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December 1976

An Evaluation of Very Large Airplanes and Alternative Fuels: Executive Summary

W. T. Mikolowsky

A Project AIR FORCE report
prepared for the
United States Air Force

Rand
SANTA MONICA, CA 90406

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PREFACE

This executive summary presents the principal results and recommendations of the research described in a report by W. T. Mikolowsky and L. W. Noggle, with contributions by W. F. Hederman and R. E. Horvath, *An Evaluation of Very Large Airplanes and Alternative Fuels*, The Rand Corporation, R-1889-AF, December 1976. That report explored the military utility of very large airplanes (over 1 million pounds gross weight) and examined several alternative fuels that could be used by such airplanes. The research was jointly conducted by Rand and the Aeronautical Systems Division of the Air Force Systems Command under the Deputy for Development Planning (ASD/XR). Larry W. Noggle of ASD/XRL coordinated the Air Force elements of the study.

This analysis of the military applications of very large airplanes is an extension of research initiated in early 1974 at the request of Rand's Air Force Advisory Group and the Air Force Chief Scientist (then Dr. Michael Yarymovych), acting in his capacity as chairman of the Air Force Energy R&D Steering Group. The general objective of this research was to identify R&D programs that, in the near term, would lessen and, in the far term, perhaps would eliminate the Air Force's total dependence on aviation fuels derived from petroleum. This research is summarized in J. R. Gebman and W. L. Stanley, with J. P. Weyant and W. T. Mikolowsky, *The Potential Role of Technological Modifications and Alternative Fuels in Alleviating Air Force Energy Problems*, The Rand Corporation, R-1829-PR, December 1976. That report describes the cost and energy implications of alternative aviation fuels, implications that pertain directly to the present work; it also discusses the near-term technology options for reducing Air Force jet-fuel consumption and the possible longer-term benefits of being able to utilize jet fuels (JP) derived from various primary energy resources (e.g., petroleum, coal, oil shale).

In mid-1974, the Chief Scientist requested that the initial detailed assessment of alternative aviation fuels be made in the context of the potential military applications of very large airplanes--a request that served as the impetus for the present work. Thus, not only energy considerations but also the increased capability which may be provided by very large airplanes have motivated this research.

The present work was performed as part of a Project AIR FORCE (formerly Project RAND) applications analysis of very large airplanes under the research project entitled "Technology Applications Research." The research results presented here should assist the Air Force to formulate policy with respect to future aviation fuel options and also to develop the requirements for advanced-technology large airplanes. The report should be of interest to long-range planners in the Air Staff and Air Force Systems Command, to future systems and operational requirements personnel in the Military Airlift Command, Strategic Air Command, and Tactical Air Command, and to the Air Force laboratories.

CONTENTS

BACKGROUND

Air Force interest in very large airplanes (VLAs) is motivated principally by the potential for increased capabilities that such vehicles might provide. For example, a recent Air Force study--*New Horizons II*--has suggested that the capability to deploy combat units worldwide, without reliance on foreign bases, may soon emerge as a definite requirement. Such an operational capability substantially exceeds that provided by any contemporary airplane. Rather, an airplane with a maximum gross weight in excess of one million pounds (our working definition of a VLA) may be needed. Given historical trends, airplanes of this size could become operational as early as 1985.

The widespread recognition of the ultimate depletion of U.S. petroleum resources further suggests that a very large airplane might benefit from the employment of a fuel other than a conventional hydrocarbon jet fuel (JP) refined from crude oil. Indeed, such energy considerations are sufficiently important for the Department of Defense recently to direct that the concept of energy-effectiveness be included with cost-effectiveness when the relative merit of alternative weapon systems is being judged.

The specific objectives of the present study are to:

- Evaluate very large airplanes in the context of existing and potential future Air Force missions.
- Determine the most attractive alternative fuel for airplanes of this type.

Each of the VLAs examined in this work employs a different candidate fuel, and the candidates include nuclear fuel as well as synthetic chemical fuels. (We define a synthetic fuel as one that can be manufactured from a primary energy resource other than petroleum or natural gas.) As a useful benchmark for our evaluation of very large airplanes, we have included in the analysis a proposed new production version, the C-5B, of a contemporary large airplane.

Our analysis provides a framework for formulating policy conclusions and recommendations with respect to very large airplanes and alternative fuels. Appropriate future research and development activities are also identified.

DESCRIPTION OF THE VLA ALTERNATIVES

A summary description of the VLA alternatives is presented below. Our view of the desirable characteristics of VLAs is given first, followed by the results of our screening analysis, which identified the most promising candidate fuels. We then describe some important attributes of the alternative airplanes that were developed and analyzed in this work.

DESIRABLE CHARACTERISTICS

Candidate applications of very large airplanes include: strategic airlifter, tanker, missile launcher, tactical battle platform, maritime air cruiser, and C^3 (command, control, and communications) platform. The viability of a VLA would be substantially enhanced (in terms of system cost and flexibility) if a single basic airframe were capable of performing two or more of these missions. Thus, the objective of this phase of the analysis was to define the aircraft performance characteristics which would be compatible with the requirements of these missions and consistent with the expected state of the art (based on historical trends) for aircraft entering the inventory between 1985 and 1995. This was accomplished by identifying the mission that would most strongly influence airplane design and by defining appropriate performance requirements for this mission, but also including any design compromises necessitated by the remaining missions.

Our analysis indicated that an airplane primarily designed for the strategic airlift role could most easily be adapted to the other mission applications. The associated airplane performance characteristics that evolved from this analysis are presented in Table S-1. In addition, the airplane must permit the rapid installation of a three-boom tanker mission kit and be able to air-launch vehicles as large as a 100,000-lb intercontinental ballistic missile. (This latter requirement probably implies the need for a rear-loading capability; consequently, the VLAs incorporate both front and rear cargo compartment doors.) These requirements lead to maximum gross weights in the 1.5 to 2.0 million-lb class for JP-fueled airplanes--values thought to be attainable between 1985 and 1995.

Table S-1

MINIMUM REQUIRED VLA PERFORMANCE CHARACTERISTICS

Characteristic	Suggested Value
Design radius[a]	3600 n mi[b]
Design payload	350,000 lb[b,c]
Cargo compartment	
Maximum width	25 ft
Maximum height	13.5 ft
Length	220 ft
Cruise Mach number	0.75 to 0.80
Initial cruise altitude	30,000 ft
Takeoff critical field length	8000 ft

[a]On a radius mission, the payload is off-loaded at the destination and the airplane flies the return leg without taking on additional fuel at the destination.

[b]Limit load factor of 2.25 g.

[c]Maximum payload to be carried on 3600 n mi range mission at 2.25 g.

SCREENING ALTERNATIVE FUELS

The candidate synthetic chemical fuels which survived an initial screening are listed in Table S-2. Other fuel candidates were considered for inclusion in this list (e.g., acetylene, hydrazine, monomethylamine, and propane), but a cursory examination of their characteristics indicated that none was substantially more suitable than those shown--either in terms of its physical characteristics (e.g., heat content per pound) or its expected costs.

The six candidate fuels listed in Table S-2 were further screened by developing rough conceptual airplane designs for each fuel. The resulting gross weights of those airplanes (sized to the previously described design point) are shown in the far right-hand column of Table

S-2. Observe that owing primarily to their poorer heat content per pound, the alcohols and ammonia are clearly inferior in this application.

Thus, JP, liquid, hydrogen (LH_2), and liquid methane (LCH_4) were the only chemical fuels retained in the more detailed analysis. To these, nuclear propulsion was added as a fourth alternative.

Table S-2

SCREENING OF ALTERNATIVE FUELS

	Gravimetric Heat of Combustion (Btu/lb)	Volumetric Heat of Combustion (Btu/gal)	Boiling Point (°F)	Resulting Airplane Gross Weight[a] (million lb)
Synthetic JP	18,600	121,000	210	1.68
Liquid hydrogen	51,600	30,400	-423	1.22
Liquid metnane	21,500	74,500	-259	1.59
Methanol	8,600	56,700	149	>3.5
Ethanol	11,000	76,000	173	>2.5
Ammonia	8,000	45,600	-28	>3.5
Gasoline[b]	19,100	112,000	257	-

[a]For 3600 n mi radius mission with 350,000-lb payload (based on unrefined conceptual designs).

[b]Included for reference only.

REFINED CONCEPTUAL DESIGNS

Refined conceptual designs of airplanes employing each of the four alternative fuels were developed by the Air Force's Aeronautical Systems Division (under the Deputy for Development Planning). Table S-3 highlights some important characteristics of the resulting VLA alternatives--each designated by the fuel employed, i.e., the VLA-JP is the JP-fueled very large airplane. Figure S-1 illustrates their general arrangements. (A fifth alternative--the C-5B--has been included as a benchmark. The particular C-5B model described here is among the least complex of the several proposed C-5A derivatives.[a])

[a]The C-5B data in this report are based on preliminary Lockheed estimates. Were the Air Force to procure C-5Bs, the airplane selected for production would almost certainly differ from the proposed version used here as representative of a contemporary large airplane.

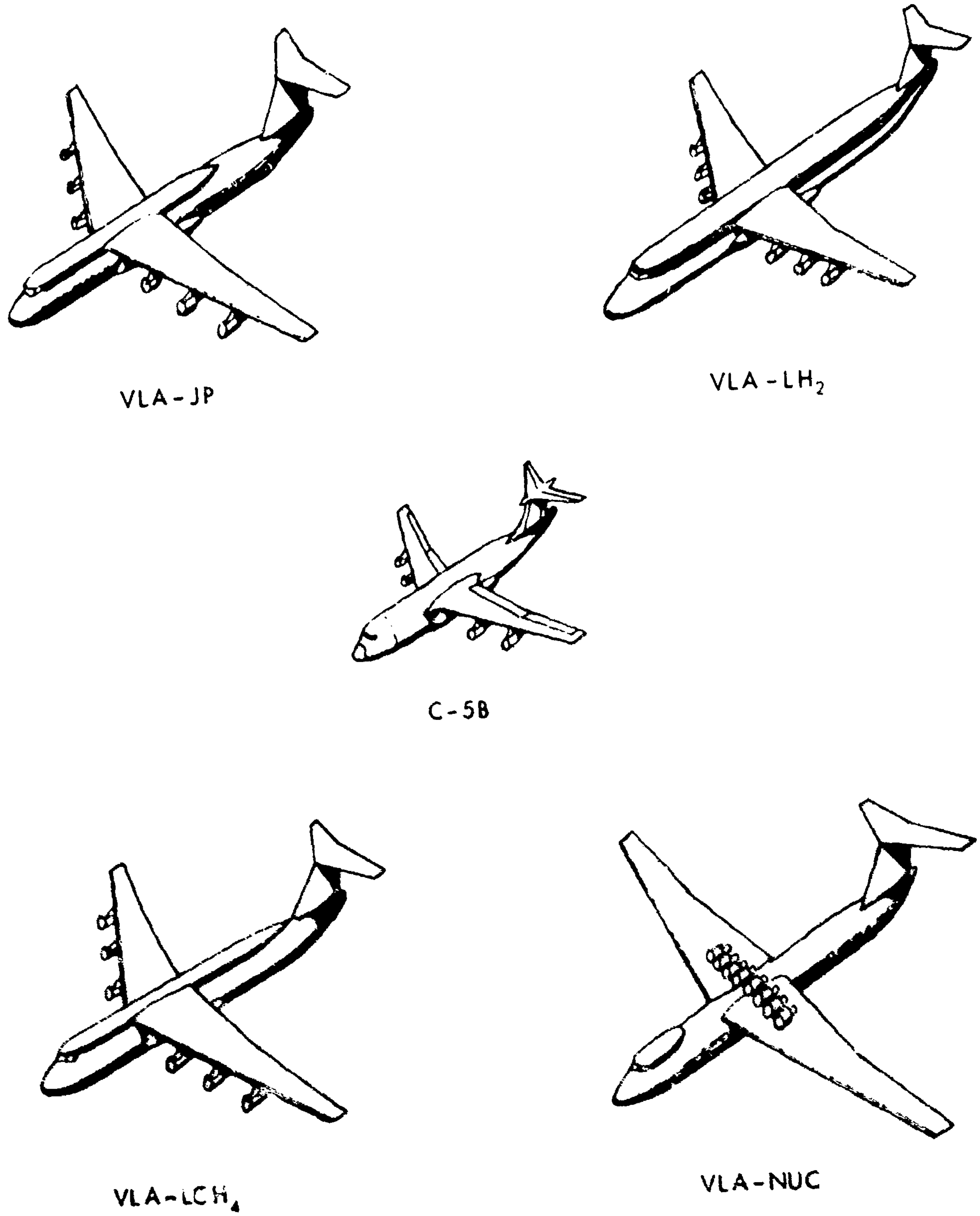

Fig. S-1 — Perspective views of the alternative airplanes

Table S-3

CHARACTERISTICS OF THE ALTERNATIVE AIRPLANES

Characteristics	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC
Weight (thousands of pounds)					
Maximum gross takeoff	769	1839	1864	1275	2660
Operating empty	362	794	872	704	1907
Design payload	216	350	350	350	350
Performance (with design payload)					
Range (n mi)	2730	6400	6500	6520	(a)
Radius (n mi)	1560	3600	3600	3600	(a)
Radius-buddy IFR[b] (n mi)	3110	5680	5570	6530	---
Radius-buddy/rendezvous IFR (n mi)	4210	7450	7500	8750	---

[a]Essentially unlimited range and/or radius capability.

[b]In-flight refueling.

Table S-3 reveals that the VLAs provide significant increases in capability compared to the C-5B.[a] However, the VLA alternatives have such differing characteristics (e.g., the unlimited range/radius of the nuclear airplane) that a straightforward assessment of their relative merit is not possible. Our approach, therefore, has been to develop life-cycle cost and life-cycle energy consumption estimates for each alternative. By determining their effectiveness (through an appropriate metric) in a variety of mission applications, we can examine relative cost-effectiveness and energy-effectiveness of each alternative.

In developing life-cycle cost estimates, we used methodologies already available. Table S-4 illustrates the results for the VLA alternatives. They are based on the acquisition of an equal number of unit equipment (UE) aircraft (which could be interpreted as providing "equal capability" on the design point mission) and include a representative peacetime utilization (UTE) rate.

[a]Performance with in-flight refueling is also displayed in Table S-3. For each alternative, we assume that the airplane is refueled by an airplane of the same type (i.e., the VLA-JP is refueled by a tanker-configured VLA-JP). A "buddy IFR" refers to a single outbound refueling, and "buddy/rendezvous IFR" includes also an inbound refueling. Tanker and receiver flights are assumed to originate at the same base.

Table S-4

LIFE-CYCLE COST ESTIMATES
(Billions of 1975 dollars)

Alternative	Acquisition Costs	20-year Operating & Support Costs	Total Life-Cycle Costs
VLA-JP	15.5	16.4	31.9
VLA-LCH_4	16.5	18.8	35.3
VLA-LH_2	13.6	21.3	34.9
VLA-NUC	32.1	24.6	56.7

NOTE: For 112 UE aircraft at 2 hours/day average UTE rate.

Estimating life-cycle energy consumption is less straightforward, since little appropriate methodology has been previously developed. Our approach was to estimate the life-cycle *total* energy consumption, as illustrated in Fig. S-2. Note that life-cycle consumption is divided into energy attributed to aircraft acquisition and energy embodied in the fuel needed for 20 years of operation.

Figure S-2 represents total, rather than just the direct life-cycle energy consumption. For example, the direct energy consumption for the 20 years of fuel is simply the energy content of the fuel consumed on board the airplane. Total consumption, however, includes the energy expended in the fuel supply process (liquefaction, distribution, storage, etc.). Similarly, energy expended in uranium enrichment, reprocessing, etc., is included. Our energy consumption estimates in Fig. S-2 are based on synthesizing the chemical fuels from coal (as are our fuel cost estimates). We believe this assumption is appropriate since U.S. coal reserves exceed (in terms of energy content) the sum of all other domestic fossil-fuel resources (e.g., petroleum, oil shale, etc.).

Figure S-2 illustrates the energy intensiveness of the nuclear airplane; direct comparisons with the other VLAs, however, are difficult since a different energy resource--uranium versus coal--is involved.

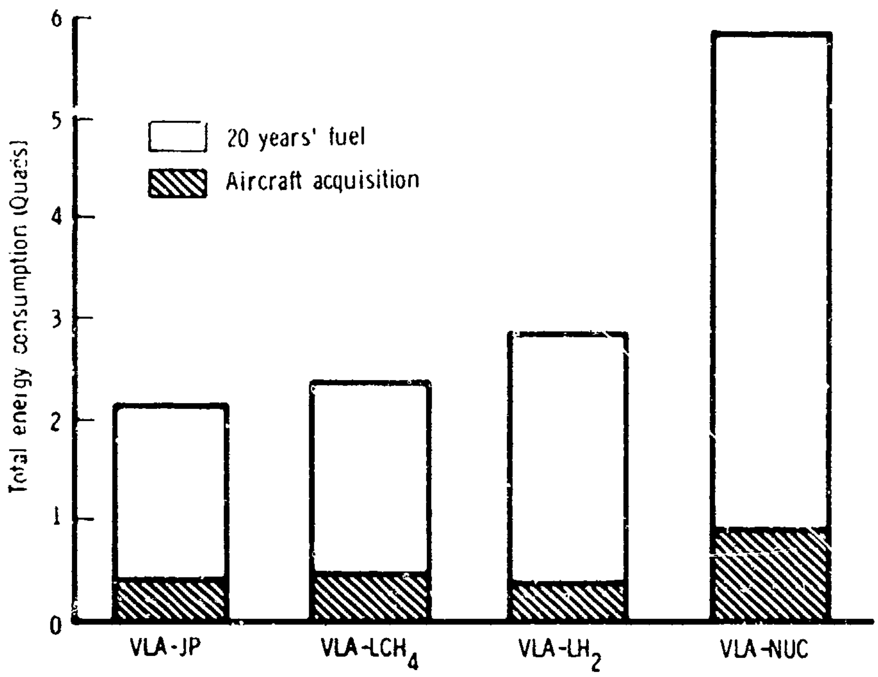

Fig. S-2 — Life-cycle total energy consumption estimates for 112 UE aircraft at 2 hours/day average UTE rate (Note: One Quad (i.e., 10^{15} Btu) is approximately equal to the energy content of 180 million barrels of petroleum.)

If nuclear energy were far more abundant than coal, the greater energy intensiveness of the nuclear airplane might be of little significance. In fact, without a commercialized breeder reactor, U.S. coal reserves exceed uranium reserves (in terms of energy content) by almost an order of magnitude; if a breeder reactor were available, this situation would be essentially reversed.

Interestingly, of the alternatives using chemical fuels, the VLA-LH_2 is the greatest energy consumer. This occurs--despite the liquid hydrogen airplane's being most efficient in terms of direct energy consumption (see Tables S-2 and S-3)--because of the energy intensiveness of the processes by which LH_2 is produced, particularly the liquefaction process. For example, at least 2.6 units of energy must be expended for each unit of LH_2 delivered to the airplane; the corresponding energy ratio for synthetic JP is about 1.6.

MISSION ANALYSES

To investigate the effectiveness of the alternatives, we analyzed them in the context of the potential mission applications described earlier. A detailed analysis of the strategic airlift mission provides insights into their utility in the airlifter and tanker roles. The remaining missions, which we term station-keeping missions, have been generically investigated.

STRATEGIC AIRLIFT MISSIONS

Because of the potential importance of the strategic airlift mission in providing mobility to general purpose forces, we structured our analysis of the alternatives on a detailed simulation of the deployment of Army divisions and their initial support increments to various parts of the world. Both range and radius missions were examined for each deployment destination. (The assumption for radius missions is that fuel for the airlifters' return flight is either unavailable or at a premium at the destination.) The scenarios are intended to reflect the spectrum of missions that would be associated with a requirement that worldwide deployment be effected without reliance on foreign bases. In some scenarios, a certain proportion of available aircraft must provide tanker support to aircraft serving as airlifters.

Table S-5 summarizes the relative cost-effectiveness and energy-effectiveness of the alternatives for each of six scenarios. The average tons per day being deployed was selected as the measure of effectiveness; cost and energy are represented by the previously discussed life-cycle parameters. For clarity, the relative cost-effectiveness and energy-effectiveness parameters presented in Table S-5 have been normalized to those of the C-5B in the NATO range scenario. With these definitions, the most attractive alternatives in each scenario are those with the smallest relative cost or energy consumption; for example, the VLA-JP is 6 percent more costly than the C-5B when examined in the NATO range scenario. The most, least, and intermediately attractive alternatives are indicated for each scenario.

Table S-5

SUMMARY OF RELATIVE COST AND ENERGY EFFECTIVENESS FOR STRATEGIC AIRLIFT MISSIONS

Airlift Mission	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC
Relative cost					
NATO range	1.00	1.06	1.24	1.28	1.63
NATO radius	1.23	1.01	1.12	1.14	1.46
Middle East range	1.84	1.65	1.86	1.88	2.57
Middle East radius	18.52	2.67	2.38	2.32	2.32
Far East range	1.84	1.95	2.25	2.23	3.09
Far East radius	1.53	1.34	1.56	1.86	2.75
Relative energy					
NATO range	1.00	0.73	0.90	1.08	1.74
NATO radius	1.23	0.70	0.82	0.97	1.56
Middle East range	1.84	1.13	1.36	1.59	2.74
Middle East radius	18.52	1.83	1.74	1.96	2.47
Far East range	1.84	1.33	1.64	1.88	3.30
Far East radius	1.53	0.92	1.14	1.56	2.93

Most attractive | Intermediate | Least attractive

Table S-5 is an aid to selecting the alternative that is, overall, the most attractive. To make this selection, however, one must attach some relative importance to each of the scenarios, as well as consider cost-effectiveness versus energy-effectiveness. Our principal observations from Table S-5 are that the VLA-JP is generally the most attractive alternative in terms of both cost and energy. The nuclear airplane is substantially inferior to the VLA-JP, and neither of the alternatives using cryogenic fuel offers significant advantages over the VLA-JP. Note, however, that if the Middle East radius mission is discounted, the C-5B is a potentially attractive competitor to the VLA-JP.

STATION-KEEPING MISSIONS

We have classified the missile launcher, tactical battle platform, maritime air cruiser, and C^3 platform applications as station-keeping missions. The required flight profile in each of these applications can be characterized by the distance from the base to the station-keeping point (the station radius) and the station-keeping duration (the time-on-station).

Some of the rationale for adapting this generic approach is provided by Fig. S-3, which associates some station-keeping missions with appropriate station radii. Note that none of the missions requires a station radius greater than about 7000 n mi. Some missions may require a long station-keeping duration (e.g., ASW), whereas others, such as the tactical battle platform, suggest much shorter time-on-station (particularly under wartime conditions when munitions are being rapidly expended).

An analysis similar to that of the strategic airlift mission was performed for each of the station radii highlighted in Fig. S-3. Both short (12-hour) and extended (324-hour) times-on-station were considered. Life-cycle cost and energy-consumption calculations were premised on a second aircraft buy. That is, it was assumed that the airlifters/tankers would be bought initially and that additional aircraft would be procured later. Therefore, no R&D costs were associated with the station-keepers. The maximum payload tonnage that could be maintained on-station continuously (with the fleet size fixed) was selected as the effectiveness measure. This choice precludes any insights into the merit of the station-keeping missions themselves, but does provide an appropriate means for judging the relative attractiveness of the airplane alternatives when performing those missions.

A comparison of the resulting cost-effectiveness and energy-effectiveness parameters revealed that the VLA-JP was the most attractive alternative for the smaller station-keeping radii, whereas the VLA-NUC was the most attractive for those with larger radii. All of the remaining alternatives displayed characteristics significantly inferior to these two.

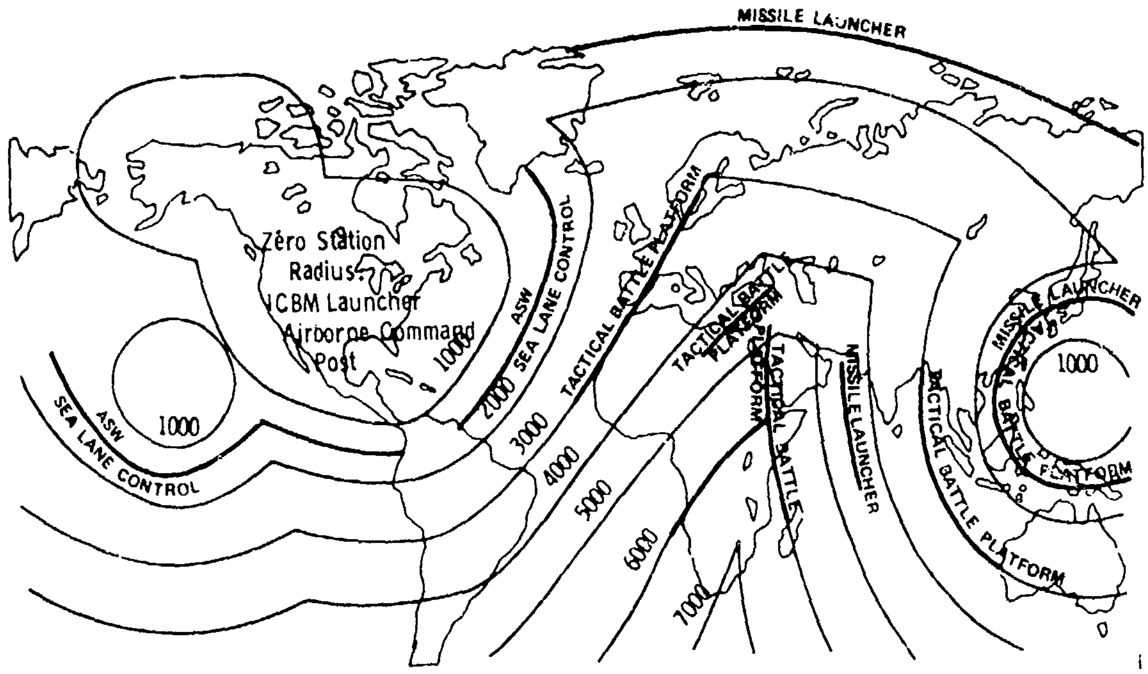

Fig. S-3—Potential station-keeping missions matched with approximate contours of equal distance (n mi) from air bases in the United States and Guam

The relative cost-effectiveness behavior of the VLA-JP and VLA-NUC is more explicitly detailed in Fig. S-4. (Again, some fraction of the VLA-JP fleet serves as tankers.) In terms of effectiveness, the VLA-NUC is superior only at the very largest station radii. Within the "region of uncertainty" depicted in Fig. S-4, either alternative can be argued to be the most cost-effective--depending on one's perspective (e.g., whether or not costs are discounted to reflect a time preference for expenditures) or the operational concept employed.

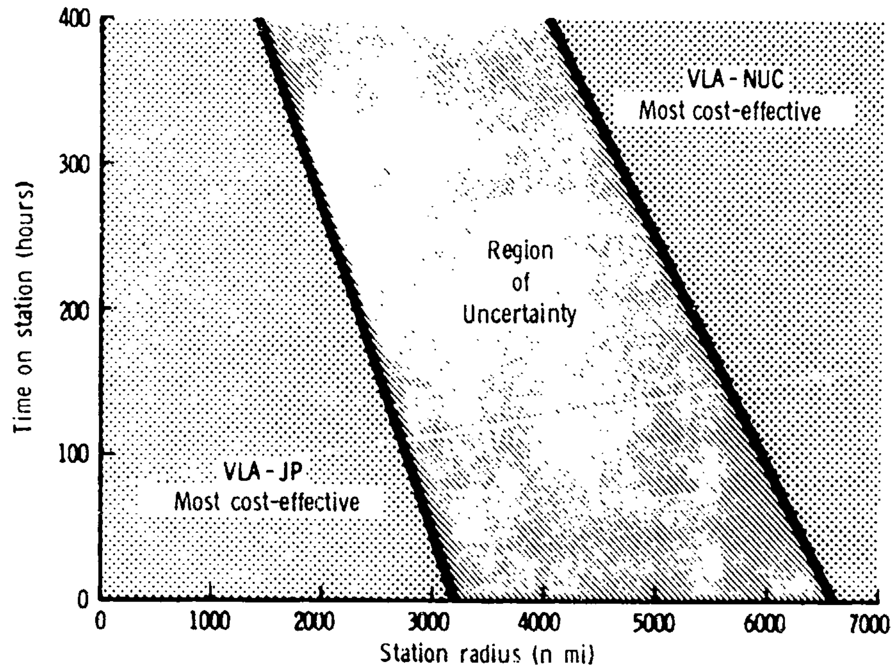

Fig. S-4 — Comparison of the VLA-JP and VLA-NUC in the station-keeping role

It is apparent from Fig. S-4 that the VLA-NUC begins to dominate the VLA-JP at station radii greater than 4000 n mi. Interestingly, Fig. S-3 suggests that most of the large-radius missions are tactical battle platform applications. As noted previously, these applications imply a limited station-keeping duration; as shown in Fig. S-4, shorter time-on-station tends to be an unfavorable result for the VLA-NUC.

POLICY CONCLUSIONS

Regarding the most attractive fuel alternative:

- o Overall, a conventional hydrocarbon jet fuel (derived from either petroleum, oil shale, or coal) remains the most attractive fuel for military aircraft.
- o Liquid hydrogen and liquid methane will offer little potential as military aircraft fuels, at least, until U.S. petroleum, oil shale, and coal resources are approaching exhaustion. Associated analyses suggest that coal reserves will not be significantly depleted before the second quarter of the next century.
- o Nuclear propulsion for aircraft is only attractive for station-keeping missions requiring large station radii (greater than 4000 n mi).[a]

Regarding the potential of advanced-technology very large airplanes compared to contemporary airplanes:

- o Very large airplanes may not be substantially more cost-effective for some strategic airlift mission applications.
- o If a worldwide deployment capability (without reliance on overseas bases) is required, then the attractiveness of very large airplanes is manifest--particularly, if fuel availability at the destination is uncertain.

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[a]Modification of design constraints imposed upon the VLA-NUC could enhance its attractiveness. Specifically, allowing the nuclear airplane to take off and land with the reactor in full-power operation (perhaps with some assistance from chemical fuel) could result in a substantial reduction in gross weight. On the other hand, much uncertainty exists in the weight estimates of the nuclear reactor system. For example, more stringent crash containment criteria might result in a still heavier reactor system.

- For station-keeping applications, very large airplanes are clearly superior, and this superiority becomes increasingly dominant with large station radii. (Of course, the increased vulnerability attributable to performing a given mission with a small number of large airplanes will somewhat lessen the strength of this conclusion.)

Note, however, that we have not concluded that the design constraints (range, payload, etc.) employed in our analysis form a definitive requirement for an airplane of this size. Rather, the analytical results suggest that an advanced-technology airplane with significantly greater capabilities than those of any existing equipment is a promising future option. The ultimate resolution of how large such an airplane should be, and what capabilities it should possess, must await further analyses.

We believe that these conclusions are substantially strengthened by our analytical approach. We resolved uncertainties in favor of the cryogenic and nuclear-fueled very large airplanes rather than the JP, and in favor of the C-5B rather than the VLAs. That the VLA-JP still appears to be the most attractive alternative is, in our view, a powerful result.

RECOMMENDATIONS: ALTERNATIVE AIRCRAFT FUELS

No apparent reasons exist for the Air Force's actively pursuing R&D that is aimed at the utilization of cryogenic fuels in aircraft entering the inventory before the end of the century.[a] Neither liquid hydrogen nor liquid methane is likely to be more cost-effective or energy-effective in the large, subsonic airplane application than synthetic JP. This conclusion is further strengthened by the unsuitability of the cryogenic fuels for use in smaller airplanes like fighters. Furthermore, NASA's ongoing work on the potential utilization of LH_2 as a fuel for commercial aircraft is sufficient to keep the Air Force's options open should developments not yet foreseen occur.

Nuclear propulsion is a more complex issue. Clearly, interest in this alternative should not be viewed as energy-motivated, for as long as significant U.S. fossil-fuel reserves (petroleum, coal, or oil shale) are available (and they will almost certainly be available until 2025, at least) nuclear propulsion is not a particularly attractive competitor of JP-fueled airplanes in most mission applications. Nonetheless, several mission applications do exist for which nuclear propulsion's unique performance characteristics make it an attractive option. But R&D on nuclear-powered airplanes should proceed only if a firm requirement evolves for these missions; thus far, no such requirement has been identified. In any event, basic research that would eventually be useful to an airborne reactor program is warranted. Specifically, the materials problem within the reactor heat-exchanger systems may require substantial advances in the current state of the art. Of course, extensive development of nuclear aircraft propulsion

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[a]The notable exception may be the use of liquid hydrogen for hypersonic (and perhaps supersonic) vehicles. Such R&D should be motivated, however, by a requirement for a flight vehicle capable of hypersonic speeds rather than by the assumption that in this time frame LH_2 will prove to be a substitute for present-day applications of liquid hydrocarbon fuels. In this instance, the research objectives might be considerably different from those motivated by a large, subsonic airplane application (e.g., use of LH_2 for structural cooling).

should proceed only if research demonstrates that public safety can be assured. Research is necessary not only on technological problems but also on the political issues associated with the acceptance of nuclear aircraft. The difficulties encountered with nuclear submarines and the ways these difficulties were overcome should provide some guidance for implementation of a nuclear airplane fleet. Furthermore, how the public eventually accepts the civilian nuclear reactor programs should provide a barometer of possible attitudes toward nuclear aircraft.

Air Force R&D on future aviation fuels should concentrate almost exclusively on synthetic JP derived from oil shale or coal. Although this may seem at first to be a comforting outcome (since synthetic JP and JP-4 or JP-8 from crude oil will probably have similar properties), significant research will still be required. Of principal importance is the problem of assuring an adequate JP supply in the coming years. The fact that sufficient fossil-fuel reserves are available and can be economically exploited for the synthesis of jet fuel does not necessarily mean that the JP will be available when needed. For example, if ERDA were to place an early emphasis on the development of processes aimed at providing clean boiler fuels (which are generally not suitable for refining to jet fuels), then processes yielding premium syncrudes for transportation uses may not be timely developed. Therefore, an analysis of the available Air Force options for assuring the future availability of JP is required.

Significant technical work is also required. Limited experience to date indicates that refining synthetic crude oil to meet the exact specifications of JP-4 or JP-8 is likely to be expensive. Obviously, trade-offs between relaxing the Air Force's fuel specifications (with the attendant implications for airplane performance) and improving the refining process through advanced development should be examined. In addition, further consideration should be given to a multifuel engine --that is, an engine capable of operating on JP-4, JP-8, or a synthetic JP (from oil shale or coal) that might be refined to relaxed specifications. Again, pertinent trade-offs should be explored.

RECOMMENDATIONS: VERY LARGE AIRPLANES

The Air Force should maintain a strong and active interest in advanced-technology large airplanes and should consider pursuing the R&D required to ensure that such an aircraft will be available. Needed work includes additional system-design studies as well as research and development on specific aircraft technologies.

AIRCRAFT SYSTEM DESIGN

The most important question that must be addressed through further system-design work is: *What performance characteristics should an advanced-technology large airplane have to provide the greatest compatibility with military requirements and the available resources?*

Primary Mission Considerations

Since the primary Air Force mission requirement is almost certainly for a strategic airlifter, the most important items to be defined are:

- The design point (i.e., the design payload and associated design range).
- The cargo compartment dimensions.

These can be identified by developing a family of modest-fidelity conceptual designs (representing various design points, etc.) and then exploring their suitability in a detailed applications analysis where cost and effectiveness are explicitly taken into account. The conceptual design that provides a capability most closely attuned to Air Force requirements thus defines the optimum performance characteristics.

Numerous secondary design considerations also should be evaluated. These include:

- The appropriate field lengths for takeoff and landing.
- The appropriate runway bearing constraints.

- Whether both front and rear loading should be provided.
- Whether the cargo compartment floor should be at truck-bed height during loading.

Although such studies may be complex, they are manageable.

Multimission Considerations

Providing an advanced-technology large airplane with a multimission capability will complicate the analyses recommended above. The desirability of this capability is basically predicated on spreading the development costs over a larger number of airframes and lowering the average unit flyaway costs through learning-curve effects. Although our analysis indicated that the VLA-JP could probably be justified in terms of cost-effectiveness on the basis of the strategic airlift mission alone,[a] the overall attractiveness of such a weapon system would be powerfully enhanced by the benefits that should accrue from a multimission capability.

Two classes of potential secondary missions exist, and they are not necessarily mutually exclusive. The first is to employ the advanced-technology large airplane in commercial aviation as an air-cargo carrier. Beside the cost benefits mentioned, these commercial airplanes could be part of the civil reserve air fleet and provide additional wartime or emergency airlift capability.

The major question which must be addressed is: Is it possible to achieve a reasonable compromise between the diverse requirements of military and commercial cargo airplanes? An "Innovative Aircraft Design" study is presently being funded by the Deputy for Development Planning, Aeronautical Systems Division (ASD/XRL) which will examine conceptual designs of several advanced-technology large airplanes at several design

[a]We believe it is axiomatic that an airplane designed as a strategic airlifter should also be capable of serving as an aerial tanker. To design it otherwise would greatly decrease the utility of the airplane in the strategic airlift role.

points. A primary objective of this work will be to assess the practicality of a common military/commercial cargo airplane. Thus it should address several of the study areas recommended above.

The second multimission possibility is to utilize these airplanes in what we have termed the station-keeping role. Several potential mission applications seem particularly interesting; these are tactical battle platform, maritime air cruiser, and strategic missile carrier. The present study has shown that an advanced-technology large airplane --procured under multimission assumptions--may be substantially more attractive than any contemporary equipment in these applications.

The next logical question to address is: Should any of these types of missions be performed by a large, subsonic airplane? Further studies should explore whether an advanced-technology large airplane can be effectively utilized to supplement or replace other means of performing these missions and should also identify what airplane characteristics (e.g., size) would be most suitable in these applications.

AIRCRAFT TECHNOLOGY

ASD's previously mentioned "Innovative Aircraft Design" study should provide much richer detail on needed aircraft-technology R&D, inasmuch as the conceptual designs will be prepared in greater depth. However, our experience in the present research has indicated that additional R&D in some technology areas should be considered.

Of course, any USAF R&D effort must be cognizant of related NASA efforts in this area. Specifically, NASA has recently begun a research and technology program on aircraft fuel conservation--the major elements of which are:

- Propulsion (engine-component improvement, fuel-conservative engine, and turboprop)
- Aerodynamics (fuel-conservative transport, laminar flow control)
- Structures (composites in primary aircraft structures)

Anticipated funding for this program through 1985 is $670 million (in then-year dollars).

The NASA program, as presently structured, is compatible with the needs of a USAF advanced-technology large airplane which could enter the inventory after 1985. The Air Force, therefore, should cooperate fully with the NASA effort where appropriate. Several technology areas of possible benefit to large military airplanes may be particularly suitable for Air Force investigation, either because they are not being extensively supported by the NASA work or because they may become candidates for reduced funding if the commercial aviation community fails to show an interest in them.

Propulsion

Advancing the state of the art of aircraft turbine engine technology (e.g., increased turbine inlet temperature) is included in the NASA program. The importance of this work is undeniable for obvious reasons.

The NASA program also includes the consideration of turboprops. To date, the airlines remain cool toward the idea of switching back from jets to props--fearing massive passenger unacceptance. (Such unacceptance could probably be tolerated if all airlines introduced turboprops, but it certainly lessens the likelihood of any single airline's being a leader in its introduction.) Thus, NASA may ultimately assign the turboprop work a relatively low priority.

The turboprop, however, might be much more acceptable for Air Force (and/or commercial air cargo) applications. One concept is particularly intriguing--the so-called propfan developed by Hamilton Standard. (This propeller-like device somewhat resembles a high bypass ratio turbofan with the shroud removed.) Work to date suggests that reductions in mission fuel requirements of 15 to 20 percent may be possible, and this at a cruise Mach number of 0.8 rather than the 0.60 to 0.65 typical for standard turboprops. Such a potential payoff warrants at least cursory examination by the Air Force.[a] The first objective should be to determine whether efficiency improvements of this magnitude are, in fact, achievable.

Aerodynamics

Laminar flow control is also included in the planned NASA effort. Again, however, possible airline resistance to this essentially new technology could prove fatal. Furthermore, the available studies indicate that the benefits of laminar flow control are more significant for long-range aircraft (i.e., aircraft with ranges greater than 5500 n mi). Extreme range is probably of much greater interest to the Air Force than to the commercial sector. Therefore, the Air Force should monitor the NASA efforts (assisting where appropriate) and be prepared to continue the work should NASA deemphasize laminar flow control--assuming, of course, that the c ncept remains technically and economically promising from a military viewpoint.

One additional aerodynamic technology item has not received a great deal of attention thus far: the potential applications of relatively thick supercritical wings (e.g., thickness ratios as large as 20 percent). The intent here is to permit a reduction in wing weight for cruise Mach numbers near 0.8 rather than to increase the cruise Mach number--the original goal of supercritical airfoil technology. Of course, supercritical airfoils also permit reductions in wing sweep (with a concomitant increase in the aerodynamic aspect ratio) for this cruise Mach number. Thus, trade-offs must be made among wing thickness, sweep, and aspect ratio to obtain an optimum M = 0.8 cruise configuration. Unfortunately, little is known, either theoretically or from experimental data, about the characteristics of thick supercritical

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[a]An interesting feature of the propfan (and propellers in general) is its intrinsically superior propulsive efficiency when operating at flight speeds less than the design maximum. This characteristic could provide significant payoffs in missions that included extended loiter periods.

sections. A relatively modest research program would indicate whether the potential of thick supercritical wings merits more intensive theoretical and experimental investigations.

Structures

The principal advances in aircraft structures center on the possible use of composite materials in primary structure. Again, the NASA work and related Air Force efforts seem sufficient--with a notable exception. Recent studies have indicated that the attenuation characteristics of composites with respect to electromagnetic waves are markedly different from those of the commonly used metal alloys. The consequences of this may be of great importance. For example, composite material would afford little, if any, protection from lightning strikes. Because of the very substantial weight-saving possibilities of composites, a vigorous R&D program on these potential problems is clearly required. (An interesting point is that if using composites in primary structure proves impractical, the potential benefits of advanced aerodynamic technologies, such as laminar flow control, would become increasingly important. These technologies provide a much greater payoff when applied to an all-aluminum airplane than when applied to one incorporating composites.)

Finally, additional research on the aeroelastic implications of high-aspect ratio wings is needed. Some work in this area will undoubtedly be included as part of NASA's effort on fuel-conservative transports.

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