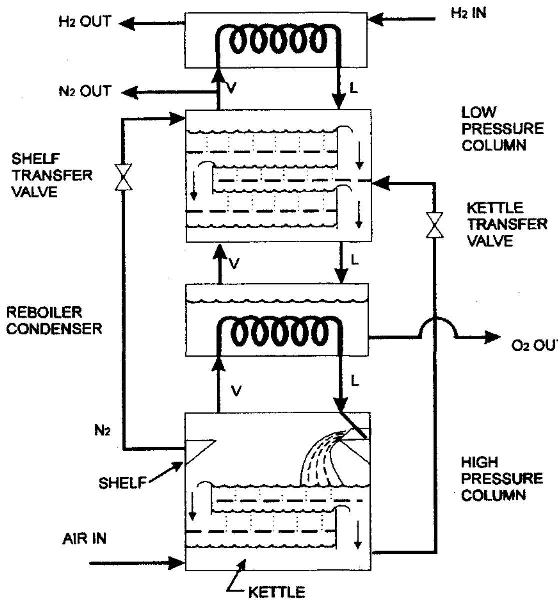


Fig. 7 Double column air separator.

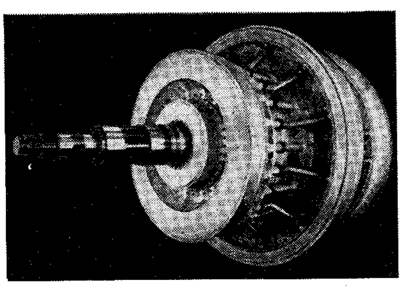

Fig. 8 Boilerplate rotary air separator test unit.

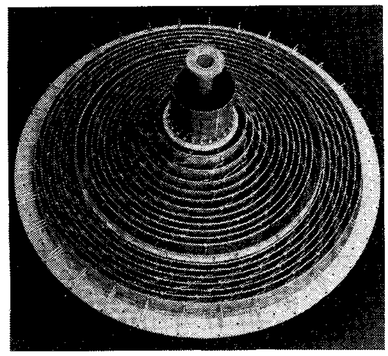

Fig. 9 Boilerplate rotary air separator–low pressure column.

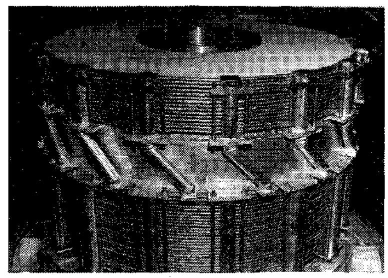

Fig. 10 Reboiler–condenser assembly of boilerplate rotary air separator.

Table 3 Boilerplate rotary air separator test results

| Parameter | Predicted value | Actual performance |
|---|---|---|
| Airflow, kg/s | 45 | 23–35 |
| Inlet pressure, atm | 16.3 | 11.2–14.6 |
| Waste pressure, atm | 3.1 | 3.1–4.1 |
| Product purity, wt% $O_2$ | 90 | 80–94 |
| Product purity, wt% $N_2$ | 98 | 96–99 |
| Design speed, rpm | 570 | 280–380 |
| High-pressure column tray efficiency, % | 80 | 63 |
| Low-pressure column tray efficiency, % | 56 | 57 |
| Reboiler–condenser overall heat transfer, W/m$^2$-K | 370 | 476 |

what lower than predicted, but it was believed this could be easily corrected through minor tray design modifications, and the overall heat transfer coefficient of the reboiler–condenser was even greater than predicted. The degree to which predicted performance of the boilerplate separator was achieved is indicative of the validity of the design correlations needed to design the various components of the separator. Thus, this very successful test program validated the weight and volume estimates for a flight-weight rotary air separator. Although hardware used in this program is no longer available, results from the rotary separator development program can be confidently used today as the basis for continuing development of the concept. The work is documented in Refs. 12 and 13.

## Related Heat Exchanger Work

The ACES vehicles studied in the 1960s required a complex heat exchanger system to cool air from the incoming stagnation conditions down to the saturated vapor condition required by the air separator. Even though heat exchanger use is common in conventional aircraft, the ACES heat exchanger system presented a unique requirement. Large quantities of air had to be cooled from temperatures as high as 1666.7 K (3000°R) to temperatures as low as 111.1 K (200°R). Unlike conventional aircraft heat exchangers, the ACES heat exchanger system was a major contributor to the overall weight of the propulsion system. Thus, developing very compact, lightweight, and high-performance heat exchangers was a primary goal of the propulsion system component development efforts undertaken in the 1960s.

The design of the ACES heat exchanger system was thoroughly studied by several researchers. The generally favored approach for ACES heat exchangers was a cross-counterflow tube and shell design using very thin-gauge materials. The materials selected for the various temperature regions along with achieved tube wall thicknesses for these materials are shown in Table 4. The cooling fluid, either hydrogen or waste nitrogen from the separation process, flowed inside the tubes, while the air to be cooled flowed outside. Figure 11 shows the generic design used. A total heat exchanger system specific weight of 10 kg per kg of airflow per second was estimated for the 1964 Point Design Vehicle. To confirm these weight estimates, several exploratory development programs were undertaken between 1962–1968. The objectives of these programs were to prove the validity of the various heat exchanger design and fabrication concepts and to demonstrate the overall performance of the heat exchangers. Because of funding limitations, full-scale systems were never demonstrated. Rather, modules sized for roughly 1/50 of the total airflow were generally evaluated. Figure 12 depicts a 444-tube core, 45.72-cm- (18-in.-) long module using 3.175-mm- (1/8-in.-) diam, 0.0508-mm (2-mil) wall stainless steel alloy for low-temperature application. A stainless steel heat exchanger module for use with air temperatures as high as 1388.9 K (2500°R) was also built. The core of this module had 3.048-m- (10-ft-) long stainless steel tubes, with a 3.175 mm (1/8 in.) diameter and 0.0508-mm (2-mil) wall thickness. A heat exchanger module designed to handle air temperatures up to 2666.7 K (4800°R) can be seen in Fig. 13. The core of this module was made up of 585 L-605 alloy tubes, with a 2.54 mm (1/10 in.) diameter and being 0.2032 mm (8 mil) thick. Plans to evaluate a full-scale heat exchanger system were made but never carried out.

**Table 4 ACES heat exchanger materials**

| Maximum metal temperature, K | Tube material | Tube wall thickness, mm |
|---|---|---|
| 1667 | Niobium-1% zirconium-coated alloy | 0.152 |
| 1256 | Hastelloy-X | 0.102 |
| 811 | Aluminum alloys | 0.102 |

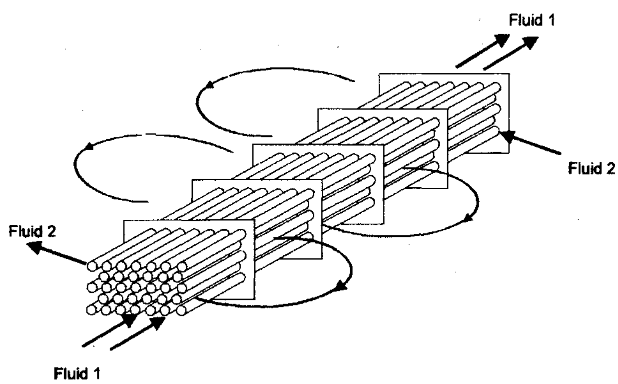


**Fig. 11 General arrangement of cross-counterflow tube and shell heat exchanger.**

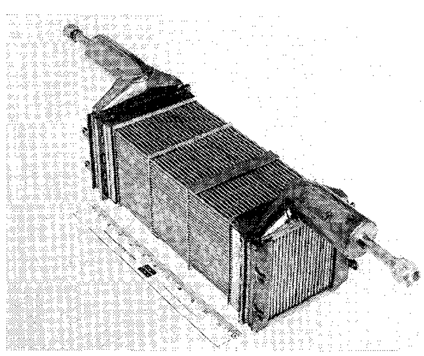

**Fig. 12 Cryogenic heat exchanger, 3.175-mm stainless steel tubes, 0.0508-mm wall.**

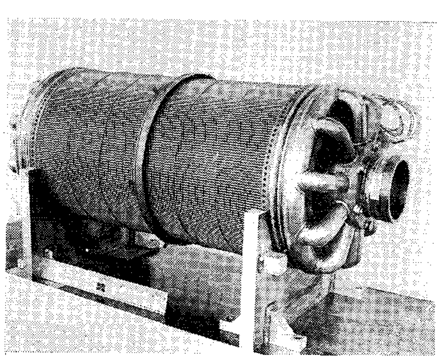

**Fig. 13 High-temperature heat exchanger, L605 material, 2666.7 K inlet air temperature.**

The various tests were generally successful, proving the validity of the heat exchanger designs and fabrication techniques and the reliability of the elements of the heat exchanger system. A new specific weight estimate of 17.2 kg per kg of air per second was derived based on the experimental results. This represents a substantial increase from the original estimate. However, given the many advances in heat exchanger technology and fabrication techniques realized since the 1960s, substantial reductions to the total weight of the heat exchanger system are very likely and the extensive design database available from the 1960s programs will serve as the foundation for future programs. The heat exchanger work is documented in Refs. 14–16.

## Current System Studies

To study the application of ACES technology to vehicles of current interest, two-stage vehicles capable of delivering payloads of 29,483.8 kg (65,000 lb) (vehicle B) and 68,039.6 kg (150,000 lb) (vehicle C) were designed. These payloads are representative of a shuttle class and a heavy-lift vehicle, respectively.

These vehicles are fully recoverable and use horizontal runway launch. The study ground rules specified that the sizes and vehicle weights would be determined that satisfied the payload goals.

Vehicle size and weights were estimated using the digital computer program PDWAP (preliminary design and weight analysis program).[17] The vehicle sizing part of this code was developed by the author. The weight estimation part of the code was the NASA WAATS (weights analysis of advanced transportation systems) program, which was enhanced and updated for use in a microcomputer. Reference 18 describes the WAATS code. To ensure that the program accurately modeled a two-stage ACES vehicle, the weight adjustment coefficients were calibrated using the 1964 Point Design Vehicle weight information.

Once the size and weights of the vehicles were established, they were flown using a two-degree-of-freedom trajectory code, ETOC1 (Ref. 19). The inputs for the trajectory code consist of weight, aerodynamics, engine performance, and flight-path command data. Representative aerodynamic coefficients were obtained for both vehicles. The engine performance data were based on a turboramjet and obtained from Ref. 20. The flight path command data controlled the vehicles acceleration to Mach 5. At a Mach 5 cruise, the ACES system was used to collect a predetermined amount of LEA as computed by Eq. (6). The vehicle then accelerated under rocket and ramjet power to Mach 8 at which point staging occurred.

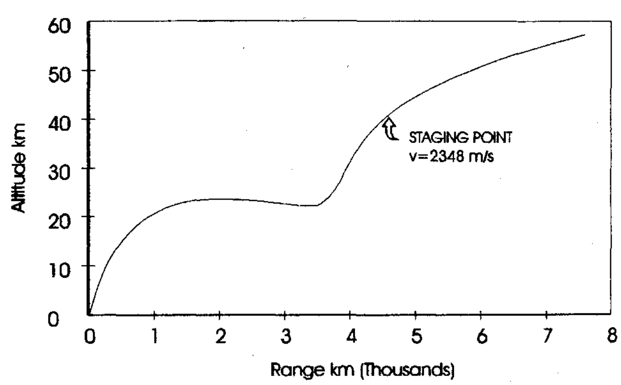


**Fig. 14 Trajectory for vehicle C.**

**Table 5 Weight statement for shuttle-class and heavy lift vehicles, kg**

| | Shuttle class | | Heavy lift | |
|---|---|---|---|---|
| Vehicle item | Stage 1 | Stage 2 | Stage 1 | Stage 2 |
| Aero/body structure | 60,395 | 16,198 | 122,300 | 29,824 |
| Thermal protection system | 20,842 | 8,695 | 43,560 | 15,106 |
| Launch/landing gear | 9,956 | 3,480 | 19,147 | 6,243 |
| Propulsion | 47,121 | 6,878 | 111,641 | 13,560 |
| ACES | 14,969 | —— | 31,502 | —— |
| Electric/hydraulics/avionics | 12,131 | 3,764 | 20,227 | 5,760 |
| Crew | 356 | 356 | 356 | 356 |
| Payload | —— | 29,484 | —— | 68,040 |
| $LH_2$ | 138,562 | 28,662 | 364,329 | 59,653 |
| Vehicle dry weight | 165,414 | 39,015 | 348,377 | 70,493 |
| Gross takeoff weight | 401,849 | —— | 911,604 | —— |
| Total LEA collected | 326,222 | —— | 816,991 | —— |
| Collect airflow, kg/s | 1,103 | —— | 2,100 | —— |
| Collect time, min | 23 | —— | 27 | —— |
| Maximum vehicle weight | 626,875 | —— | 1,427,134 | —— |
| Orbital mass | 71,078 | —— | 141,885 | —— |

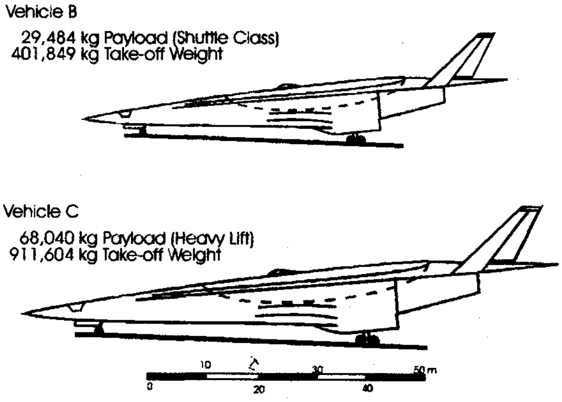


**Fig. 15 Current study vehicles.**

The second stage then accelerated to orbit using rocket propulsion. A typical two-stage trajectory is shown in Fig. 14.

The study process involved a series of iterations between PDWAP and ETOC1, proceeding until vehicles large enough to deliver the specified payloads were achieved. The resulting vehicles are summarized in Table 5 and Fig. 15. Both vehicles delivered a payload fraction of approximately 7.4%.

## Conclusions

The broad-based ACES propulsion technology database that was generated in the 1960s has been reviewed. This technology offers the potential for relatively lightweight, fully recoverable launch vehicles capable of delivering substantial payloads to orbit. The ACES vehicle concept compares favorably with scramjet-powered options in payload fraction and is about one-half the launch weight of rocket-powered systems. ACES shares with scramjet the prospects of operating flexibility that come with horizontal launch and runway-like operation. ACES avoids the need for carrying LOX at takeoff that virtually mandates that rocket systems be vertically launched. ACES exhibits the effective performance of scramjets in the hypersonic regime without having to rely on scramjet function.

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