ADVANCED NAVAL VEHICLES STUDY TECHNOLOGY ASSESSMENT
AIR CUSHION VEHICLES

7 November 1975

Preface

"Any new advanced craft must have a peculiar capability which makes it sufficiently attractive to be developed for use. All craft cannot do all things. In the wrong arena, the most capable advanced craft will be a poor performer. Thus, we must apply the ACV where its peculiar virtues lie: in the interface between sea and land, over ice and snow, over marginal terrain, and wherever natural or man-made underwater obstacles impede. In this arena, the ACV provides us with a platform that is in limited contact with the medium over which it is operating. Where this is important, the ACV has no competitor."

from M.W. BROWN
Advanced Marine Vehicles - MIT
Professional Summer, 1975

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I. INTRODUCTION

A. Description of Concept

In general, air cushion vehicles (ACV's) operate in the proximity of the surface over which they travel as a result of lift generated through pressurized air flow beneath the hull contained by a flexible skirt. They differ from surface effect ships (SES's) in that there is no rigid sidewall penetrating the water surface.

The ACV has the following major characteristics:

- Amphibious capability for over-water, over-the-beach, arctic and marginal terrain operations; capable of dry well operation from a ship;
- Provides potential for high speed capability over all types of surfaces;
- Ability to cross over obstacles up to cushion depth on water, land, tundra and ice;
- Low vulnerability to torpedoes and underwater mines when on cushion;
- Highly accessible and flexible cargo space; configuration easily accommodates modularized payload, including roll-on roll-off capability;
- Ecologically acceptable for operation over tundra;
- Not susceptible to damage from floating debris;
- Year-round mobility and all-weather capability in Arctic;
- Technology base available from U.K. commercial development.

Inherent limitations of ACV's include those associated with <u>all</u> high performance vehicles, namely:

- Relatively high cost per ton compared to conventional craft and ships
- Complex systems which impact on maintainability, reliability and training;
- Speed is degraded by excess weight;
- High power and fuel consumption;

- All aluminum structure requires special attention to a fire protection system.
- Although there is not an inherent size limit to ACV's in general, fully-amphibious ACV's currently under consideration for the year 2000 time frame appear to be in the 500 to 1000-ton range stemming from limitations of air propulsion systems.
- Requires both water and air propulsion systems to provide efficient long range waterborne performance while preserving amphibious capability;
- Air propulsion produces high airborne noise levels;
- Speed is degraded in high sea states (as in most marine craft)
- Speed and controllability are sensitive to wind conditions.

B. History of Effort (Reference 152)

The historical development of the air cushion vehicle has been adequately covered in earlier texts and only a brief overview will be given here, sufficient to identify the key developments.

Hayward provides an excellent search into the past to uncover such devices as Emmanuel Swedenborg's man-powered air cushion platform in 1716. Other historical research of note includes the first patent for air lubrication issued in England to another Swedish engineer, Gustav Lavalle in 1882. Lavalle's experiments were not successful however, and it was not until 1916 when Von Tomamhul built a torpedo boat for the Austrian Navy where fans were used to pump air beneath the hull to form a small air cushion. After that time various types of air cushion principles began to evolve. In 1925 a patent was issued to V. F. Casey for the use of the energy saving re-circulation principle, a principle that has been revived periodically over the last ten years but has been overshadowed by the development of skirts.

In 1927, K. E. Tsiolkovski, a noted Russian scientist, developed what today might be called the "hovertrain". This concept proposed to run trains supported by a thin air cushion layer along a track.

In 1929, D. K. Warner won the boat races on Lake Compounce, Connecticut by the use of the trapped air cushion or "Captured Air Bubble" principle on his sidehull craft with planing bow and stern seals. Then, in 1935 Toivio Kaario, the Finnish engineer, developed both a plenum principle craft and the first ram wing principle craft.

While many scientists and engineers around the world uncovered the principles of the air cushion, it was not until 1955 that the modern development began.

In 1955, Christopher Cockerell was awarded a patent for his annular or peripheral jet principle which, because of its power saving features, offered most promise for the air cushion craft. Cockerell then proceeded on a development path to build the first annular jet craft in 1959. This craft was built by Saunders-Roe, Ltd. (now British Hovercraft Corporation) by a team of engineers headed by R. Stanton-Jones and designated the SR.N 1. The trials and tribulations of such a development are best described by Cockerell and Stanton-Jones themselves in the proceedings of the Princeton Symposium on Ground Effect Phenomena, October 1959.

In this same period research was being conducted in the United States along similar lines. Melville Beardsley narrowly missed being first with his work on annular jets in 1955. Dr. Harvey R. Chaplin was responsible for most of the basic research in air cushion craft (or GEM's) at DTMB (now David W. Taylor Naval Ship Research and Development Center) which began in May 1957 with V/STOL research.

C. Present Status of Development

During the last ten years, Navy laboratories have engaged in ACV technology efforts. Also, technology developed by the SES program has contributed to the advancements in ACV technology. However, the present status of ACV development can best be described in context of two major programs, Arctic Surface Effect Vehicle (SEV) and Amphibious Assault Landing Craft (AALC).

<u>Arctic SEV</u>. The Arctic Surface Effect Vehicle (ASEV) program was established in 1970 under the sponsorship of the Defense Advanced Research Project Agency (ARPA). The program has extended the technology base

in three major areas:

- Surface effect vehicle technology for operation in the Arctic;
- Arctic environmental definition including terrain and ice mapping:
- Obstacle detection and navigation.

By sponsoring these technological studies for the Arctic SEV, ARPA has carried out its traditional role of catalyzing applied research. It now remains for the military agencies with operational responsibilities in the Alaskan Arctic to use this body of information and extend it into the hardware development and operational phases. The technology for construction of at least a 500-ton ASEV has been developed. There are several problem areas specific to Arctic SEV operation which need to be further addressed in a full-scale vehicle test. These include:

- Skirt wear and ride quality in over-ice operation;
- Navigation and obstacle avoidance;
- Adverse effects of low temperature on materials, equipment, and personnel.

Amphibious Assault Landing Craft (AALC). The major U.S. Navy development currently underway in the Air-Cushion Vehicle area is the Amphibious Assault Landing Craft (AALC) Program (SAW02). This program commenced in 1965. Preliminary designs of several sizes of ACV's were completed in October 1970. Contracts were awarded in March 1971 for detailed design, construction, and test of two 150-ton air cushion vehicles, one by Aerojet General Corporation (JEFF(A)) and one by Bell Aerospace Company (JEFF(B)) in parallel development efforts. It is planned that construction will be completed and testing will start in mid 1976. A production decision is expected in FY-1978. The Advanced Development Program will then shift focus to other sizes and types of AALC.

Significant problems which are being addressed in this program include lateral control of ship when in transit and entering the dry-well deck of mother ships, and cushion seal life.

Certain problem areas applicable to all ACV's are also being addressed in order to design and construct more effective and reliable production craft:

- Air cushion dynamics including stability, resistance and ride quality;
- Skirt materials, fasteners, and fabrication technologies;
- Structural design criteria;
- Navigation, ship control, and collision avoidance equipment and integration of these elements;
- Lift-fan technology.

D. Description of Existing Hardware

This section will be limited to a description of U.S. hardware, either existing or under construction.

1. Patrol Air Cushion Vehicle (PACV). These craft were deployed by the U.S. Navy in Vietnam in 1965-66 to assess the operational value of ACV's in combat. They were modified British SR.N5 craft having a length of 39 feet and a beam of 23 feet with a gross weight of about 9 tons. They were powered by a single 900 SHP marine gas turbine driving the lift fan and the controllable/reversible pitch air propeller. Maximum speed was about 60 knots. Range was 150 miles and payload was about 3 tons. The craft was controlled by a pair of rudders mounted aft and by puff-ports forward and by skirt lift at all four corners of the craft. Pitch trim was available from a horizontal control surface between the vertical stabilizers.

2. Army Assault ACV (AACV) and Transport ACV (TACV). The performance demonstrated by the PACV led the Army to procure three Bell SK-5's designated as AACV and TACV. While considerably modified, these craft were nevertheless quite similar to the SR.N5. They featured mainly flat decks, increased armament and armor. This increased the gross weight to about 10 tons and the power was increased to about 1100 SHP. Other features and characteristics were similar to the PACV. The Army deployed these craft to South Vietnam in 1968 where they saw considerable action and were successful in carrying out their mission as tactical patrol craft.

3. Amphibious Assault Landing Craft (AALC). As mentioned previously, two designs, JEFF(A) and JEFF(B), are being developed in a parallel program. These prototypes are currently under construction with completion scheduled in mid 1976. They are functionally equivalent, but technically different, employing different concepts in craft control, propulsion, transmission system, skirt system and structure.

E. Overall Summary of Current Planning for Future Effort

As noted earlier, the only on-going Navy effort involving ACV's is the AALC program. The developmental vehicles of this program are nearing completion and will be tested through FY-78 by both the contractors and the Navy. NAVSEC has commenced work on the prototype design for an expected production version designated as Landing Craft Air Cushion (LCAC). Production is expected in the early 1980's. The AALC program is scheduled to develop two other assault craft, one of which may be an ACV. Other ACV efforts in the Navy are an attempt to revive the ASEV program, an ACV proposal to the Landing Vehicle Assault program, and effort to develop the twin cushion ACV concept as an open ocean platform.

The Advanced Naval Vehicles Study provides an opportunity for the Navy and the ACV community to explore other application of ACV's. Although currently being developed as landing craft, the AALC are capable of being readily modified to serve in other amphibious warfare roles such as minesweeping and minelaying, defense against high speed small boat attack, reconnaissance, and medical evacuation. Studies have been carried out which define feasible concepts for search and rescue, ASW search and attack, ECM decoy, and missile launching. A brochure covering projected other mission applications of the AALC will be furnished under separate cover. The inherent advantages of ACV concepts in the Sea Control Mission are speed, small waterborne signature, and safety from mines and torpedos. The amphibious capability of the ACV can be employed for the Sea Control Mission in coastal regions and regions such as the Arctic Ice Cap.

II. STATUS OF VEHICLE TECHNOLOGY

A. Technology Performance Areas

1. <u>Aerodynamics</u>. Predictions of the external aerodynamic

characteristics of ACV's can be defined by wind tunnel testing once the configuration is selected. However, influx and efflux of the lift, thrust and power systems are generally not included in such tests and the ability to incorporate such effects analytically are questionable. Results from wind tunnel test programs have been incorporated in 6-Degree of Freedom aerodynamic prediction routines able to predict, with a high degree of accuracy, aerodynamic characteristics through 180° of yaw for various forward velocities and craft geometries. However, effects of cushion air influx and efflux on aerodynamic characteristics require further study. Also, there have been only limited opportunities for correlation between model test results and full scale operating data.

Internal aerodynamics is a critical technology to an ACV, since it must rely on its air cushion to perform properly. The lift system that supplies the pressurized air to the cushion consists of inlets, fans and ducting. The skirt system may be part of the lift system if the air is ducted through the skirt to the cushion but its principal purpose is to contain the cushion under the vehicle while minimizing resistance and air leakage. The dynamic nature of the cushion interaction with a seaway or rough terrain makes the internal air flow dynamic in nature, not steady state. The SES program, in efforts to improve ride quality, has done much to increase knowledge about this problem and has explored several variable-geometry fans for the purpose of controlling air flow to minimize cushion pressure fluctuations and resulting motions. Little, however, has been done in this area for the ACV because present vehicles could not justify the cost of such an approach. Any attempt to design an ACV for open ocean operation in sea states of 4-6 will require further investigation of internal aerodynamics.

2. Hydrodynamics. Due to complexities of the air-sea interface, the hydrodynamic drag associated with ACV's is not completely reducible to analytical expression, but empirical laws have been developed to describe the individual components of drag not easily expressed analytically. Data gathered in various ACV development projects (full scale and model scale) has resulted in accepted expressions for these components. The ability to predict drag differences, for example, for two somewhat different skirt

configurations is doubtful. However, accuracy is believed adequate for performance prediction and preliminary design purposes when supplemented with follow-up model testing of new concepts and designs. Further model data would also be desirable for better definition of yawing effects on the hydrodynamic forces for more accurate predictions of vehicle stability and control. Further opportunities for correlation between model test results and full-scale operating data are required to define scaling laws more accurately.

3. Stability and Control. Considerable effort has been expended in the area of stability requirements for ACV's. The effects on stability of craft characteristics such as skirt height, effects of various skirt configurations, and cushion compartmentation have been established. Dynamic responses of models passing over obstacles have been recorded and incorporated into computer simulations.

Hydrodynamic forces and moments that effect vehicle stability and control during operation in a seaway are difficult to determine either analytically or experimentally. They cannot be determined on an instantaneous basis even at prototype size, but the successful operation of a free-running model or full-size vehicle can provide confidence of the successful integration of such instantaneous effects.

Current static and dynamic stability design parameters, which are known to favor safety vs. smooth ride considerations, need to be expanded and improved as was demonstrated by the high skirt development for ASEV.

Control methods for ACV's have also been investigated. Computer simulations for vehicle maneuvering and control have been developed and exercised. Of primary importance to the success of these simulations is the ability to accurately predict the transferred aerodynamic and hydrodynamic forces due to terrain interaction. The ability to design control systems for ACV's has been demonstrated and improved through British and American operational experience. This key area has been addressed in the AALC craft, the JEFF(A) and JEFF(B), and the control systems being developed in these craft are expected to greatly improve ACV controllability.

4. Materials. General construction materials for ACV's have been thoroughly analyzed and pose no particular problems. The area of highest potential operational problem is the skirt material. Many candidate skirt materials have been developed and tested for their ability to withstand operational environments ranging from overwater to the extreme low temperature, hard surface environment of the Arctic. This combined with operational experience has resulted in materials with marginally acceptable wear limits although improvements in this area are being sought.

5. Structures. Modern structural design techniques can yield efficient structures for ACV's, assuming accurate predictions of loads. The ability to predict loads for air cushion vehicles similar to those already in service must be recognized as being good based on experience alone. Unfortunately, for vehicles of equal tonnage but of grossly smaller planform (resulting from high cushion pressures), the capability is less promising. There are, however, relatively new methods which have considerable promise and need only further experimental verification. In general for vehicles under 200 tons, the loads can be predicted with enough accuracy so that substantial weight penalty will not result. This may not be true, however for larger craft (200-800 tons). This area should show a marked growth in knowledge and confidence in the next 3-5 years, provided the two AALC test craft (JEFF(A) and JEFF(B)) can be effectively utilized to gather data and to provide full-scale validation of prediction techniques.

Optimization of structural components such as stiffened panals is generally available. Integration of these basic data is progressing, but a total method for selecting and integrating a structure for ACV's is not generally available. Methods for static-elastic structural analyses are in hand, in as much as detail as is necessary (Finite Element Techniques, principally). Good correlation can generally be expected.

The design sequence is well known, though not automated in any detailed sense. Also, the effects of new constraints (primarily cost) are not easily integrated. A major problem is lack of concrete measures of cost effectiveness. At present, cost effectiveness can only be a comparative evaluation on an arbitrary basis. The situation becomes much better if precise operational requirements are known, and payoffs or penalties can be defined. The experimental efforts of the AALC (Amphibious Assault Landing Craft) program may allow some improvements to be made in the setting of requirements and will validate design capability for ACV's.

The major measures of performance of the structure are light weight, reliability, and reasonable cost. Reasonably light structures have been designed and constructed (i.e. structural weight fractions of 30% - 34%), but at greatly varying cost. Current prices are likely to be in the neighborhood of $20/lb or greater, which compared to standard ship construction (even aluminum ships) must be considered expensive. The emphasis, at least for the smaller size (<300 ton), short range (<200 N.M.) ACV's must shift from lowering structural weight towards structure that is cheaper, easier to construct and maintain. For larger (300-600 T) longer range (800 - 1200 N.M.) where lower than state-of-the-art structural weight is required, the emphasis must still be on finding the cheapest alternative that is satisfactory. Cost considerations must enter the design cycle much earlier than previously. The major problem is the development of a data base well founded in actual fabrication experience, so that confidence can be gained in predictive methods. This is simply not available at present.

Life cycle performance of the structure is difficult to evaluate due to the comparatively short service life of craft built to date. The longest in service craft of any size is the British SR-N4 Class and its structure has had a minimum of problems beyond initial shakedown.

6. Propulsion. Free and shrouded propellers are the current propulsors for ACV vehicles. The axial fan propulsor is under development and offers an alternative to these propulsors for future vehicles. Theoretical methods are available to predict the characteristics of free propellers in straight line performance and in the yawed condition. Similar methods for shrouded propellers are available for straight line performance, but not for performance in a yawed condition. Few propulsors have been specifically designed for an ACV. Instead, existing aircraft propulsion assemblies have

been modified to fit particular ACV's. Specific designs should offer better efficiencies than those obtained from existing hardware modifications. In terms of performance, free and shrouded propellers are similar, with the shrouded propeller offering more thrust at low speed, more safety and less noise to personnel onboard, but are much more expensive. They add a stabilizing effect if they are mounted on the rear of the vehicle. An unresolved technical problem is when and where to use the axial fan propulsor. Its higher thrust loading offers more thrust in a smaller package but sacrifices some efficiency for this. With the development of larger vehicles, this may be the only way to obtain sufficient thrust within the space available on the vehicle. The installation of all the propulsion units must be examined to include the effect of the structure on the aerodynamic inflow to the propulsor.

7. Human Factors and Crew Equipment. Acceleration levels experienced during ACV operation due to seaway/terrain-vehicle interaction are of primary importance to ride comfort. Various groups (e.g., International Organization for Standards) have developed ride criteria for acceptable crew performance and comfort with considerable disagreement for the limiting levels. Better definition of these criteria is necessary for design considerations. The methods for attaining these ride levels is discussed in a later section.

There are no special crew accommodations or equipment necessary for ACV's other than protection from noise. The AALC craft will be used in conjunction with mother ships in the amphibious fleet, resulting in decreased crew requirements.

8. Reliability. Large advances have been made in this area in recent years. The primary problems for ACV's lie in the skirts (previously discussed), and the use of gas turbines and lift fans in the salt water environment. However, the ever increasing operational experience is providing much information identifying ACV reliability problems which leads to their solution.

9. Unique Avionics. The ACV requires no special avionics other than navigational systems and a biaxial speed sensor. Development of a biaxial speed sensor is an urgent requirement and will be addressed in the

AALC Program if funds permit. The true motion of the ACV is often not in the direction that the craft is heading due to craft yaw. Accurate navigation demands that the true motion velocity be known. To take full advantage of the ACV's high speed capability and to allow for more efficient operation in high sea states, an accurate, long range wave height sensor would be desirable. This type of sensor would allow for higher speed operation near design limited sea states by giving advance warning of an approaching high wave to avoid ship damage or distress to the crew. For high speed operation over terrain such as the Arctic surface, an obstacle detection system of this type becomes a necessity. The Arctic SEV project has addressed this type of sensor system to avoid unnegotiable obstacles at high speeds.

B. Technology Hardware

1. Hull. As ACV's have developed in size, a parameter, defined as cushion pressure over cushion length and titled cushion density, has tended to increase. This is particularly true for the JEFF(A) and JEFF(B) where, in spite of the high payload requirement, the planform dimensions were stringently limited by the requirement to operate within the well-deck of the LSD and LPD. Cushion density is a term like lift to drag ratio that does not change when the rules of Froude scaling are applied to convert a small vehicle to a larger one. The driving force that causes this trend toward higher cushion density in larger craft is the need to reduce the structural weight fraction of the hull. A more dense hull requires less of the gross weight of the vehicle to be spent on structure to obtain similar strength. Designers are prevented from choosing the optimal structural density because, as cushion density increases, hump drag increases and stability decreases. The hump drag increases by the square of the cushion pressure and is the major problem facing the propulsor designer. Stability decreases as skirt height increases. Greater skirt heights require larger cushion beams and in the Arctic SEV program this factor limited cushion density growth. The JEFF craft have the highest cushion densities attempted so far and represent the approach in ACV hull design for the future, especially for large ACV's.

2. Propulsion. The propulsion system of the ACV can either be integrated with the lift system, as on most small ACV's and the JEFF(B), or it can be independent of the lift system, as on the JEFF(A). Integrated or not, gas turbines will supply the power for propulsion. The light weight of the gas turbine in terms of pounds per horsepower makes it superior to any other type of power source. Lift and auxiliary systems will also derive their power from gas turbines. The development of second generation gas turbines has resulted in improved fuel economy. Marinized gas turbines are not available in optimum HP ranges currently, but suitable sizes for immediate future development of the ACV are available. Filtering of salt/sand from the turbine inlet air is a particular problem currently and is being addressed in the AALC Program. Improved filtering will provide more reliable gas turbine operations. Other parts of the propulsion system are not off-the-shelf items like the turbines. Gearing, particularly Z-drives, must be custom designed and need improvements, but the ACV is again being aided by other advanced naval vehicle programs in this area. The dependency of ACV's on air propulsors is unique to ACV's among surface vehicles, but shared with aircraft. However, the thrust-speed curve required by a large ACV will be different from any aircraft other than a Wing-in-Ground Effect (WIG). The size, efficiency and thrust characteristics of the propulsor and its effect on the design of the ACV will probably be the factors that limit the maximum practical size ACV. To undertake the ASW role in the open ocean that includes rough weather (Sea State 4-6) operation, the vehicle will need to be larger than any current ACV, so the need for improvements in air propulsors is obvious. The option of water propulsion requires exploration, especially the question of whether the resulting loss in amphibious capability is justified.

3. Electrical Systems. Modern, lightweight electrical systems are required by ACV's. Such systems are available, but must be designed to operate reliably in the marine environment.

4. Auxiliary Systems. Lightweight auxiliary system components would improve ACV performance and the Navy has only begun work in this area. However, the technology appears to be in hand to reduce the weight of

auxiliary system components without prohibitive cost per unit.

5. Lift System. The lift system consists of inlets, fans, ducts, and diffusers (and may have heave alleviation devices) that pressurize and transmit air into the cushion. Most work has centered on the lift fans since the lift fans are the heart of the system. At the fore front of emerging concepts is the internal sleeve, variable geometry (VG) fan which has been assessed in an extensive series of tests on fans of up to 2-feet diameter and for which efficiencies of 85% have been achieved. Equally promising, although presently not as developed as the VG fan, are fans which use blade trailing edge blowing to change the blade lift coefficients, thus modifying the pressure-flow characteristics. Two air-augmentation fan designs, both of which require a source of pressurized air, are the circulation control fan, developed at DTNSRDC, and the jet flap fan. Both of these fans have been tested under steady-state conditions, and dynamic tests are presently planned for the circulation control fan. All of these concepts are centrifugal fans which are preferred because of ruggedness and overall performance. In the axial flow fan spectrum, preliminary designs have been completed for variable pitch fans, but no hardware has been built. The axial flow fan shows future promise as an ACV fan. For the JEFF(A), where 1/3 of the installed power is dedicated to the lift system, the lift fans range in total efficiency from 64-73%, but the overall lift system efficiency is about 41%. Thus not only must the lift fans be improved, but other components of the lift system as well to permit a greater proportion of power to be committed to propulsion. Little has been done to assess fan system components in the dynamic mode that will arise during rough seas.

6. Outfit/Furnishings. The outfit/furnishing is usually mission oriented. To date, ACV's have required minimum outfit/furnishing. As the ACV mission expands, outfit/furnishing will increase. No special problem should develop in this area, but minimum levels to perform the missions will be the rule for ACV's. Mother ships may be a valid approach to supporting the best ACV operational concept for the sea control mission.

7. Specialized Systems. The skirt system for an ACV is the only specialized system introduced. Improvements in material and fabrication that will increase skirt life, reduce weight and reduce drag in a seaway would aid this concept development, but present technology is adequate for development of large ACV's. The ACV may ultimately share with the SES the need for a motion alleviation system in order to operate in state 4-6. The JEFF vehicles do not require such a system.

8. External Support Systems. The ACV's being developed by the AALC Program are amphibious assault landing craft and, like previous landing craft, will be ferried to the assault zone by amphibious ships. Larger ACV's may not be able to transit 3000 n.m. with fighting gear or supply adequate accommodations for the crew for long periods of time. Thus, a mother ship may be required. This mother ship would provide space, equipment and personnel for maintenance of the ACV. The major maintenance areas requiring external support are the gas turbines, the skirts, the lift fans and the air propulsors. These are unique to this vehicle and will require specialists for repair work. The ACV also requires a specialized "jacking" system.

C. Specific Designs

Representative past, present and future designs of ACV's are presented in the Appendix of this paper. Table 1 shows the characteristics of many of the earlier ACV designs. Following these tables are several pages presenting pictures and brief descriptions of some of the most important designs that have been built, along with military version concepts including the Amphibious Assault Landing Craft (AALC) developmental prototypes. These developmental vehicles are scheduled to roll out in mid 1976. Both the JEFF(A) and JEFF(B) are applications of the ACV's high speed and amphibious capabilities to provide rapid ship-to-shore transit, delivery of the payload directly ashore beyond the surf line and an increase in the number of available beaches.

Since ACV's larger than the JEFF craft or the SR.N4 will be required for open ocean operations, conceptual designs for large ACV's which were developed by the Arctic SEV program, but never built, are presented in the Appendix. The Arctic is a region where the amphibious capability of the ACV can be exploited to expand naval operations. These designs may not be optimal for open ocean operation, however.

III. STATUS OF PERFORMANCE DATA

A. Speed-Power

The installed power requirements for an ACV are primarily dependent on the craft size and its speed-drag characteristics. Other factors, such as maximum design speed and design sea state also affect propulsor size and craft drag. Of the total installed power, approximately 30-percent is directed toward operation of the lift fans. In almost all existing ACV's, the power is supplied by marinized gas turbine engines. They are used in either an integrated system to drive both the lift fan and the propulsor, or in a non-integrated system where separate engines are used to drive the lift fan and propulsor. The chief difficulty in powering an ACV arises from the inability of reasonably sized air propulsors to generate sufficient thrust. An answer to this problem is the axial fan propulsor currently under development, which sacrifices efficiency to obtain higher thrust. This permits a more reasonably sized propulsor package for larger ACV's.

Within recent years results from scale model tests and limited full scale ACV testing have been combined with theoretical expressions to significantly improve the ability to predict vehicle drag and power requirements. Computerized prediction routines have been developed which can be expected to reasonably predict the various drag components and corresponding power required. Representative drag and power data are illustrated in Figure 1. The accuracy of these predictions is very good in calm water. However, further investigations including full scale testing are needed to improve the techniques utilized to determine the rough water drag.

B. Range-Endurance

The range/endurance capability of an ACV is primarily a function of the speed/power characteristics of the craft and the specific fuel consumption (SFC) of the gas turbine engine. Unlike conventional diesel engines, the SFC of a gas turbine can vary significantly with the output horsepower. From the engine SFC and the speed/power characteristics, the

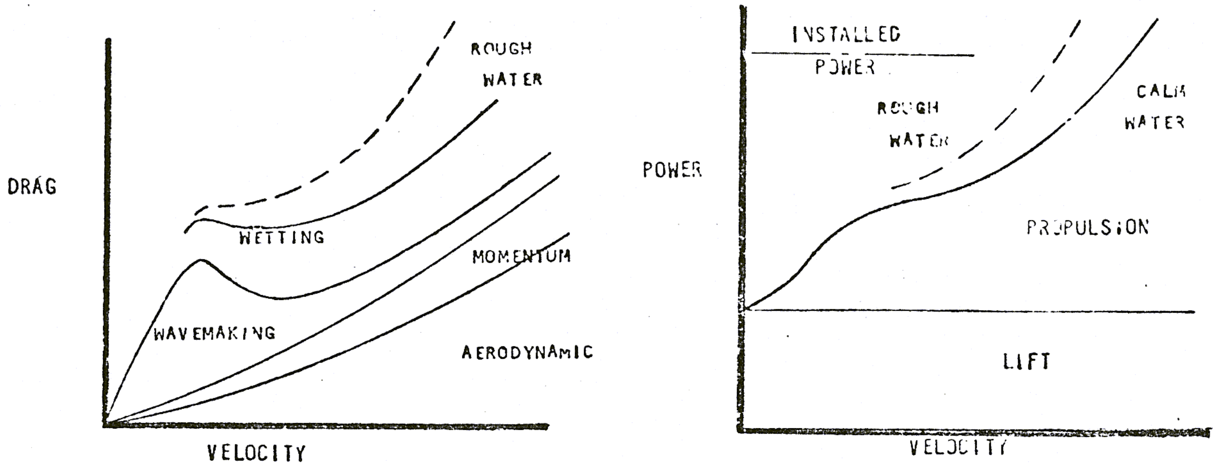

Figure 1

range and endurance of an ACV can be predicted. It should be noted that the lift system is continuously operating and requiring fuel regardless of speed.

The range/endurance capabilities of an ACV are affected by operating characteristics, such as sea state, winds, temperature and off-design efficiencies; however, the range is most sensitive to the cruise speed. At high speed, high propulsive horsepower is required due to the high drag. At lower speeds drag can still be substantial, due to the wavemaking (hump) drag characteristics. In addition, constant fuel flow for the lift system at any speed results in less miles per pound of fuel as speed is reduced. As shown in Figure-2, the ACV should be operated within a limited range of cruise velocities to achieve maximum range.

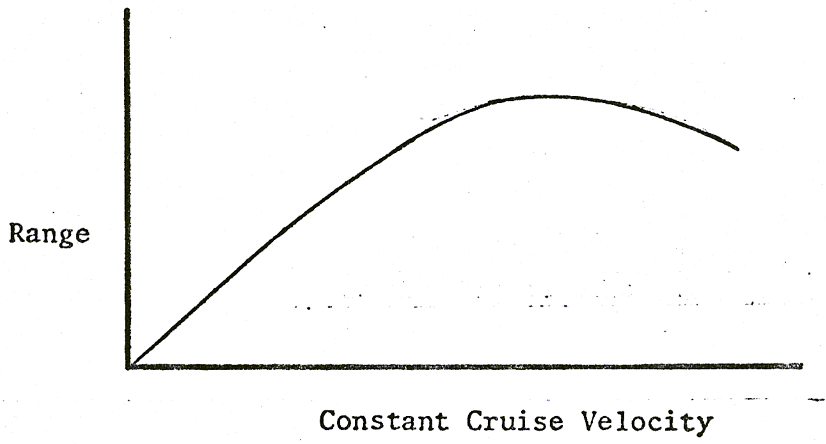

Figure 2

C. Maneuverability

The maneuverability of existing ACV's is primarily obtained from thrust deflection or from the use of aerodynamic surfaces. Most common on smaller craft are large rudders which can be deflected to generate the required side force and yawing moment. On larger craft, such as the BH-7 and the SR.N4, a swiveling pylon can rotate the propeller, deflecting the thrust and generating the necessary maneuvering forces and moments. Maneuvering forces and moments are also obtained from the craft itself as the craft is intentionally yawed with respect to its flight path. The increased aerodynamic forces on the projected side area assists the craft in completing a turn. The controlled venting of cushion air through puff ports located fore and aft on each side of an ACV has also proved to be an effective means of control for low-speed maneuvering.

Analytical tools have been developed that can predict the maneuvering characteristic of an ACV configuration with various types of control devices. The equations of motion have been combined with model test results to enable more accurate prediction of ACV maneuvering characteristics. Control system response and pilot lag times have also been simulated. Steady-state characteristics of actual craft from limited full scale testing have been correlated reasonably with predicted characteristics for the turn. Further work in defining the skirt contact forces during a maneuver is necessary to enable more accurate prediction of an ACV's maneuvering characteristics. Extensive full scale testing will be required before current prediction techniques can be validated.

D. Stability

The problem of evaluating the dynamic stability of an ACV is complicated by the undeterminable changes of the cushion geometry as the flexible skirt deflects due to changes in the operating surface. Cushion pressure, skirt system stiffness and skirt contact produce rapidly changing non-linear forces which affect craft stability. The skirt design is the predominant factor influencing the overall stability. The best means to evaluate the unique characteristics of the skirt design is through scale model experiments. From model tests and operational experience, changes in conventional skirt systems have evolved which have significantly increased vehicle roll and pitch stability and have decreased the possibility of craft "plow-in" (skirt folding under the hull). There are several different skirt designs used on existing craft today that provide an adequate operating height with sufficient stability. The bag/finger, with stability cells, the jupe and the perijupe are skirt designs which have been extensively used and experimentally tested in the United Kingdom and France. For the Arctic SEV program, new skirt designs were tested that provided strong evidence that deeper skirts were adequately stable and could be considered.

The skirt design is also a factor which influences the heave stability of an ACV that effects the ride quality and motions. Other factors, such as the lift fan characteristics and the internal aerodynamics of the lift air distribution system are also very important considerations. Attempts have been made to express the contribution that the skirt system and other factors have made to the overall stability in a multi-degree-of-freedom "simulation" of an ACV. The interaction of all these components on each aspect of craft motion has been extremely difficult to represent accurately. Progress has been made in the simulation area but further testing and full scale operations are needed before further improvements can be expected.

E. Ride Quality

Ride quality pertains to the comfort and habitability of an ACV as it operates over a random surface. The ride quality is presented in terms of the vertical accelerations that result as the craft passes over a wave or obstacle. Numerous model tests have been conducted over waves and over simulated Arctic and land terrains to measure the vertical accelerations encountered. Various criteria have been stipulated that define limiting vertical accelerations (g's, rms) that should not be exceeded over a specific time versus frequency of the response. From human response tests and actual ACV and SES operational tests, these criteria are being evaluated and modified to address adequately human tolerances and safe operating proficiency of operating personnel. Extensive full scale measurement will be required before these criteria can be fixed.

Testing of new fan designs and ride control systems that modulate the fan flow rate or allow cushion venting are currently ongoing to improve the ride quality of an ACV or an SES in rough water. The British SR.N4 carries passengers across the English Channel in reasonable comfort without any specific ride control system. Only during rough seas do the passengers become uncomfortable. For continuous operation of a high speed, military ACV over long durations, either an improved lift fan system or a specific system to control the ride quality will be necessary. The technology appears available to provide the necessary improvements in the ride quality.

F. Internal Environment

The internal environment of an ACV is little different from other craft of similar size. Large scale designs of ACV's have adequate space for crew sleeping and dining, ship operations and maintenance. Higher noise levels from the lift fans, gas turbine engines and air propulsors do exist, but on present craft these have not adversely affected crew comfort or proficiency. Regardless of the size or number of these noise and vibration generating components, means are available to isolate their effects and prevent them from affecting the crew.

G. Payload Capabilities

The payload capability of an ACV is primarily determined from the range requirement and the disposable load. From the disposable load (the gross weight less the empty weight), the fuel for range can be traded off with the payload requirements (see Figure 3). The SR.N4 and the AALC craft are designed as high payload, short range vehicles.

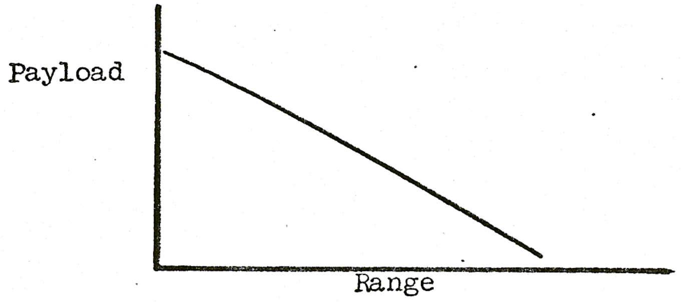

Figure 3

An important factor to be considered in the design of large scale ACV's is the payload density. It will be necessary for larger ACV's to be more dense, limiting minimum payload density that can be carried. Current designs of larger scale ACV's have minimum payload densities from 6-10 lbs. per cubic foot.

V. VULNERABILITY CONSIDERATIONS

A. Signatures

Although some measure of ACV signatures has been made by both the United States and the United Kingdom, the information is limited. However, the two major emissions from the ACV will be airborne noise from propulsion and lift systems and the heat signal from the gas turbines. Radar cross section is small, compared to ships, as a result of the lesser volume of an ACV. Waterborne noise should be considerably less since there is no hard structure or propulsor in the water.

B. Weapon Vulnerability

The AALC Program has investigated the vulnerability of the JEFF vehicle to small arms and anti-armor weapons including small missiles. The vehicle can be armored so as to protect the crew and vital components. The design can incorporate redundancy in vital subsystems and components, separation of vital subsystems, shock resistance, and special attention to fire protection, watertight integrity and dewatering capability. However, the ability of the enemy to increase the capability of the anti-armor type weapons using recoiless rifles and hand-held missiles reduces armor defense. Large ACV's will be subject to attack from aircraft, surface and subsurface vehicles that carry missiles and guns against which an ACV could not be armored. On the other hand, the ACV is not vulnerable to either mines or torpedos due to the air cushion separating the vehicle from the water. High speed movements help against unguided weapons and the ability to run away, or go around a superior enemy will work when the enemy's position is known and the enemy is slower.

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