PERSONNEL TRANSPORT MODULE FOR LANDING CRAFT AIR CUSHION

John E. Ducote
Coastal Systems Station
Amphibious Crafts Branch

Abstract

The U.S. Navy's 81 ft long LCAC can carry a payload of up to 150,000 pounds, but was designed to carry Marine Corps vehicles- not large numbers of people. The craft has a large open cargo deck ideal for griping down tanks, but is not a hospitable place for people due to high wind, noise, salt spray, and airborne sand and dirt.

As a result, the Navy has developed the Personnel Transport Module which assembles on the deck and allows the LCAC to carry up to 180 additional passengers in a protected environment. The PTM is a pack-up kit which deploys aboard an amphibious ship and used as needed. Space aboard deployed amphibious ships is always critical, so the PTM is designed for minimum stowage cube- all parts fit in one 8' x 20' ISO container. Shipboard mobility can also be severely limited, so no crane or forklift is needed for PTM assembly since all parts are lightweight enough to allow hand carrying by two to four people. The PTM structure consists of interchangeable light-weight foam core/aluminum skin sandwich panels with an integral welded aluminum frame. The panels assemble together by means of commercial 3/4 turn latches. Assembly time including outfitting is under four hours. The PTM provides seating with lapbelt restraints, forced ventilation, lighting, and can also accept standard pole-type military stretchers to serve as a MEDEVAC. The PTM draws 400 Hz electrical power from the LCAC, and can communicate with the craft via the LCACs Internal Voice Communication System. The PTM is modular; the entire unit can be used, or smaller sized units can be used which leaves room on the LCAC cargo deck to also carry vehicles. One PTM kit can even be divided and used among two different LCACs.

Originally two prototypes were built on a highly accelerated development schedule in order to meet urgent fleet requirements. These have been used with success on several deployments including the 1995 Somalia troop withdrawal. Based on lessons learned experience, various improvements have been made to the design. Seven production units are now under contract, with the seventh unit to be delivered to the Fleet in June 1998..

Introduction

The scenario of an amphibious landing of large numbers of troops on a beach invokes images of D-Day, with Marines pouring off a landing craft, wading through the surf with rifles held over head. Even today virtually the same landing craft are still in service. These craft can carry large numbers of troops, but are slow. And because they are a displacement craft the draft and tides limit

how close in these craft can get, depending on the beach gradient. Often troops are dropped off into waist deep or chest deep water, sometimes deeper. Many of the D-Day casualties were actually not from bullets but from drowning in the surf while being dropped off in deep water with heavy packs on.

Now the United States Navy has the Landing Craft Air Cushion (LCAC). This state-of-the-art hovercraft is fully amphibious. Not limited by draft or tides, the LCAC can transit at speeds over 40 knots to hard landing sites well beyond the waterline, and can access beaches that are beyond the reach of conventional landing craft. Yet since it was designed primarily to carry Marine Corps vehicles and material, the basic LCAC's ability to carry personnel is rather limited; there is room for only 24 troops plus crew in the port and starboard cabins. Other military vehicles have limited troop capacity also. Even the H-53 Super Stallion heavy lift helicopter's capacity is 55 troops, while the V-22 Osprey can only carry 24 combat loaded troops or 12 litters.

With its 60 ton nominal payload and 27 ft by 77 ft open cargo deck, the LCAC could potentially carry very large numbers of personnel. But personnel are not allowed on-deck underway without being in hard-structure embarked vehicles. So just piling a bunch of troops onto the cargo deck like with a conventional landing craft is not an option, as the LCAC's cargo deck is a very inhospitable place for people. The noise level on-deck is extremely high at up to 130 decibels, and due to the high speeds involved, restraints are needed. With the craft propellers in reverse pitch parts of the deck see hurricane force winds. Plus, anyone on deck underway would endure hot exhaust gases and get blasted with salt spray and airborne dirt and sand. Also, there would be a good chance of foreign object damage to the craft when someone's helmet or other personal belonging gets blown off and finds its way into the LCAC's propellers or lift fans. For these reasons, carrying personnel on the LCAC's cargo deck requires some type of shelter for protection.

Troop transport need identified

A way was needed to greatly increase the LCAC's ability to carry personnel. The Top Level Requirements originally written for LCAC included an option for troop transport capability with expeditionary accommodations utilizing the cargo deck area. The need began to take precedence late in 1992 when the Unites States Marine Corps wrote a fleet operational statement and a draft mission needs statement outlining requirements. In spring of 1993, the Naval Surface Warfare Center, Dahlgren Division, Coastal Systems Station (COASTSYSTA), located in Panama City, Florida was tasked by Naval Sea Systems Command to define requirements for a LCAC personnel transport shelter and to perform a study to evaluate and identify potential shelters available which could meet requirements.

Requirements emerge

COASTSYSTA formed working group meetings with the Fleet to define requirements for what would eventually be called "Personnel Transport Module" or "PTM". Representatives from Naval Operations, Naval Sea Systems Command,

the Assault Craft Units, Fleet Marine Forces Atlantic, Marine Corps Combat Development Group, Surface Warfare Development Group, and Coastal Systems Station took part. The operational concept that evolved from the working group meetings was that the PTM would be a pack-up kit that would deploy with a Marine Expeditionary Unit (MEU) aboard amphibious shipping (LCAC mothership) until a mission profile dictates its need at which time it would be installed on the LCAC. The primary mission role would be troop transport of combat loaded Marines, with secondary mission roles of Medevac and non-combatant evacuation operation (NEO). Since the PTM would remain embarked aboard the amphibious ship as an organic asset, the required stowage cube would have to be kept to a minimum while providing maximum capacity when erected. This requirement was crucial since stowage space aboard ship on deployment is always critical; there is never enough room for the Marines to take along everything that is desired. Also, mobility on ship is often severely limited. The ship's vehicle decks are crammed to capacity, with only narrow fire lanes between vehicles available which precludes the use of a forklift for transport. Crane service is not available on some ships and when it is available can be risky to use underway in a sea state. Despite precautions a container swaying due to ship motion could easily take out a LCAC propeller shroud or bow thruster, which would be a major predicament since long lead spare parts would be difficult to obtain. Therefore the PTM would ideally be transportable/erectable by manpower only, and would not require the use of crane or forklift.

Results of feasibility study

Of existing shelters identified in the study, none were found which could be readily modified to a viable PTM. The Navy has experimented previously with the Marine Corps Expeditionary Shelter System (MCCESS). The MCCESS is basically a knock-down version of a standard 8 ft by 20 ft MILVAN type container, and was modified to provide rudimentary seating, lighting and ventilation. The unit has been deemed marginally acceptable in limited situations. Deficiencies include the need for a crane/forklift for both assembly and transport, and excessive stowage requirements. Another drawback is that to achieve maximum capacity six MCCESS units must be loaded in the athwartships position with the doors alternately facing port and starboard. This configuration is not well suited for rapid troop egress because of the obstruction of the container tie-downs, and is incompatible with medevac due to insufficient clearance for loading stretchers. The MCCESS also has insufficient thermal/acoustic insulation. Other shelters that were evaluated in the study included the Army Standard Family (ASF) Expandable Units, the Army Modular Extendible Rigid Wall Shelter (MERWS), and the Wall Panel Assembly Shelter (WPAS). For various reasons, these shelters were not suitable as a PTM. Fabric/tent shelters were also given consideration, but these were rejected because of the lack of sound attenuation, doubts about whether they could stand up to prolonged high buffeting winds, and the need for seat and litter support structures, which negates the benefits of simplicity that a tent would provide.

Design development

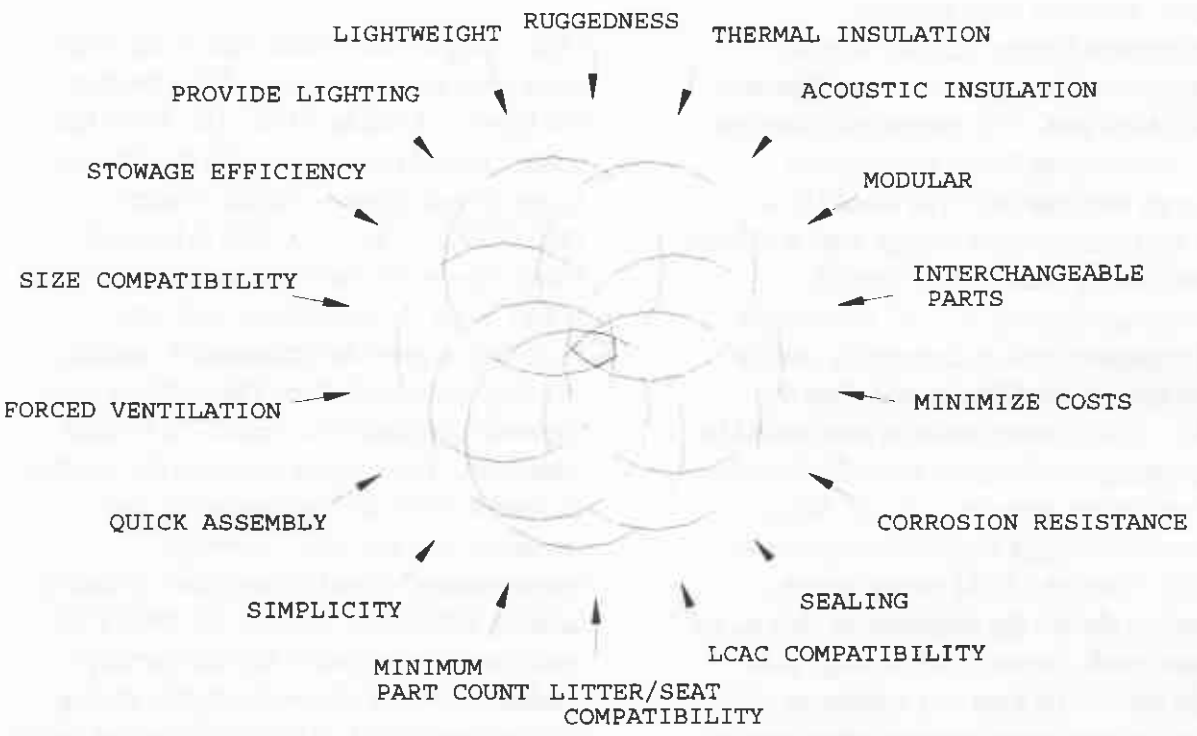


Figure 1: Representation of PTM tradeoffs, intersection of circles is do-able envelope

Since no existing shelters would meet requirements, development of a new design PTM was initiated. The requirements to stow in one 8 foot by 20 foot container and assemble without crane/forklift would be the primary design drivers and the most difficult to meet. Without these, putting a shelter on LCAC would have been fairly straightforward; the only real design driver would have been cost.

It was determined that an arrangement with three aisles running longitudinally and bounded by bench seats facing the aisles, with egress at the forward and aft ends would be the most efficient for capacity and egress, and would most easily accommodate stretchers. A structure consisting of light weight structural panels incorporating as many features as possible was chosen. The panels would not only provide a shell for protection from the environment, but would also be the support structure for seats and litters. The arrangement would also allow for a high degree of modularization, giving two distinct kinds of panels. End panels incorporating doors would terminate the structure at the forward and aft ends, and roof/floor panels and vertical exterior and interior panels would comprise the intermediate aisleway/seating areas. The structure size could then be varied according to mission needs. Smaller than the full compliment could be built by assembling a fewer number of sections of the roof/floor/vertical panels. This would allow the LCAC to carry other cargo/vehicles in the leftover deck area.

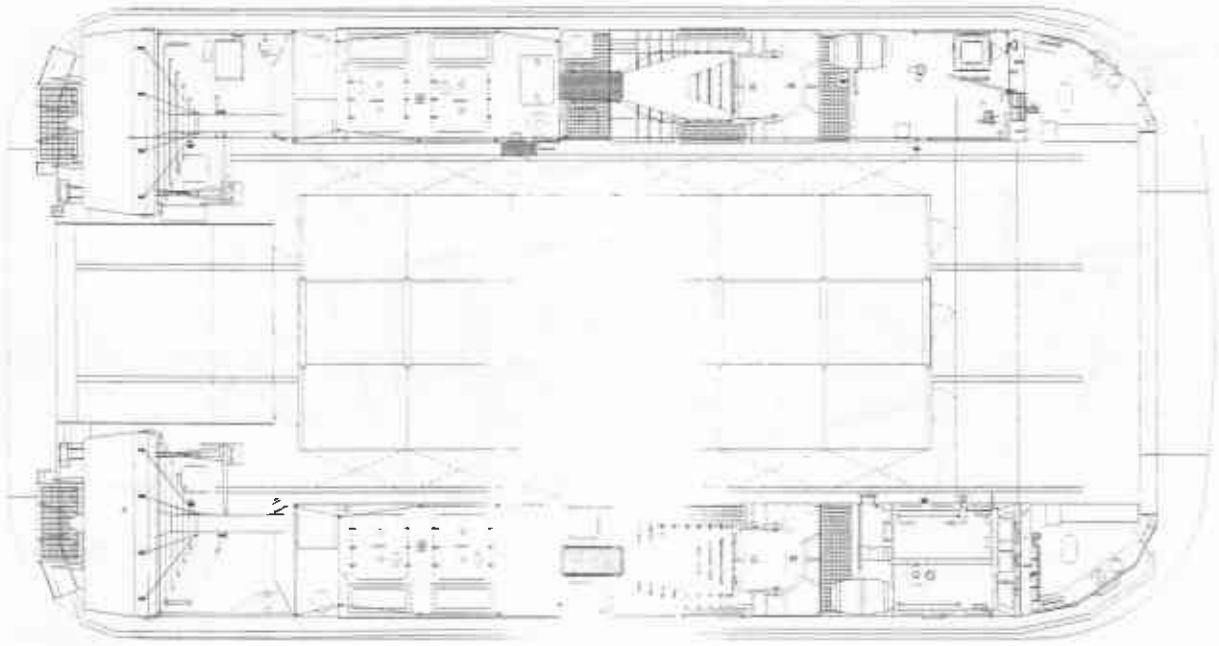


Figure 2: Plan view of full compliment PTM on LCAC

Design tradeoffs

Many secondary requirements evolved from the working group meetings, most of which were in conflict with the primary requirements of minimum stowage and hand assembly, requiring tradeoffs. Attachments for seats, litters, and other outfitting had to be done without any panel protrusions, or stowage would be impacted. The assembly time had to be minimized which requires minimum parts count i.e. larger panels, yet the structural panels had to be of a sufficiently small size and light weight to permit hand carrying through narrow lanes by two to four individuals. The size of the panels also had to allow efficient stowage within the container, be compatible with seat and stretcher geometries, and give an assembled size that would meet ergonomic requirements of accommodating the 5th to 95th percentile troops. Though light weight, the structural panels had to be strong enough to react all dynamic forces resulting from a heavy sea state, and be rugged enough to withstand abuse during assembly (sailor-proof). The minimum panel weight requirement also conflicted with acoustic requirements, as sufficient mass is needed to attenuate the high-intensity, low-frequency noise of the LCAC. To simplify assembly, part interchangeability was required to minimize the number of unique parts. The PTM had to provide adequate lighting and ventilation, yet it was desired not to complicate the design or assembly with excessive ducting and electrical wiring hookups. To provide enough ventilation for 180 people requires a significant portal area

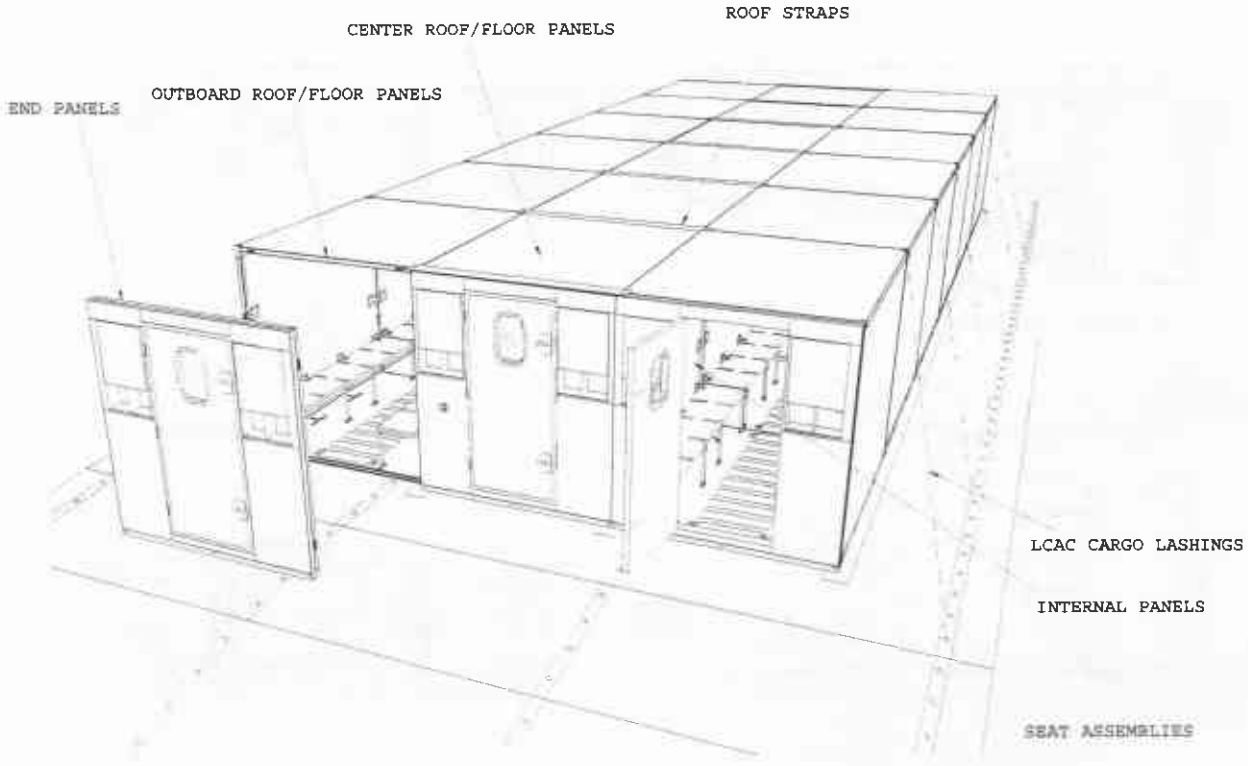


Figure 3: Assembled full compliment PTM

for air inlet/exhaust, yet any openings had to be baffled to prevent noise intrusion, and stowage requirements dictated minimum panel thickness which would also limit air portal area. Separate red and white lighting circuits had to be provided with minimum impact to the other requirements. Incorporating light fixtures into the roof panels was not desirable since the roof and floor panels were to be interchangeable, and also this would have required increased panel thickness which would have impacted stowage. Making the light fixtures detachable would have impacted assembly time. It was also desired not to complicate the panel design by running wiring/conduit through the panel cores. To minimize assembly time, the panels had to assemble together quickly and easily with some type of quick connectors, preferably captured. The number of loose parts had to be kept to a minimum. To make the shelter weather-tight, the panel edges had to incorporate gasketing at the mating surfaces, and to seal the panel connection devices had to draw together to provide compression. Getting a good seal would be especially difficult, since flat roofs are notorious sealing problems even for permanent buildings. Yet the PTM would have a flat roof with numerous intersecting roof seams, and the requirement for quick assembly/tear-down precluded the use of liquid sealants at the seams. For maximum comfort, the panels had to provide thermal insulation yet this conflicted with the requirements for minimum panel thickness/stowage. Finally, all parts had to be corrosion resistant to

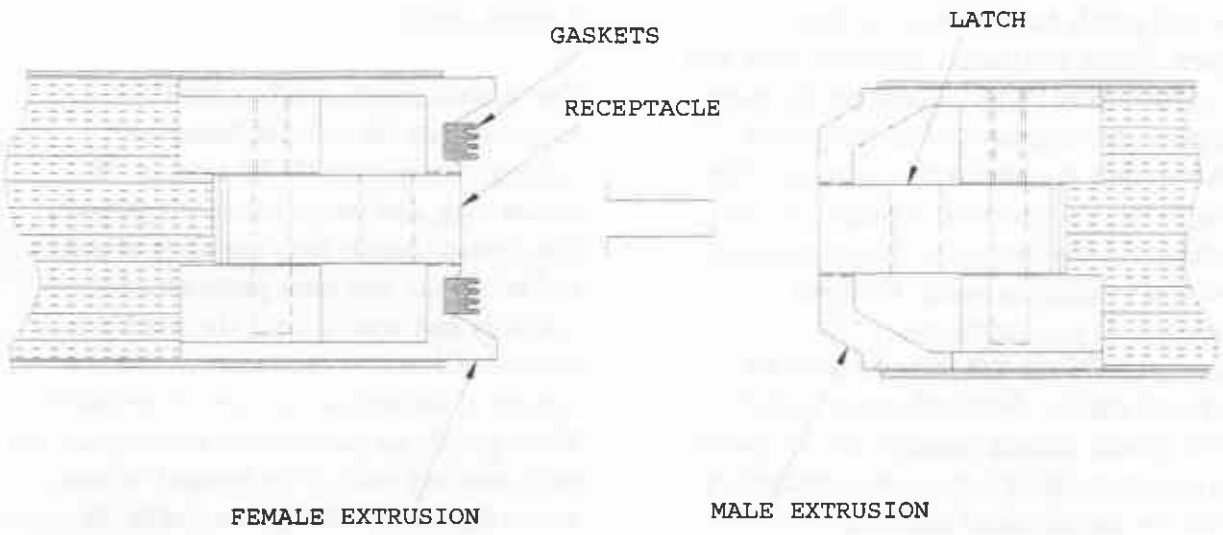


Figure 4: Cross-section of panel edges showing mating extrusions

withstand the harsh LCAC marine environment.

Design overview

The design of the PTM is therefore a balance between conflicting requirements. The structure consists of lightweight aluminum skin/ foam core panels with a welded aluminum frame. The frame consists of interlocking male or female extrusions which mate with the opposite sex extrusions on the adjacent panels. The welded frame provides a continuous load path for the contained high strength latch connection points, and also gives a rugged edge for protection during handling and assembly. Structural members are incorporated into the panel frames to provide reinforcement for seat and litter attachments. The PTM panels connect together with commercially available 3/4 turn cam actuated latches located in the panel frame, which provide a significant amount of draw for gasket compression of the rubber gaskets which for protection are located in the recess of the female extrusions. At the panel corners are corner blocks which serve to blend together the extrusion surfaces, provide an interlocking capability to resist shear loads, and also provide hard points for a secondary securement system.

There are eight different panel types which can be divided into three classes. The panel types feature commonality: any panel of a particular type is identical to and

interchangeable with any other panel of the same type..

End panels

The end panels have a basic thickness of 4 inches. Three end panels terminate each end of an assembled PTM. These are the most complex and expensive of all the panels, however they are the least in quantity. They are also the heaviest with a weight of 170 pounds, and the thickest to accommodate a door and ventilation ports. Forward starboard/aft port panels are interchangeable, as are forward port/ aft starboard panels. Forward center and aft center panels include penetrations for power and communication cables, and attachment points for the electrical enclosure.

Roof/floor and side panels

The next class of panels are the two inch thick panels, weighing about 140 pounds each, and includes the outboard roof/floor panels, center roof/floor panels, and side panels. Panels making up the roof and floor are interchangeable. These have non-skid strips on the center aisleway area, and have four stud plate fittings for accepting litter bracket straps. Four outboard roof/floor panels are required per section. These panels are 76 inches wide by 91 inches long, and have a threaded fitting to accept bolts for connecting internal vertical panels. The panel's outboard corner blocks have threaded fittings for accepting tiedown fittings, and the inboard corner blocks have threaded fittings for attaching roof straps for secondary securement. Two center roof/floor panels are required per section; these are 74 by 91 inches. Two side panels per section are required, making up the exterior wall. These panels are 91 inches long by 78 inches high, and incorporate key-hole fittings on the interior face for accepting seat or litter attachment brackets.

Internal panels

The internal panels are 3 inches thick to accommodate the integral flourescent lighting fixtures, are 90 7/8 long by 78 inches high, and weigh about 145 pounds. The internal panels have openings above and below the seat-back panel area for visibility and ventilation. The welded panel frame consists of 3-inch square tubing instead of the tongue and groove extrusions. These panels do not connect with latches but with standard bolts at the top and bottom which thread into fittings located in the outboard roof/floor panels. The lighting fixtures are located on the upper opening area, with the wiring located within the frame square tubing. The internal panels also have seat/litter attachment keyhole fittings identical to the side panels, but these are located on both faces of the panel.

Electrical system/ communications

The PTM has an electrical system to power the ventilation fans and separate white and red lighting circuits. The PTM draws power from the LCAC's 400 Hz 3 phase electric system, plugging into a receptacle located in the starboard command module. The main power cable is routed through a penetration on the center end panel, and plugs into a NEMA-4 class electrical control enclosure with switch/circuit breakers. The six ventilation fans and the light cables for the first internal panels plug directly into the electric enclosure. Power connection for the remaining internal panels is made by

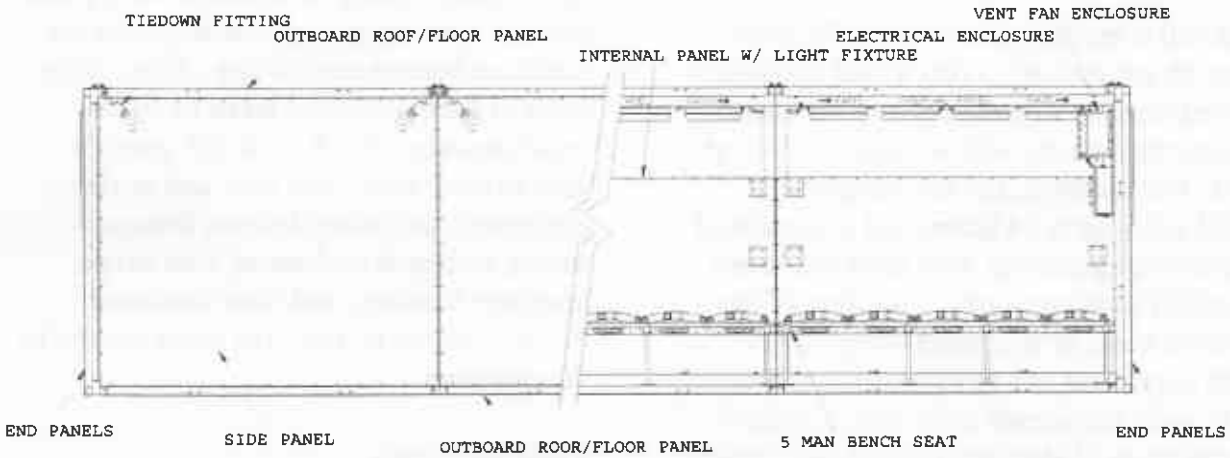


Figure 5: PTM side view cut-away

plugging the wire pigtail of one panel into the receptacle of the previous adjacent panel.

To communicate with the LCAC, an Interior Voice Communication System (IVCS) headset can be run into the PTM. The stuffing tube penetrations on the center end panels accommodate the IVCS cable, which is routed to the craft's IVCS hookup.

Ventilation system

The PTM has a forced ventilation system which includes six fans mounted on either the forward or aft ventilation ports to give positive or negative pressure. For positive pressure the fans can be mounted on the forward end, drawing air in through the forward ventilation ports, and exhausting out the aft ventilation ports. In negative pressure mode, the fans can be mounted on the aft ventilation ports. The front-to-back arrangement gives a constant flow though the PTM no matter how many sections are assembled. The ventilation fans are located in enclosures which attach to the ventilation ports and include doors for closure. The ventilation ports are located on the end panels on each side of the door. A common port is used for both the forward and aft ends. For sound baffling and to prevent water intrusion, the exterior port opening is offset lower than the interior opening, and the entire sheet metal enclosure is lined with sound absorbent material. To eliminate water spray, dirt, and sand from the incoming air, a foam filter pad is included.

The pad is canted to achieve maximum surface area within the given thickness constraints.

Seat and litter provisions

The full compliment PTM holds 36 bench seats (6 per section) giving a total maximum seated capacity of 180. For combat loaded troops the capacity will be reduced to about 150. For Medevac, the full compliment PTM holds up to 54 litters, and is capable of mixed configurations, with seats and litters installed simultaneously. Each face of the internal panel or side panel accept one 5-man bench seat or a three-high tier of litters. The seats are aircraft style, with a welded frame made of aluminum tubing and a nylon fabric covering, and include a pocket underneath for stowing an inflatable life jacket. The seats have legs which fold in for stowage. Seat attachment to the panels is made with commercially available litter brackets, which quickly clip into keyhole fittings locate in the panel face. The same brackets are used for attaching one handle of the litters to the panel face. The litter handles closest to the aisle are secured with litter straps, which have clips at each end for attachment to the stud fittings of the roof/floor panels, and have litter brackets sewn into the webbing.

Stowage

All parts of the PTM stow in one 8 foot by 20 foot shipping container. Though the PTM containers are ISO standard on the exterior, they had to be specially procured to meet unique requirements for inside length and width and other features. Double-opening doors are included at both ends to give maximum accessability. A special removal header is included at the doorway in order to accommodate the required panel height without increasing the container height. The panels stow vertically in the container, sliding into tracks consisting of tee or square tubing partitions at the top and bottom. Low-friction plastic sheets on the container bottom ease sliding. Most of the room in the container is taken up by the panel stowage. Small areas left over are used to stow seats, vent fans, and auxiliary equipment, including tiedown fittings, cables, electrical enclosures, roof straps, seat/litter brackets, and other hardware. Figure 7 shows all the PTM items stowed in the container.

Tiedown to craft

The PTM is secured to the LCAC deck by means of the standard LCAC cargo lashings which come with the craft. Tiedown fittings are provided with the PTM kit to allow connection of the lashing to the PTM structure. The fitting threads into the female threaded fittings located on the outboard edge of the upper outboard roof/floor panels, and provides a shock mitigator which limits the amount of pre-tension which can be applied to the PTM structure. The fittings are shown in figure 5. Four tiedowns are required per PTM section, for a total of 24 for the full compliment PTM.

Roof straps

Though the panel latches provide a structural connection between the panels, a secondary structural connection system is also employed for maximum safety. Roof straps are provided with the PTM kit which are essentially a simple 6 inch by .25 inch thick aluminum plate with 4 bolt holes.

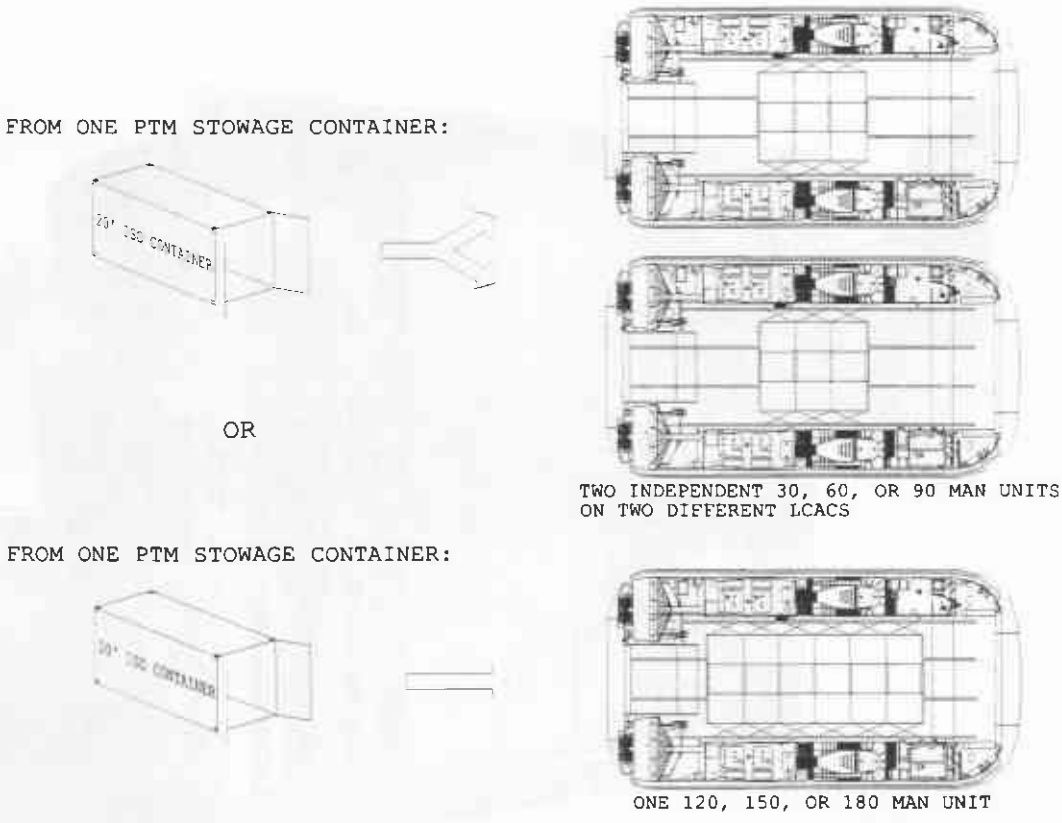


Figure 6: PTM configuration options

Bolts are used to secure the straps to the threaded fittings located in the inboard corner blocks of the outboard roof/floor panels. The roof straps serve to tie together the entire PTM roof, providing a redundant connection both between opposite outboard roof panels of the same section and between the outboard roof panels of adjacent sections. With the tiedowns attached to the welded frame of the outboard roof panels, the roof structure is completely secured to the LCAC deck independent of latches or bonded joints, preventing the structure from either lifting up or racking over.

Modularity

The modular construction of the PTM allows smaller units to be built- anywhere from one to 6 sections with a seated capacity of 30 men/section. The PTM kit also includes a redundant set of end panels, electrical enclosures, cables, and other items to give the capability to erect two different partial PTMs on two separate LCACs. This is illustrated in figure 6.

If it is desired to use a single section PTM with a seated capacity of 30, it can be built on fixtures that allow transport by crane or forklift. Forklift fixtures are provided with the PTM kit.

Add-on options

The PTM design is capable of accommodating optional heating/air conditioning,

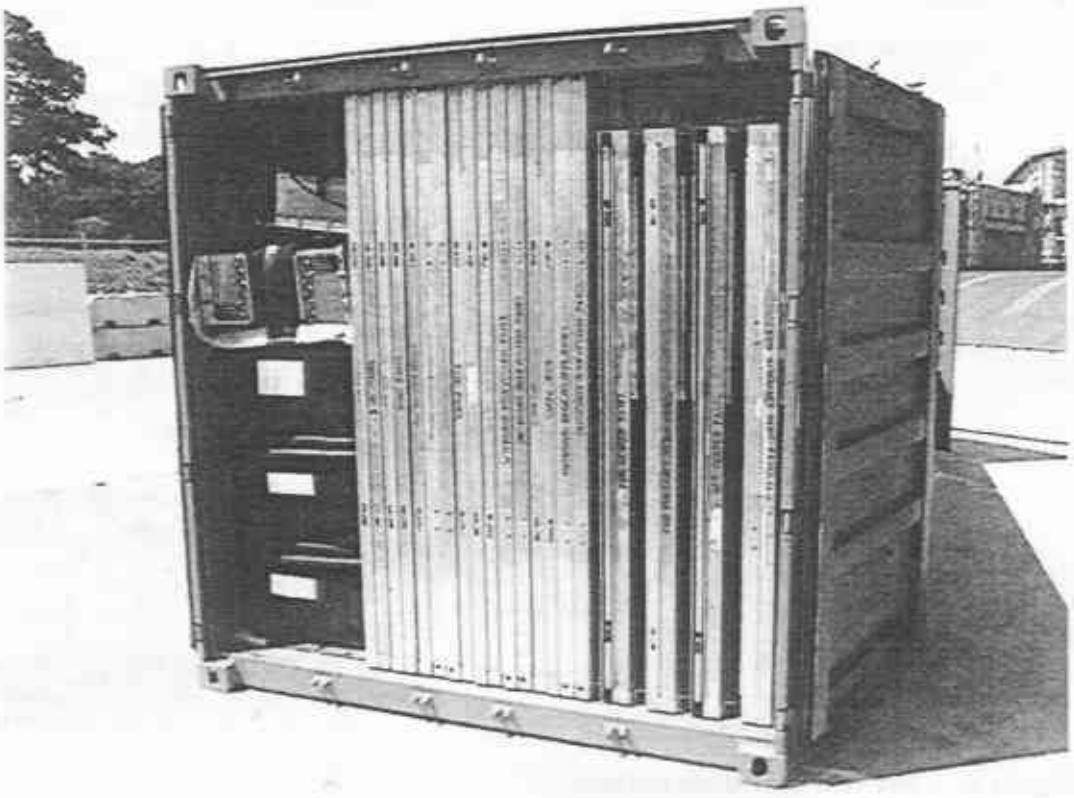


Figure 7: Fully loaded PTM stowage container

chemical/biological/radioactive (CBR) protection, or ballistic armor protection. These features were not included in the basic design because it was not feasible without impacting the other design requirements. An air conditioner or CBR filtration unit with capacity for 180 individuals would be very bulky and heavy, and would not have met the stowage/transportability requirements. Also air conditioning or CBR unit electrical power requirements would have exceeded that available from the LCAC, requiring a separate generator unit which would further impact stowage. Consideration was given to incorporating ballistic material into the panels, but even with modern lightweight materials this would have made the panels too heavy to be hand transportable, or would have made the panels so small that assembly time would have been impacted. So the PTM structure was designed to support the addition of parasitic armor panels to the roof, which would attach to threaded fittings located in the roof corner blocks. The PTM ventilation ports have the capability to accept ducting routed from separate HVAC or CBR pallet-mounted modules, which would be positioned on deck behind the PTM.

Procurement/ development history

By fall of 1993, the PTM design requirements had been accepted by the working group, and a preliminary design

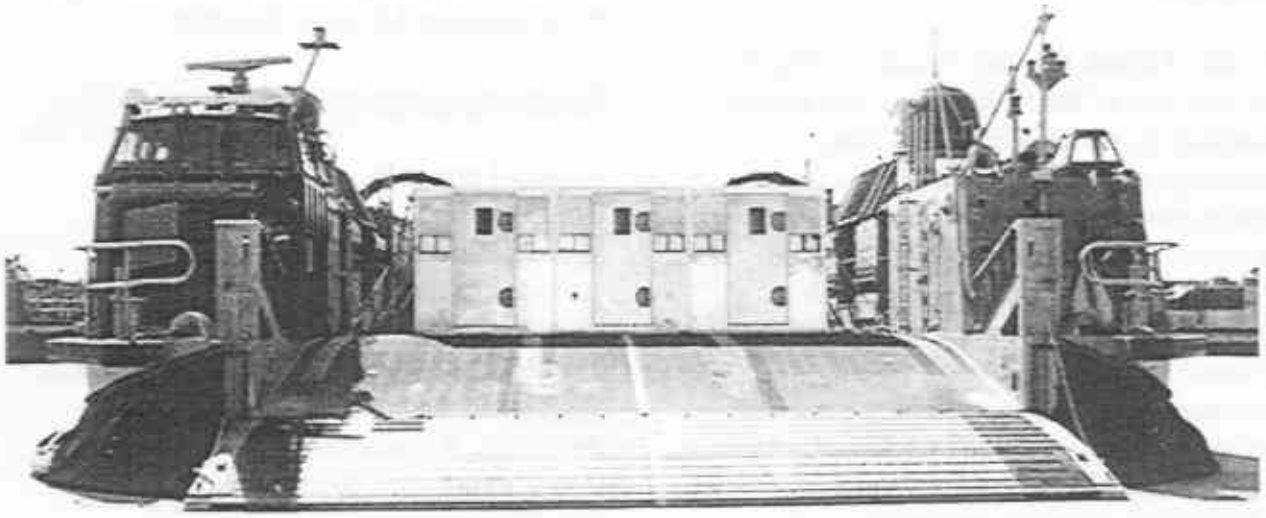


Figure 8: PTM installed on LCAC

concept had been developed. Approval was given by Chief of Naval Operations to proceed with development. COASTSYSTA then wrote a detailed specification in order to procure the detailed design and fabrication of two prototype units.

In December 1993, due to political events in Korea the PTM effort began to take the highest priority. On 27 December, COASTSYSTA received an urgent request to procure two PTM prototypes so that the first unit could be built, tested, and delivered to the Fleet in time for Deployment with the USS ESSEX Amphibious Readiness Group in October 1994. This was an extremely ambitious schedule considering the typical time required for Government procurement, the demanding set of design requirements that were to be met, and the fact that the detailed design, engineering drawings, material procurement including long lead items, and fabrication all had to be accomplished.

Request for proposals (RFPs) were soon sent out, giving potential contractors a meager four weeks to respond with estimated costs and a technical details of how the specification would be met. This time had to be extended another two or three weeks when a series of blizzards hit the East Coast and a major earthquake hit Southern California. By late February, a contract was signed with Western Instruments Corporation of Ventura California.

To meet schedule required immediate procurement of long lead items, especially the ventilation fans which had a 7 month lead time. The extrusion design for the male and female tongue and groove extrusions that make up the panel edges had to be finalized immediately. The schedule also required a concurrent design approach, with part fabrication of some parts commencing before design details on other parts was

completed.

By late August, fabrication and bonding of the first half of the PTM panels was nearing completion. After doing some shop assembly testing and making some final design modifications, the first three sections of panels were delivered to Assault Craft Unit Five (ACU5) at Camp Pendleton, California on 6 September. During the next 6 weeks, piecemeal delivery of the remaining panels, seats, stowage container, and other items was made while at the same time an intensive schedule of Fleet introduction, training, and testing was accomplished at ACU5. Ventilation, noise, lighting, and well deck exhaust gas levels were measured. During this time, a total of six at-sea missions were performed, with over 700 personnel transported. A mock beach landing of Marines was done. Demonstrations were given to various Flag and medical officers. During this time, many difficulties had to be overcome to meet schedule. Various fabrication and design discrepancies were discovered and corrected. When the fan vendor did not deliver on time interim ventilation fans had to be substituted, and adapter hardware made. Last minute fit-up problems with the stowage container required an eleventh-hour all weekend effort to correct. Finally, on 17 October, the PTM was loaded onto the USS FORT FISHER, just in time to make the deployment.

On its first deployment the first PTM prototype was used in several operations, including the Somalia withdrawal. It received favorable feedback from the Fleet, and was featured in several publications, including Defense Trends, Defense News, and the Marine Corps Gazette. An issue of the New York Times included a picture of a PTM-equipped LCAC in Somalia.

Design improvements

A second prototype unit was built, incorporating as many lessons learned improvements in-line as possible. The keyhole attachment for seats and litters, the attachment of the internal panels to the roof/floor panels, the electrical system, latch access, and the bonding processes were improved. A major re-design of the stowage container interior was done. The first PTM prototype was eventually upgraded to the same configuration.

PTM production

With the two prototype PTMs delivered to the Fleet and in service, the program progressed to the production phase, with a total of seven production units to be delivered. Though the two prototypes demonstrated that the PTM concept was valid, many deficiencies were in need of resolution. A production drawing package was produced which incorporates many modifications to the original prototype design. Difficulty of assembly was the primary deficiency experienced with the prototypes. To improve this, tolerances on panel dimension, flatness, and straightness were made more stringent. The ventilation system was re-designed for more compact stowage, simplicity, and reduced assembly time. The sealing was improved by adding ribs to the gaskets and doubling the thickness. Material improvements were made to the seat belts, latch/litter brackets, litter stud plates, and latches to give better corrosion resistance. The latch pocket design was changed to reduce welding

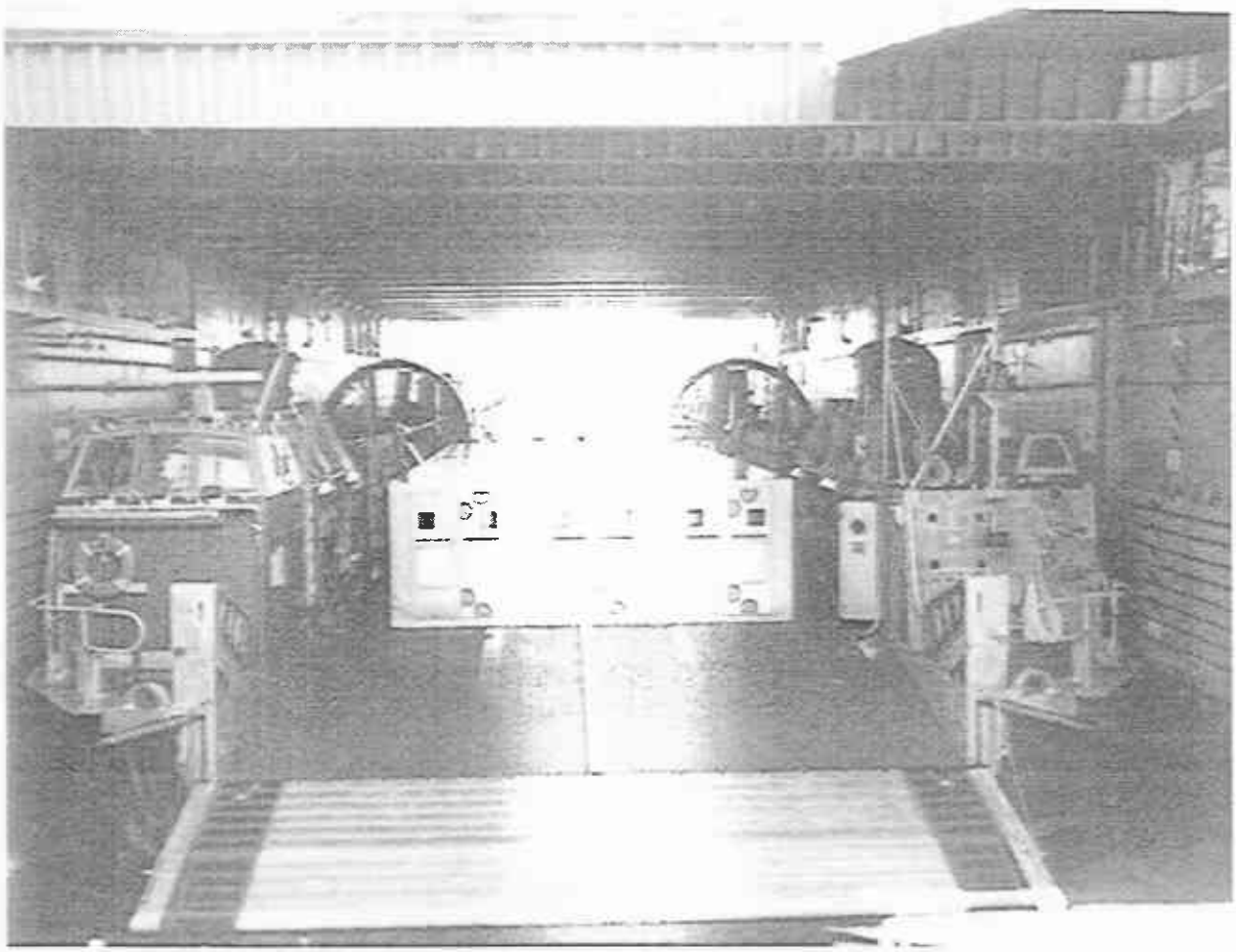


Figure 9: PTM #1 (prototype) in well deck of USS FORT FISHER

distortion. The adhesive for bonding the panel skins was improved for better bond strength and to prevent delamination. Doors on the forward end were changed from double to single to reduce costs, increase panel interchangeability, and accommodate the improved ventilation system. Seat profile was reduced for more compact stowage. Some latches were moved for better access. The electrical system design was revised to improve cable connections. Many minor changes were made to panel design to improve producability. After completion of the drawing package, a contract for the fabrication of production units was eventually awarded in 1996 to Piquniq Management Corporation of Panama City, Florida. Six of the seven production units have now been successfully delivered to the Fleet. Preliminary indications are that the production units offer a significant improvement in the areas of assembly, stowage, durability, and maintainability over the prototypes. Assembly time has been reduced to about three hours for the full compliment PTM, versus about eight hours or more for the prototypes. The last of the production units is scheduled to be delivered in June 98.

LANDING CRAFT AIR CUSHION
SURF ZONE LANE BREACHING

APRIL 1998

DONALD CAMPBELL
COASTAL SYSTEMS STATION

INTRODUCTION

Prior to implementation of Ship to Objective Maneuver (STOM), US naval tactics for conducting an amphibious assault had remained static from World War II until the 1980s. Conventional amphibious assault tactics required massing a large armada of ships near an amphibious objective area and delivery of a concentrated barrage of naval and aerial firepower directed at the beach defenses prior to the landing. The limited speed and mobility of the conventional assault and landing craft required the amphibious fleet to close within 1-2 miles of the intended landing area to discharge the assault forces. Additionally, the operational characteristics of the assault craft restricted potential assault areas to a small percentage of the world's beaches. These limitations minimized the potential landing areas available to the amphibious forces and allowed enemy forces to concentrate their defense forces on the potential landing areas. Traditional amphibious operations entailed a high risk to the assault forces with casualties often reaching 30% of the assault forces during the World War II assaults on the Pacific Islands. "From the Sea" and "Forward From the Sea" proposed a bold new thrust for the Navy and Marine Corps team to implement amphibious operations that would take advantage of emerging technologies in amphibious warfare and significantly reduce the risk to the amphibious forces.

SHIP TO OBJECTIVE MANEUVER

By using the increased speed, range, and maneuverability provided by the Landing Craft Air Cushion (LCAC), V-22 Osprey, and Advanced Amphibious Assault Vehicle (AAAV), amphibious operations can be conducted from over the horizon allowing the tactical advantages conceptualized in "From the Sea" to be realized. Additionally, the amphibious capability of the LCAC significantly increases the potential landing areas for the amphibious assault. In future amphibious operations the landing and assault craft will launch from amphibious shipping over the horizon and proceed at high speed to the objective area. In order to achieve tactical surprise, mine countermeasures and obstacle clearance systems will be employed in-stride with the assault forces offering greater flexibility to the assault forces. The amphibious shipping remains offshore out of range from most shore based threats minimizing risk to the high value assets. An integral part of the proposed tactics is the ability to breach enemy defense in-stride with the amphibious assault and deny hostile forces the ability to move reinforcements to the assault area prior to the actual landing. The most

common beach defense used to prevent an amphibious assault is a surf zone minefield. The mines are easily obtained on the open market and offer an inexpensive alternative to deploying large numbers of troops along all possible landing areas.

The U.S. Navy has the requirement to provide cleared transit lanes from over the horizon through the surf zone to support the assault with USMC combat forces. The Navy initiated a program to examine all possible alternatives and systems that offered potential for rapidly clearing the surf zone minefield. Analytical analysis followed by test and evaluation efforts revealed that precise delivery of bulk explosives in the surf zone was the most effective method of providing an in-stride breaching capability to the fleet. The Landing Craft Air Cushion (LCAC) provides a high speed, heavy lift capability to support the concept of ship to objective maneuver. The LCAC was selected to deliver the breaching systems to the surf zone from over the horizon due to its high speed and payload capability combined with a large open cargo deck. Currently an immediate capability is available to the amphibious forces with follow on improvements to the explosives in the near term, and improved system placement accuracy and delivery methods in the far term.

CURRENT CAPABILITIES

The current surf zone minefield breaching system employed by the US Navy is the Mark 5 series linear demolition charge (LDC) deployed from the LCAC. The Mk 5 LDC is a command-detonated system currently in use by the US Marine Corps combat engineers as a land mine breaching system. As a land mine countermeasures system, it is deployed from trailers towed behind armored vehicles or from a specially adapted amphibious assault vehicle in a 3 shot kit.

MK 5 LINEAR DEMOLITION CHARGE DESCRIPTION

The Mk5 LDC is 350 feet long and consists of three sections one hundred feet long and one section fifty feet long of unit charges. A core of three-quarter-inch rope and strands of PETN detonation cord pass through each section. Each 350 foot long charge contains 1750 pounds of C-4 explosive. The C-4 is distributed over the length of the charge with an average weight of 5 pounds per foot. An inert, full-scale version of the linear demolition charge is available for training exercises with a rubberized C-4 simulant that duplicates the size, weight, and appearance of the C-4 unit charges.

The Linear demolition charge is stored, shipped, and deployed from a steel charge container. The container has electrical receptacles for launching and detonating the charge; lifting rings in each corner, mounting provisions for a frame and launch rail assembly, and two skids on the bottom of the container to allow forklift access. A one-piece top is secured with steel strapping until the charge is ready for deployment.

The linear demolition charge is deployed from the LCAC by a tractor design rocket motor. The rocket motor is designated as the Mk 22 Mod 4. The motor consists of a rocket body with two nozzles, front closure, T-brackets for mounting in the launch rail, and a rear enclosure with a towing bridle. The Mk 22 rocket motor is used to deploy both the live and inert versions of the Mk 5 LDC.

A Mk 162 launch rail assembly mounts to the charge container and allows the Mk 22 rocket motor to be attached to the charge container. The launch rail assembly design allows the support frame to be mounted to the charge container without the launch rail in place. The Mk 22 rocket is installed on the launch rail and then installed onto the frame in a pivot assembly. The motor and launch rail are then rotated into the proper launch angle and locked into place.

Previous applications of the Mk 5 LDC required the launch and detonation of a single charge only with the exception of the 3-shot kit on the modified AAV. The AAV utilized three single shot selectors ganged together onto a single panel. The payload envisioned for the LCAC required the capability to launch and detonate of up to twelve LDCs. A launch control box was developed that allowed the operator to sit in the LCAC main control cabin directly behind the LCAC craftmaster and select the charge on deck, launch and detonate that charge. Figure 1 illustrates the major components of the Mk 5 breaching system as deployed on LCAC.

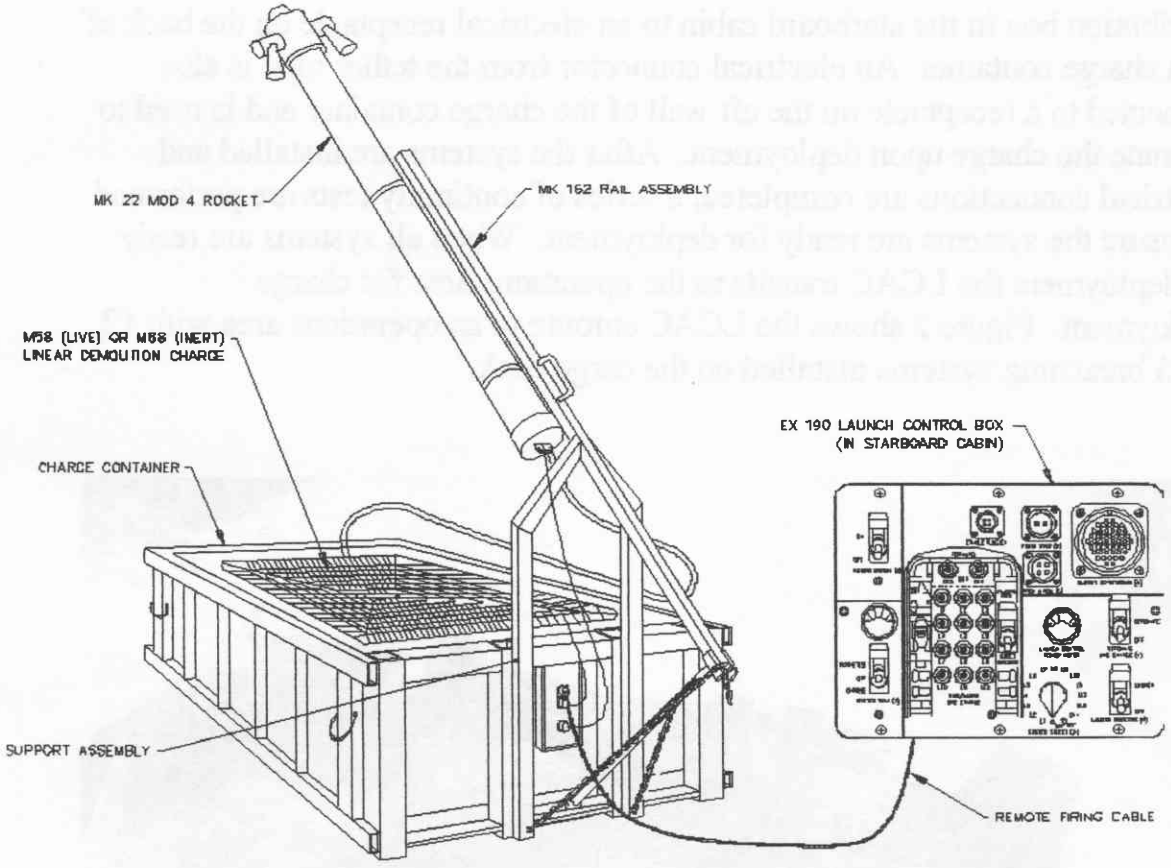


FIGURE 1 MK 5 COMPONENTS

A standard lane breaching combat load for LCAC deployment uses twelve Mk 5 linear demolition charges. The systems are secured to the deck of the LCAC using a standardized load plan with cargo lashings. Launch rail assemblies are mounted to the charge containers on deck and Mk 22 rockets are installed on the launch rails. The ¾ inch rope core in the LDC is 208 feet longer than the explosive section of the LDC. This extra length of rope is secured to an attachment point on the aft portion of the container and tethers the deploying system to the charge container. The rocket bridle is attached to the terminal end of the LDC and fuze assembly. The initiator lead from the rocket is connected to the electrical receptacle on the aft end of the charge container. The launch control box is mounted in the starboard cabin of the LCAC directly aft of the craft operator and is electrically connected to a special receptacle on the LCAC 28 VDC emergency power system. A large umbilical cable is routed to a power distribution box located below crew seating that provides a connector for each individual line charge. A cable connects the power

distribution box in the starboard cabin to an electrical receptacle on the back of each charge container. An electrical connector from the tether rope is also connected to a receptacle on the aft wall of the charge container and is used to detonate the charge upon deployment. After the systems are installed and electrical connections are completed, a series of continuity tests are performed to ensure the systems are ready for deployment. When all systems are ready for deployment the LCAC transits to the operations area for charge deployment. Figure 2 shows the LCAC enroute to an operations area with 12 Mk 5 breaching systems installed on the cargo deck.

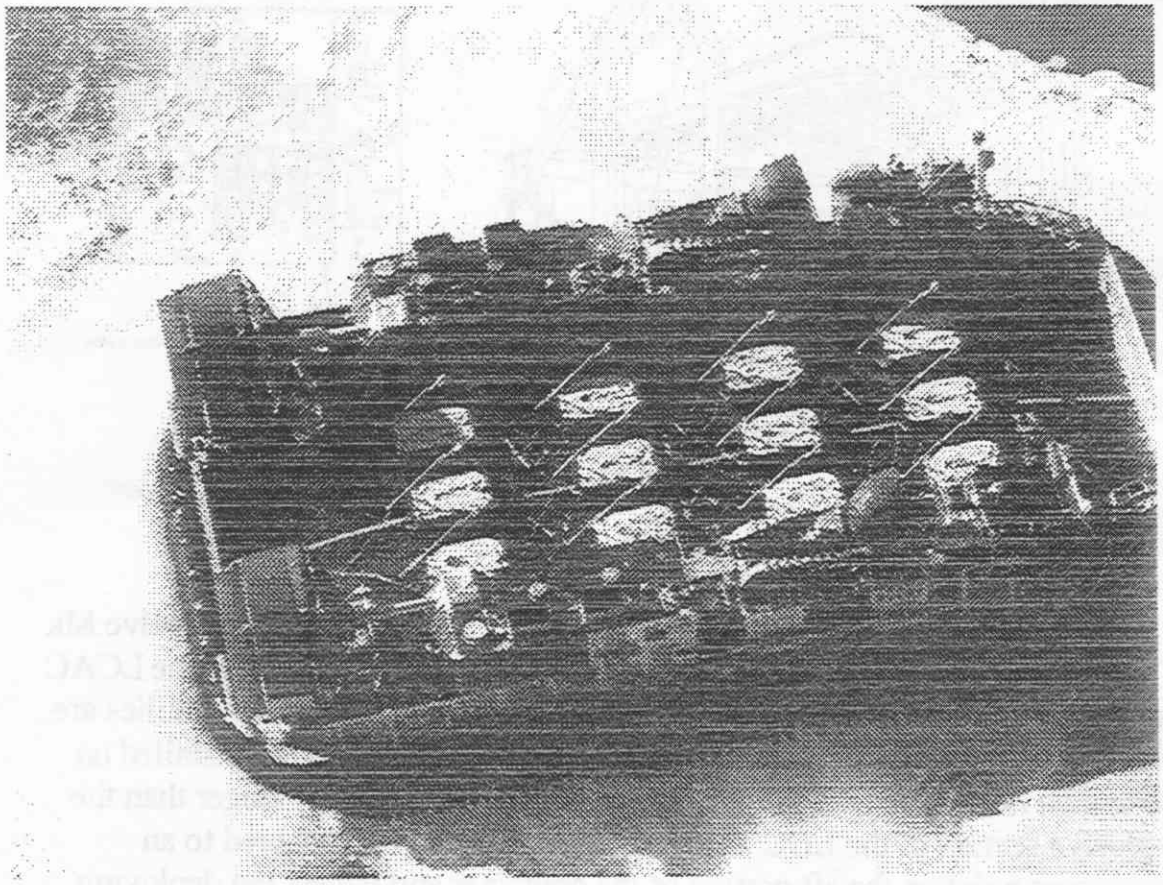


Figure 2 LCAC TRANSITING
WITH MK 5 LDC

The charges are typically launched from bow to stern with an outboard charge selected first. The rocket motor ignites upon receipt of a launch signal

from the control box and begins towing the charge down range. Approximately 2.5 to 4 seconds later, coinciding with rocket motor burnout, the line charge and tether reach full extension exerting a large pull on the system fuze. During storage, transport, and normal handling, a spring-loaded cam system internal to the fuze keeps the initiator leads out of line with the explosive charge and shunted for safety. The large linear pull exerted when the line charge reaches full extension overcomes the spring in the fuze and allows a cam to rotate the initiator leads inline with the explosive booster. Upon receipt of a detonate command from the launch control box, the system detonates. A second charge is then selected for launch and detonation and the process is repeated. Over 45 inert charges have been deployed from the LCAC through a combination of craft compatibility tests and fleet exercises.

LCAC TEST and EVALUATION

As part of integrating the Mk 5 breaching system into LCAC operations, a craft compatibility study was conducted to identify any compatibility issues associated with launching and deploying the weapon system. The first series of Mk 5 deployments from LCAC were conducted to validate the analytical results of the craft compatibility study. In January 1994 seven inert Mk 5 linear demolition charge were deployed from the LCAC overland in various operational conditions. The tests were conducted with the craft static in the landing area and on cushion in various power, main propeller, and bow thruster settings. The test series quantified the impact of rocket launches on the port and starboard cabin air quality and main engine combustion air, and potential impact of the bow thruster exhaust on rocket trajectory. Acoustic, gaseous emissions, and thermal data were collected on the LCAC along with rocket trajectory and LDC downrange impact data. All the measurements were within the established safety limits. Following the successful completion of the overland deployments verifying the craft compatibility study, inert Mk 5 LDC systems were deployed from an LCAC in the surf zone to validate the concept of in-stride delivery of lane breaching systems. Twelve inert Mk 5 breaching systems were successfully deployed from the cargo deck of an LCAC hovering in the surfzone. The surfzone deployments validated the capability of the LCAC crew and combat engineer team to accurately deliver the breaching systems to the intended impact area under dynamic launch conditions. Again during this test series, gaseous emissions, acoustic, and thermal data were taken along with downrange impact data. All measured data collected during the surf zone launches were within safe operational limits. The downrange impact data demonstrated that assault-breaching

systems could be deployed from the LCAC in a dynamic environment with sufficient accuracy to conduct an in-stride-breaching mission. Figures 3 and 4 show an inert LDC being deployed from the LCAC in the surf zone and the deployment pattern of the inert linear demolition charges after the launches were completed.

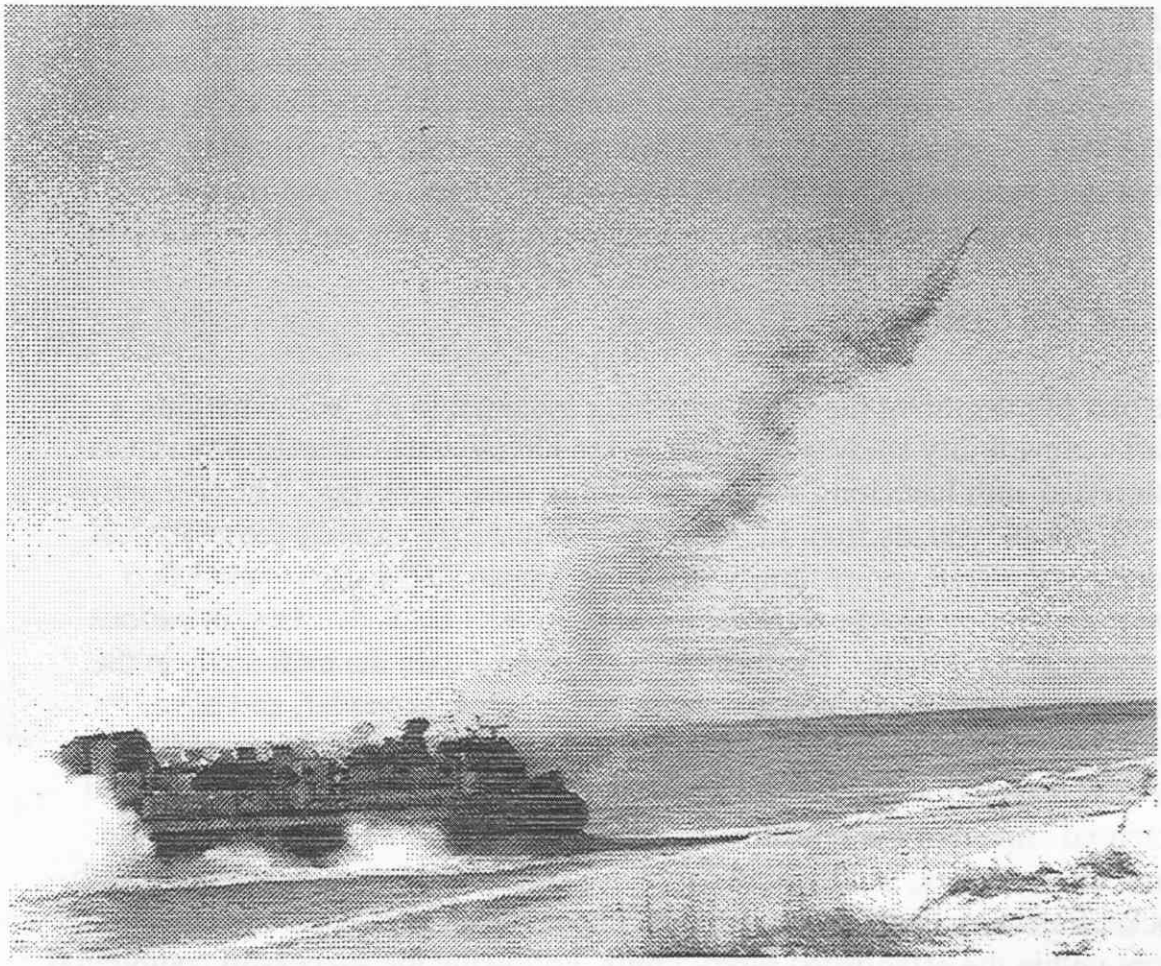


Figure 3 LCAC DEPLOYING INERT MK 5 IN SURF ZONE

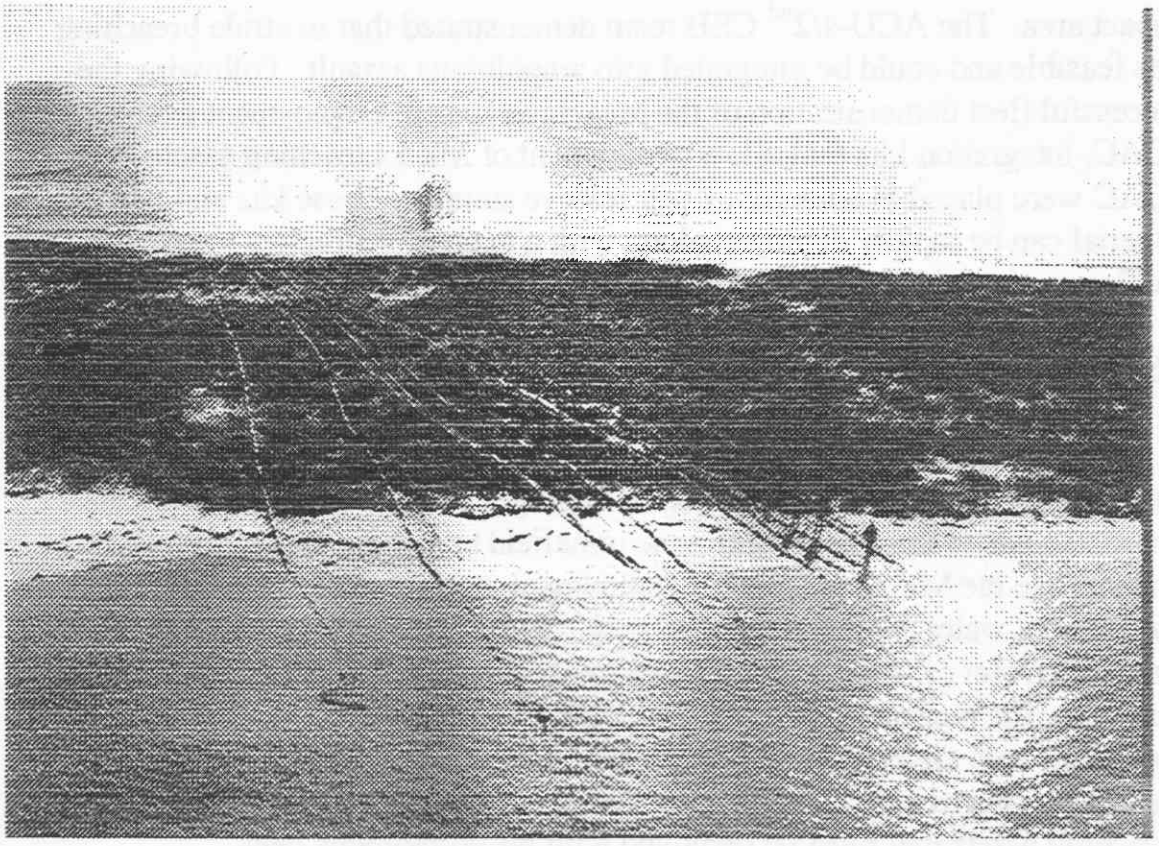


Figure 4 INERT MK 5 CHARGES DEPLOYED

As a result of the successful inert Mk 5 deployments from an LCAC, in-stride lane breaching was demonstrated in Combined Joint Task Force Exercise 1996 (CJTFX-96). The exercise planners tasked Assault Craft Unit 4 (ACU-4) in Little Creek, Virginia and the 2nd Combat Engineer Battalion (CEB) in Camp LeJeune, North Carolina with the surf zone lane breaching mission. Two LCAC crews along with ten combat engineers were trained in the integration and operation of the inert Mk 5 breaching systems from LCAC. During the exercise a beach gradient of 1:260 was used for planning the breaching mission. This beach gradient required six launch stations to successfully breach the mine defenses in the zero to ten feet water depth zone. ACU-4 and 2nd CEB deployed onboard amphibious shipping with two LCAC to support the lane-breaching mission. During the exercise each ACU-4/2nd CEB team completed two echelons of simulated firings and launched six inert Mk 5 breaching assets. The breaching mission was conducted during darkness, in-stride with the amphibious assault. All the launch echelons were completed within the time allotted and all the systems were deployed within the intended

impact area. The ACU-4/2nd CEB team demonstrated that in-stride breaching was feasible and could be integrated into amphibious assault. Following the successful fleet demonstration of the breaching system employment from LCAC, integration kits that allow deployment of Mk 5 breaching assets from LCAC were placed in emergency war reserve storage. These kits and training material can be rapidly deployed along with a team of instructors to provide the fleet an in-stride breaching capability.

NEAR TERM CAPABILITIES

The Shallow Water Assault Breaching System (SABRE) and Distributed Explosive Technology (DET) programs represent near term improvements to the current surf zone minefield breaching capability. Both systems use the Mk 22 rockets for deployment, but use explosives optimized for different water depths in the surf zone. SABRE systems are deployed in three to ten feet of water and DET systems are deployed in zero to three feet of seawater. The number of SABRE and DET systems required to clear an operations area are optimized with an analytical planning tool to provide a maximum cleared area for each deployed unit, minimizing the number of breaching assets that must be deployed with the amphibious fleet.

The SABRE system deploys a line charge with an explosive developed specifically for use underwater, PBXN-103. The explosives are packaged in individual containers each containing ten pounds of explosive, the ten-pound charges are referred to as unit charges. The unit charges are placed every three feet along the LDC for a total length of 400 feet. A fire and forget fuze is used to detonate the system after deployment minimizing the LCAC exposure to potential hostile fire while performing a breaching mission. The fuze incorporates an arming lanyard and other safety features to ensure that the system does not arm until a safe separation between the explosives and the LCAC have been achieved. Once the system is armed, the detonation sequence is initiated. The SABRE system is stored in an aluminum container that also serves as a shipping and launch container. A launch rail is incorporated to the container design to minimize the set-up time on the LCAC cargo deck.

The DET system uses two Mk 22 rockets to deploy an array of detonating cord. The array consists of three panels and measures 180 feet x 180 feet when fully deployed. This allows the distribution of the explosive charge over a larger area and minimizes the number of systems required in the very shallow region of the surf zone. Typically, the area clearance achieved by line charges decreases with water depth due to venting of the energy

released by the explosive charge in very shallow water. By using a distributed array of smaller charges, the DET system contains more of the explosive energy in the water column and increases the mine kill ratio per pound of explosive used in the very shallow region of the surf zone. The DET system is packed in a large aluminum reinforced fiberglass container that also serves as a shipping and deployment container. The container accepts a launch rail assembly for mounting two Mk 22 rockets and mounts to a LCAC Integration Platform (LIP) that provides the height necessary to launch over the LCAC bow ramp.

Inert versions of both SABRE and DET have been successfully launched from an LCAC in the surf zone. Deployments of the systems are shown in figures 5 and 6. The systems may be deployed singularly from LCAC with a maximum of twelve SABRE systems onboard and LCAC or two DET systems onboard an LCAC. A combined payload may be employed to optimize the number of LCAC required to complete a surf-zone-breaching mission with up to nine SABRES and two DET systems being deployed from a single LCAC. A test series designed to validate the concept of employment for SABRE and DET systems successfully demonstrated the deployment and end to end placement of a combined payload of SABRE and DET charges.

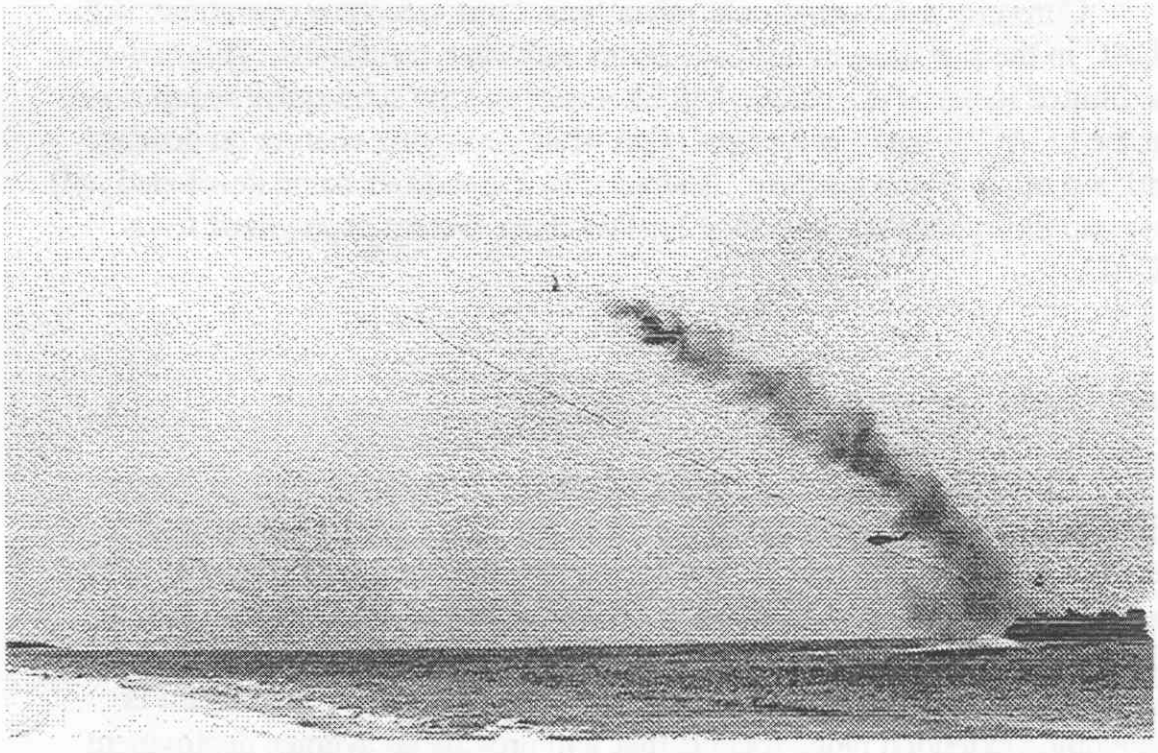


FIGURE 5 SABRE LAUNCH

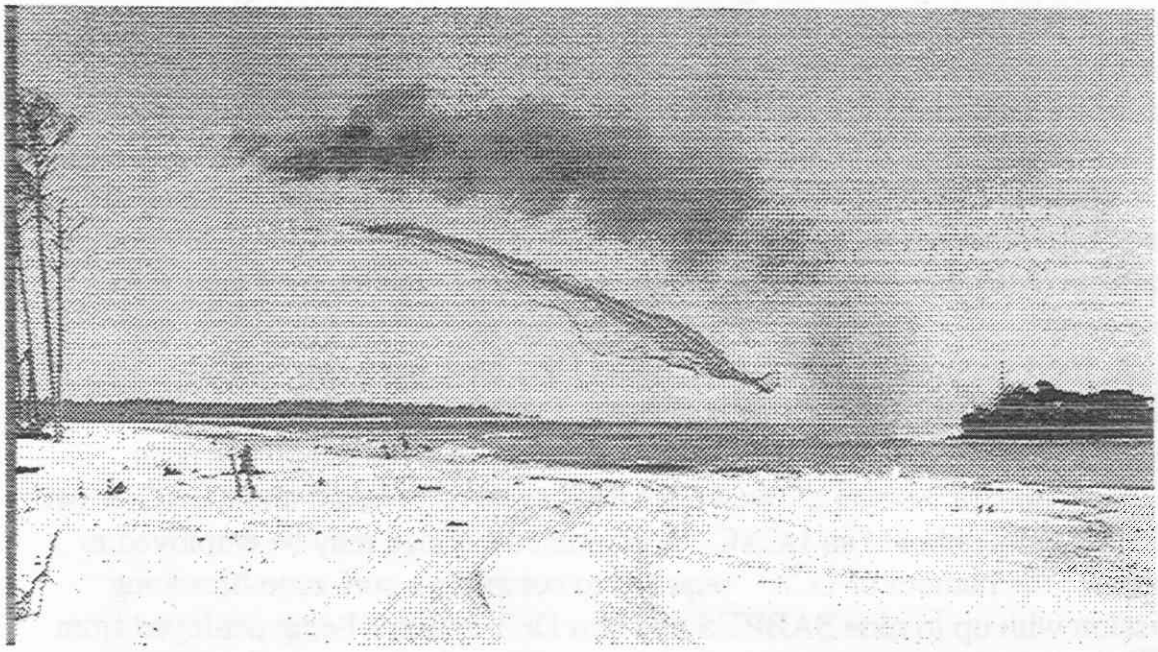


FIGURE 6 DET LAUNCH

Currently safe operational restrictions limit breaching operations with LCAC in the surf zone to mild sea states and wave conditions. This is due to the limited range of the current Mk 22 rocket and the subsequent requirement for the LCAC to hover in the surf zone while deploying charges on beaches with a shallow beach gradient. The far term capabilities being developed will increase the operational envelope for breaching system deployment from LCAC.

FAR TERM CAPABILITIES

The Explosive Neutralization Advanced Technology Demonstration (ENATD) project is using the advances in explosive systems developed for the near term solution and providing a delivery method that will allow the LCAC to operate out of the surf zone when deploying breaching systems. The ENATD system will provide the capability to conduct breaching missions in higher sea states than the current and near term systems. The program is developing extended range rockets that will provide an average deployment distance twice that of the conventional Mk 22 rocket and deploy SABRE and DET style line charges and arrays. To ensure accurate placement of the

breaching systems at the extended ranges, a fire control system that incorporates the ballistics of the breaching systems along with an autonomous controller for the LCAC was developed.

To develop the autonomous craft controller, the responses of the LCAC control surfaces were characterized during various low speed maneuvers. Algorithms were developed that described the subsequent motions of the LCAC in relation to control surface inputs and power settings and integrated with ballistic tables for the breaching systems. The fire control system calculates firing waypoints based on the desired impact point of the breaching system. An LCAC craftmaster flies the craft to the operations area where control of the craft is passed to the autonomous craft controller. The autonomous controller maneuvers the craft to the predetermined launch waypoint and deploys the breaching system when a ballistic solution is reached. After a successful launch of the breaching system, the autonomous controller maneuvers the craft to the next firing waypoint and deploys the next breaching asset. The process is repeated until all the breaching assets are deployed and the craft then departs the lanc.

Inert versions of the line charge and array have been successfully deployed from the LCAC in the surf zone using the fire control system. Through the use of the fire control system, the time required to complete a breaching mission has been reduced by approximately 30%, and system placement accuracy significantly improved as compared to the manually controlling the craft and deploying the breaching assets.

LCAC DEEP SKIRT PROJECT

By

David Vickers
Coastal Systems Station, Panama City, Florida
and
Brian Forstell
Band, Lavis & Associates, Inc.
Severna Park, Maryland

BIOGRAPHIES

David Vickers

David S. Vickers, Senior LCAC Engineer at Coastal Systems Station, has over 11 years of research and development experience with U.S Navy Amphibious and Mine Countermeasures systems the majority of which has been in the area of air cushion technology. He has participated in the design and development of the LCAC, MCAC, LACV-30 and SAM II programs. As Project Engineer for the LCAC skirt system, he was responsible for the development of the Deep Skirt system. He managed the joint industry/government technical team that brought the BLA deep skirt from concept to full-scale prototype. Under his leadership, this same team worked to develop and evaluate the Textron Marine and Land System's "Advanced Skirt" also being considered for use on the LCAC. He has a B.S. in Mechanical Engineering and graduate studies from the Florida State University.

Brian Forstell

Brian Forstell has worked exclusively on the research and development of advanced marine vehicles for 20 years. He has been engaged on projects which have supported the U.S. Navy's Advanced Naval Vehicle Concept Evaluation (ANVCE) program, the AALC ACV and LCAC ACV programs, the Rohr Marine XR1-D SES program and U.S. Coast Guard Stability Criteria Study for dynamically supported craft, the U.S. Navy LC(X) ACV and SWCM SES/ACV programs, the U.S. Army LAMP(H) ACV, LACV-30 ACV and PACK ACV programs and the German SES 700 program. Mr. Forstell was the LCAC Deep Skirt Project Manager at BLA and was responsible for the development of the Deep Skirt geometry and the model and full-scale Deep Skirt testing.

Abstract

The U.S. Navy has had a requirement to conduct shallow water mine countermeasures (SWMCM) operations for several years. The mission involves clearing mines from roughly the 15-ft water depth up through the high water mark on the beach. The LCAC has been the Navy's platform of choice for the mission, however, the nature of this MCM mission requires that the LCAC be capable of safely operating in the surf zone in sea states through sea-state 3. The Navy recognized that the current cushion height of 5 ft for the LCAC is not adequate for unrestricted safe operation in the surf zone and funded a program in 1995 to develop a skirt for the LCAC that has greater cushion height. The U.S. Navy's Coastal Systems Station (CSS) was chartered with the job of developing the LCAC Deep Skirt.

This paper describes the overall Deep Skirt Development program from inception through full-scale prototype testing. The objectives of the program along with the program constraints and approach that CSS took to ensure success are discussed.

This paper also discusses in some detail the technical development of the Deep Skirt including trade-off studies and results of sub-scale performance and safety-of-flight testing that was conducted in a towing tank. The results of full-scale prototype testing are discussed to the extent that full-scale trials data are available.

1.0 INTRODUCTION

The Landing Craft, Air Cushion (LCAC) was introduced into the U.S. Navy Fleet in December 1984 with LC01. The primary mission of the LCAC is Amphibious Warfare. The role of the LCAC in this mission is to transport weapons systems, equipment, cargo, and personnel organic to the elements of a Marine Air/Ground Task Force from ship-to-shore and over the beach. In a typical mission, the craft will embark equipment, troops and/or supplies, launch from amphibious ships and transit at high speed to the beach under assault, transit the surf zone and beach and proceed inland to a suitable offload site where it will rapidly offload and return to the amphibious ships to reload and perform follow-on sorties. Alternate missions have been assigned to the LCAC designated the Multi-Mission, Air Cushion (MCAC). These include mine clearing, lane breaching, and personnel transport.

The LCAC is a high-speed fully amphibious landing craft capable of carrying a 60-ton payload (Figure 1). The craft is capable of traveling over land as well as over water, thus exposing 70% of the world's beaches to an amphibious assault compared to 17% of the world's beaches for conventional landing craft. The LCAC operates from well-deck equipped amphibious ships. The principle characteristics of the LCAC are listed below.

Operational Capabilities:

Speed, Sea State 2	>40 knots
Speed, Sea State 3	>30 knots
Range (Nominal)	200 nmi
Temperature	-30 to 100°F

Dimensions:

Length - Structure	81 ft
Length - On-Cushion	87 ft 11 in.
Beam - Structure	43 ft 8 in.
Beam - On-Cushion	47 ft 0 in.
Height - On-Cushion	23 ft 8 in.

Displacement and Capacities:

Design Load Displacement	338,240 lb
Overload Displacement	368,240 lb
Maximum Payload	150,000 lb
Draft Off-Cushion	3 ft 0 in.
Fuel Capacity	7132 gals

Cargo and Deck Fittings:

Area	1809 sq ft
Width	27 ft 0 in.
Height Above Ground	5 ft 2 in.

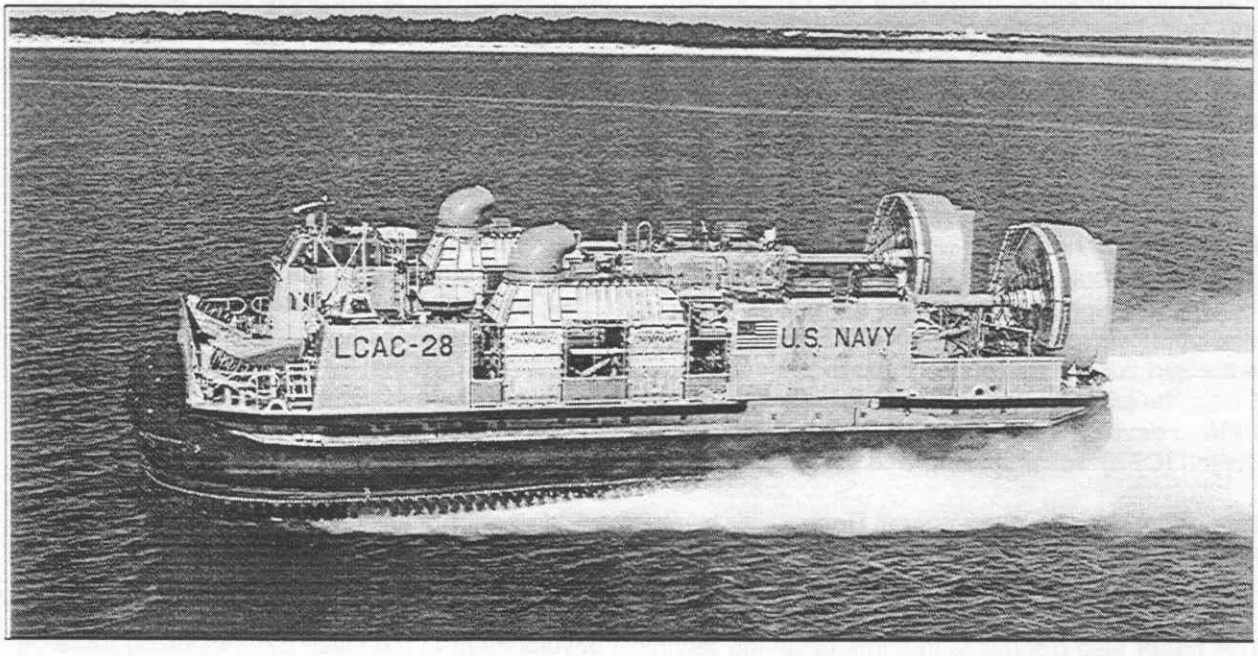


Figure 1. LCAC With the Current 5-ft Bag-Finger Skirt

2.0 DEEP SKIRT PROGRAM OVERVIEW

2.1 Mission Requirements

During the Persian Gulf War, the LCAC was involved with the Amphibious Forces which were assembled off the coast of Kuwait. The ultimate use of these forces was to tie down several divisions of Iraqi troops along the shore of Kuwait while the primary coalition forces conducted a flanking maneuver cutting off the Iraqi troops from their supply and command support. This proved to be the best use of the Marine Forces since all objectives were achieved with minimal loss of life. However, had the flanking maneuver failed and the Marine Forces been required to assault the prepared beaches along the coast, the result would have been, in all probability, significantly higher loss of machinery and life. The reason for the anticipated higher losses was due to the mines and obstacles placed in the surf zone and beach zone. The LCAC does not have the armor required to sustain multiple surf-zone mine detonations. Also, the obstacles would have severely damaged the skirt system and potentially the hull.

From the lessons learned, the MCAC project evaluated using the LCAC for deploying the Mk 5 Line Charge for clearing surf zone and beach zone mines and obstacles. The LCAC proved a very capable platform for deploying the Mk 5 and advanced concept mine clearing systems such as the SABRE and DET explosive systems. Figure 2 shows the deployment of a DET from an LCAC during operations in calm water.

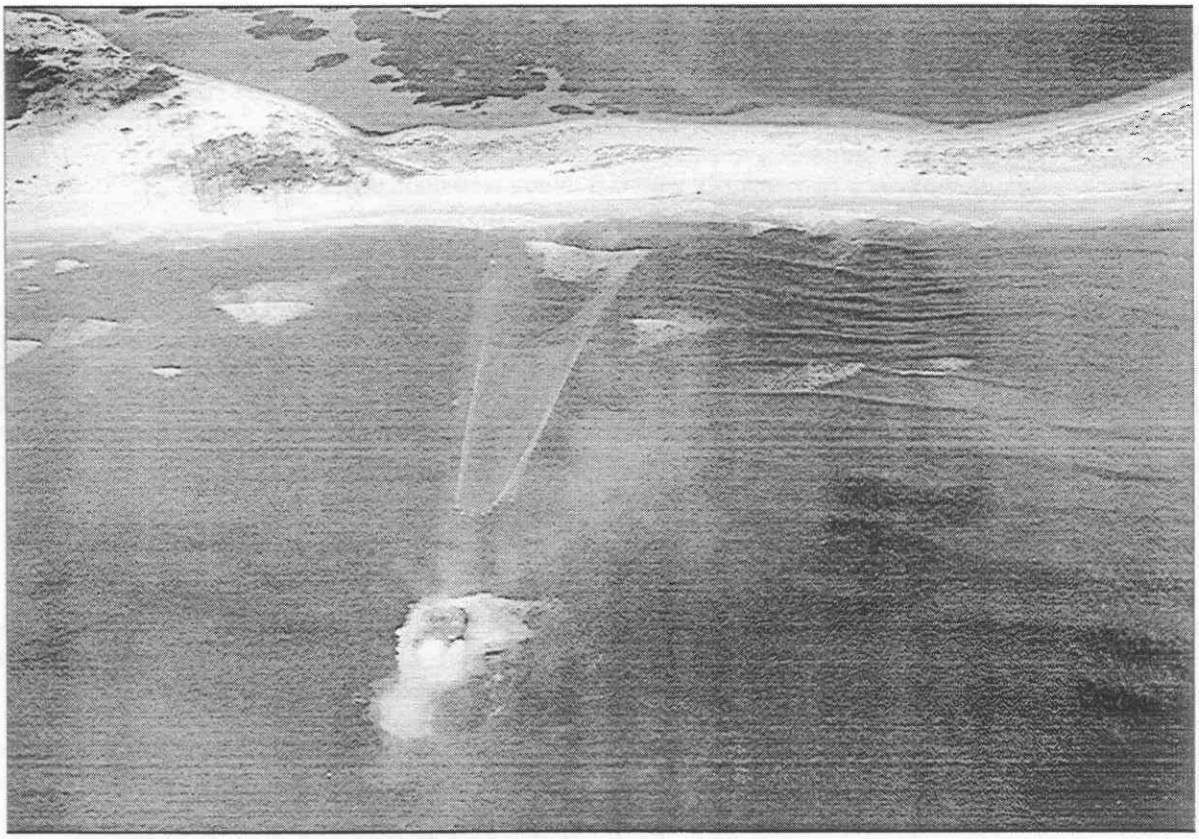


Figure 2. LCAC Launching DET in Calm Seas

However, the deployment of these systems requires the LCAC to loiter in the surf zone. The current Safe Engineering and Operations (SEAOPS) Manual requires the LCAC to maintain forward movement when in the surf zone, calibrating the craft forward motion with the waves so that following waves are not able to roll up the stern of the craft. Testing has shown that a wave height of 4 ft is capable of introducing green water into the propeller shroud resulting in the catastrophic failure of the propeller, propeller shroud and

associated drive train components. These events can result in costs as high as one million dollars. As such, the OPNAV N85 directed the development of system improvements for the LCAC to improve the craft survivability while operating in the surf zone environment.

2.2 Deep Skirt Project Initiation

In response to the OPNAV directive, NAVSEA PMS-377 directed the CSS to initiate the Deep Skirt project. The project name was taken from a JEFF(A) program study that proposed increasing the craft skirt height to 9 ft. However, the project was not directed to uniquely pursue a new skirt as the sole solution. The project kick-off meeting was held in January 1996.

An international team of ACV experts was assembled to conduct the project. The team included members from government and industry with LCAC design experience. The project manager was NAVSEA PMS-377 who directed CSS Code A41 to provide project technical management. Ray Dyke of Dyke & Dyke Consultants was the team's technical director. Band, Lavis & Associates, Inc. (BLA) developed the basic skirt geometry and was responsible for all testing. Westland Aerospace was selected as the tow tank facility. Textron Marine and Land Systems (TM&LS) provided platform interface support, and SMR Technologies was selected as the full-scale skirt fabricator.

2.3 Project Objectives

The Deep Skirt project had the following project objectives:

1. Provide a stable platform for conducting SWMCM.
2. Avoid ingestion of green water into the rotating machinery.
3. Minimize craft surge due to wave interaction in the surf zone.
4. Assure well-deck compatibility with U.S. Navy well-deck ships.

2.4 Deep Skirt Project Flow

The Deep Skirt project consisted of three basic phases. The first phase consisted of developing conceptual skirt designs combined with trade-off studies directed at selecting a skirt concept for further design development. Once the selected skirt design concept was developed by BLA to the preliminary design level of detail, the second phase of the project was conducted. This project phase entailed subscale testing with a towing tank model and with a free-flight model. After the model testing was completed, the preliminary skirt design was modified to reflect the lessons learned from the model test program and final project phase, detailed design and full-scale prototype testing, was conducted.

2.4.1 Conceptual Design And Trade-Off Studies

The project began with BLA and TM&LS conducting independent studies of the options available to satisfy the project objectives. The CSS provided a series of design requirements and weighing factors as guidance for conducting the studies. The design criteria are listed in Table 1 in order of importance.

The design solutions evaluated by BLA and TM&LS included a broad range of potential solutions. Some of the solutions included increasing the skirt height to achieve the required clearance, placing a large wave fence on the stern of the craft behind the propellers utilizing the baseline skirt or using a combination of increased skirt height and wave fence. Each solution had its pros and cons, for example, a 9-ft skirt would provide adequate vertical clearance without a wave fence, but the concept had a high technical risk due to uncertainty of the skirt's stability and difficulty with avoiding interference with the overhead in the well-deck.

Several types of skirt systems were considered by BLA including bag-and-finger skirts and loop-pericell skirts. Also, double-bubble outer bags and mechanical retraction systems were considered for controlling skirt inflated beam. Similar retraction concepts were also evaluated for reducing cushion height and, thus

overall craft height for well-deck operations. When all concepts were evaluated and the weighing factors applied, the winning concept was a 7-ft skirt system used in combination with a 3-ft stern wave fence.

Table 1. Design Criteria

Design Criteria	Weighing Factor (%)	Sub-Criteria	Weighing Factor (%)
Performance	40	Craft Stability	35
		Well Deck Comp.	25
		Technical Risk	20
		Payload	20
Cost	25	Operating/Support	40
		Material/Labor	30
		Schedule Risk	20
		Non Recurring	10
Maintainability	15	Complexity	45
		Reparability	40
		Special Tools	15
Reliability	15		
Deployability	5	Craft Mods	50
		Kit Conversion	30
		Training	20

2.4.2 Model Testing

The skirt's geometry was developed by BLA and a series of 2-D model tests were conducted at their facilities. The 2-D tests were actually single sections of the skirt scaled to 1/10th-scale and inflated on a static hull. These tests verified the inflated skirt balance and stability before incorporation into a complete 3-D skirt system. When all the skirt segments were validated, they were incorporated into a total skirt system and lofted using SHIPCAM at a scale of 1/12th for testing in the tow tank. The skirt templates were shipped to Westland Aerospace on the Isle of Wight, England, where the subscale skirt was fabricated using Briflon fabric. Figure 3 presents the 1/12th-scale LCAC model during the overland portion of the Deep-Skirt model test program.

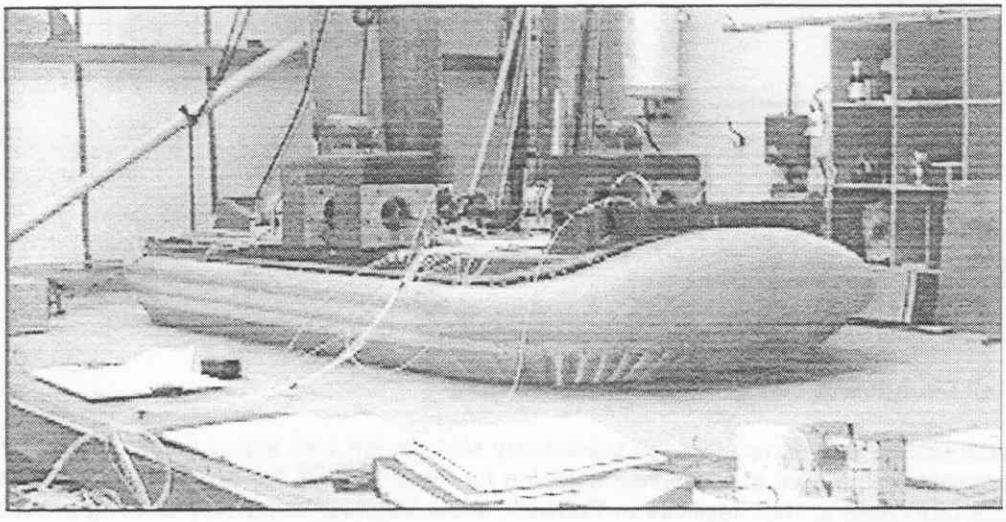


Figure 3. LCAC 1/12th-scale model with Deep Skirt

A series of 1/12th-scale model tests were conducted in the No. 3 tow tank at Westland Aerospace. The skirt was fitted to the original LCAC tow tank model that was still available at Westland Aerospace, although it did require significant refurbishing.

The model tests included static overland pitch and roll stiffness, craft motion in simulated beach surf, speed performance in calm water and waves, and evaluation of safety-of-flight issues. Initial test results that were obtained in sea-state 3 wave conditions indicated that the craft drag was unacceptably high and the installation of a transverse seal would be required to reduce the drag in sea-state 3 conditions to acceptable levels. Subsequent to this modification to the skirt design, all remaining tests were successfully completed. The test results revealed that the craft performance would meet/or exceed the baseline LCAC Top Level Requirements (TLR). After the final skirt configuration was established, the final skirt design was scaled to 1/6th-scale, and a 1/6th-scale model skirt was fabricated at CSS and the skirt was installed on a free-flight model. The model's pitch and roll characteristics were determined and values were as expected based on the 1/12th-scale test results. The free-flight model was taken to a wave pool at a local amusement park where the model was subjected to 1/6th-scale breaking surf. The possibility of green water wave ingestion was qualitatively evaluated using video and still photography. The tests revealed that the Deep Skirt with the 3-ft wave fence prevented waves as high as 6 ft from entering the propeller shrouds (Figure 4). The model was also used to verify obstacle clearance and limited over water safety-of-flight.

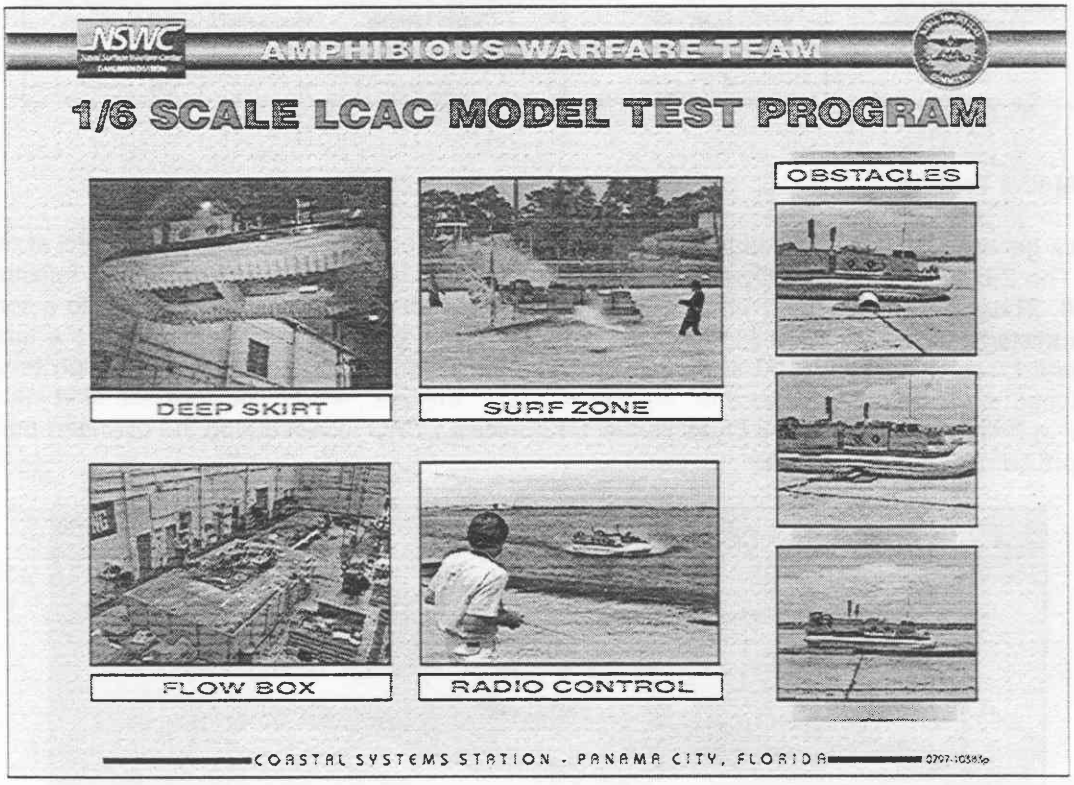


Figure 4. LCAC 1/6th-Scale Model With Deep Skirt

2.4.3 Detail Design and Full-Scale Prototype Testing

After all model testing was completed, the preliminary skirt design was appropriately altered by BLA and full-scale templates were sent to SMR Technologies for fabrication of the prototype Deep Skirt system. The skirt was fabricated at their facilities in Fenwick, West Virginia, using only existing procedures and material approved for use on LCAC. However, due to long lead time for acquisition of skirt assembly hardware, an alternative Huck aluminum "MagnaGrip" lock bolt fastener was utilized in the fabrication. These fasteners are one-size-fits-all "Universal" lockbolts. Their use and performance was so good that

the bolts are being considered for use on all LCACs. The skirt system was delivered to CSS on 25 November 1997, and installation was completed on 5 January 1998. Figure 5 shows the Deep Skirt installed on LCAC 066.

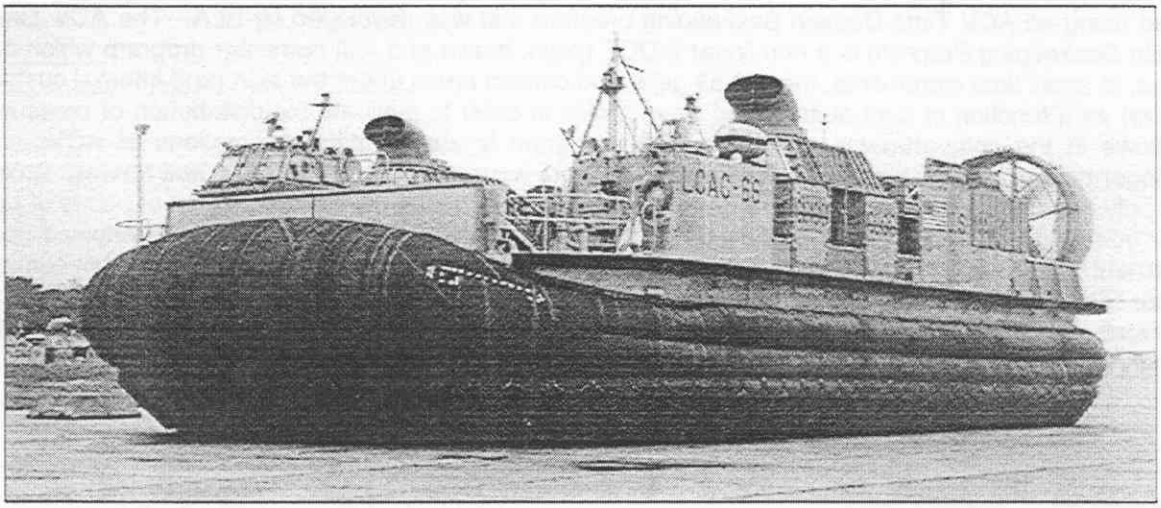


Figure 5. Full-Scale Prototype Deep Skirt installed on LCAC 066

Full-scale performance testing began at CSS with dimensional verification and static pitch and roll static stability tests. The inflated beam was approximately 6 inches wider than intended at the aft end of the craft, but investigation indicated that the excess inflated beam can be easily corrected by adjusting the inner web which forms the double-bubble on the outer bag. The pitch and roll stiffness values were in good agreement with the model test results so over water testing was initiated. A series of full-scale tests were conducted which included safety-of-flight tests, evaluation of the plow-in boundary, performance tests and well-deck interface tests. The craft's plow-in boundary was greatly improved as was ride quality. Well-deck validation was performed on 13 February 1998 with the LSD well-deck ship USS Whidbey Island. The well-deck was fitted with thermal couples in the overhead to measure the temperature rise during on-cushion operations. The overhead temperatures that were measured during the Deep Skirt tests never exceeded 350 degs Fahrenheit which was well below the maximum allowable overhead temperature. The low overhead temperatures were achieved by operating the craft at a reduced fan speed which, in turn, resulted in operations on a partial cushion height.

The Deep Skirt was originally designed without a spray suppressor in hopes that full-scale operations might not require a suppressor. However, low speed operations in wind created unacceptable spray although forward speed above 5 knots all but eliminated the spray. As such, a spray suppressor is being designed for incorporation around the forward third of the skirt.

3.0 DEEP-SKIRT DESIGN DEVELOPMENT

At the onset of the Deep Skirt Development Program, the U.S. Navy issued an Operational and Design Requirements Document that was fairly specific with respect to the operational mission requirements and the craft/support ship interface requirements. However, this document justifiably left the very specific design requirements that pertain to finger geometry, for instance, to the discretion of the designer. This, in turn, led to a series of both specified and derived design requirements which are summarized in Table 2. The requirement that was notably missing, and the one that would form the basis for all design work, was the cushion height measured from the skirt hemline up to the craft wet-deck. This was not an omission on the part of the U.S. Navy. Rather, it was an invitation to innovative design packaging that would yield a system that would provide the level of performance the Navy wanted.

3.1 Motions Analysis

A motions analysis was undertaken right at the start of the concept development phase to assess, as a function of cushion height, the risk of green water passing through the propellers. This analysis was performed using an ACV Time-Domain Seakeeping program that was developed by BLA. The ACV Time-Domain Seakeeping Program is a non-linear 3-DOF (pitch, heave and roll) computer program which calculates, at small time increments, the exit air gaps and contact areas under the skirt (and internal cushion dividers) as a function of craft attitude and wave profile in order to evaluate the distribution of pressures and flows in the compartments and bags. The program is able to simulate motions of ACVs with bag/finger type or pericell-type skirts in regular or random waves at arbitrary heading and forward speed. It not only outputs the motion statistics of the craft, but also calculates the relative motion of points of particular interest to assist in the evaluation of the possibility of deck wetness. The results showed good agreement with the model test results obtained from two prior ACV models of decidedly different configurations. The program offers a quick and reliable tool to assess the performance of various cushion configurations. Applications of the program to several projects, one of which was the LCAC deep-skirt trade-off analysis, have been very satisfactory (Reference 3).

Table 2. Specified/Derived Design Requirements for Deep-Skirt Design

Parameter	Requirement/Value	Major Driver
Cushion Beam	Same as Baseline Craft	Roll Stability, Craft Resistance
Cushion Area	Same as Baseline Craft	Craft Resistance
Location of Outer Skirt Attachment	Same as Baseline Craft	Support Ship Compatibility
Location of Inner Skirt Attachment	Potential for Relocation	Craft Arrangement, Cost
Maximum Inflated Beam, ft	48	Support Ship Compatibility
Minimum Included Finger Angle, deg	84	Finger Inflated Stability
Minimum Effective Tip Angle, deg	77	Finger Inflated Stability
Maximum Exterior Finger Angle, deg	57 for Open Finger 65 for Closed Cell	Finger Inflated Stability - Pitch/Roll Stability
Maximum Ratio of finger Height to Cushion Height	0.75	Finger Stability/Recovery
Maximum Ratio of Finger Width to Cushion Height	0.75	Finger Stability/Recovery

The motions analysis considered three general approaches to providing the necessary protection to the LCAC rotating machinery. The three general approaches examined were:

1. Examine the feasibility of using a skirt of depth greater than the existing 5-ft bag-and-finger skirt to increase freeboard;

2. Consider protecting the propellers with a large bulwark, without the need for increasing skirt height, and accept a performance penalty due to blockage of propeller air flow; and

3. Consider combined solutions such as increased skirt height plus additional bulwarks. In this way, the complexities and disadvantages of a large bulwark or otherwise a very deep (e.g., 9 ft) skirt could, perhaps, be avoided.

Both Bag-Finger and Loop-Pericell skirt systems were included in the motions analysis.

The Time-Domain Seakeeping program was used to develop a series of 360 second time histories of the relative motion between the water surface and the craft deck edge at selected locations on the craft. A typical example of such a time history is shown in Figure 6. The effect of varying the sea spectra and the bottom bathymetry were also included.

Histograms of the time histories were developed and fitted with a Beta probability distribution function to determine the probability, within a specified period of craft operating time, of water spilling over the edge of the deck of the craft.

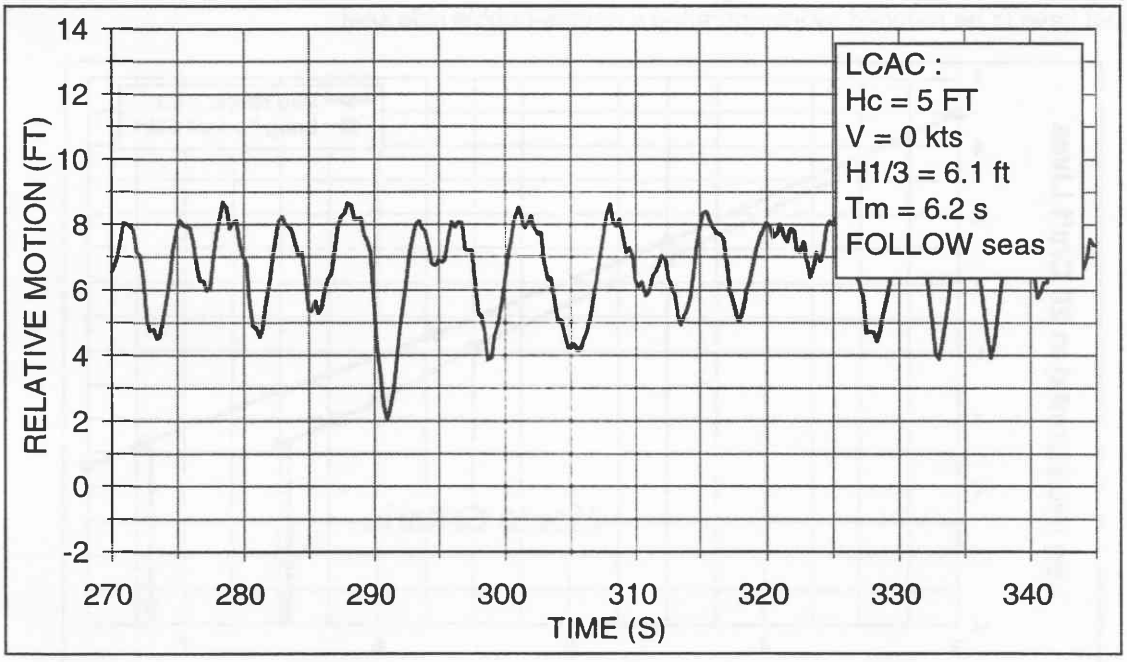


Figure 6. Typical Predicted Time History of Relative Motion at Deck Edge

In order to assess the acceptability of the results of the parametric analysis, a criteria was established which stated that the frequency of occurrence of green water over the deck of the LCAC must be less than 1 event in 100 craft lives.

Based on the established criteria, it was concluded that approximately 14.5 ft of freeboard would be required to satisfy the established criteria. This equated to a required skirt height (H_c) of approximately 9 ft. The analysis results further showed that the effective freeboard required to satisfy the criteria could also be obtained by effectively raising the critical flooding point on the aft deck edge of the craft by installing a wave fence (or bulwark) around the stern of the craft. Figure 7 shows the required height of the wave fence that would have to be installed on a craft that has a 5-ft cushion height in order to provide the required level of protection. The same information is shown in Figure 8 for a 7-ft cushion height. Based on the information presented in Figures 7 and 8, it was concluded that the most promising configuration for a Deep Skirt system that incorporated a wave fence consisted of a 7-ft skirt height combined with an aft bulwark which had a vertical height of 3 ft.

3.2 Configuration Trade-Off and Selection

Subsequent to establishing freeboard requirements, concept designs were developed by BLA for both bag-finger and pericell skirts with both 7-ft cushion height and 9-ft cushion height. In order to preserve the capability for the LCAC to operate into and out of the well of a support ship, all concept designs incorporated mechanical systems to reduce the cushion height to 5 ft and to reduce the inflated beam to 48 ft or less. These systems ranged from brut-force cables and pulleys to novel passive inflated secondary structures. In all, six skirt-concept designs were developed for use in a trade-off and design selection analysis.

The trade-off and design selection process considered cost, reliability, predicted craft performance and risk. The results of the trade-off analysis showed that the 7-ft pericell skirt in conjunction with a 3-ft bul-

wark was the preferred design option. It was further concluded that this design could be further simplified if the variable cushion height capability was eliminated from the design. This was possible because the overhead height in most of the support ships that would host an LCAC fitted with a deep skirt could allow dry well operation with a 7-ft cushion height. However, this also meant that the inflated beam of the deep skirt would have to be reduced by incorporating a double-bubble side seal.

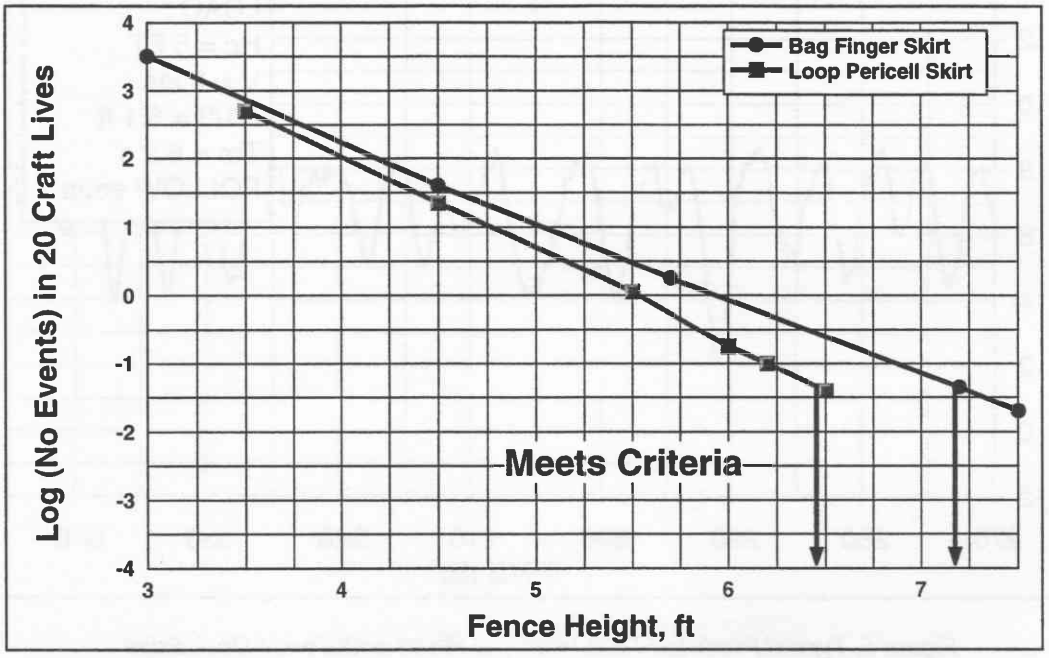


Figure 7. Fence Height to Avoid Propeller Swamping With 5-ft Skirt

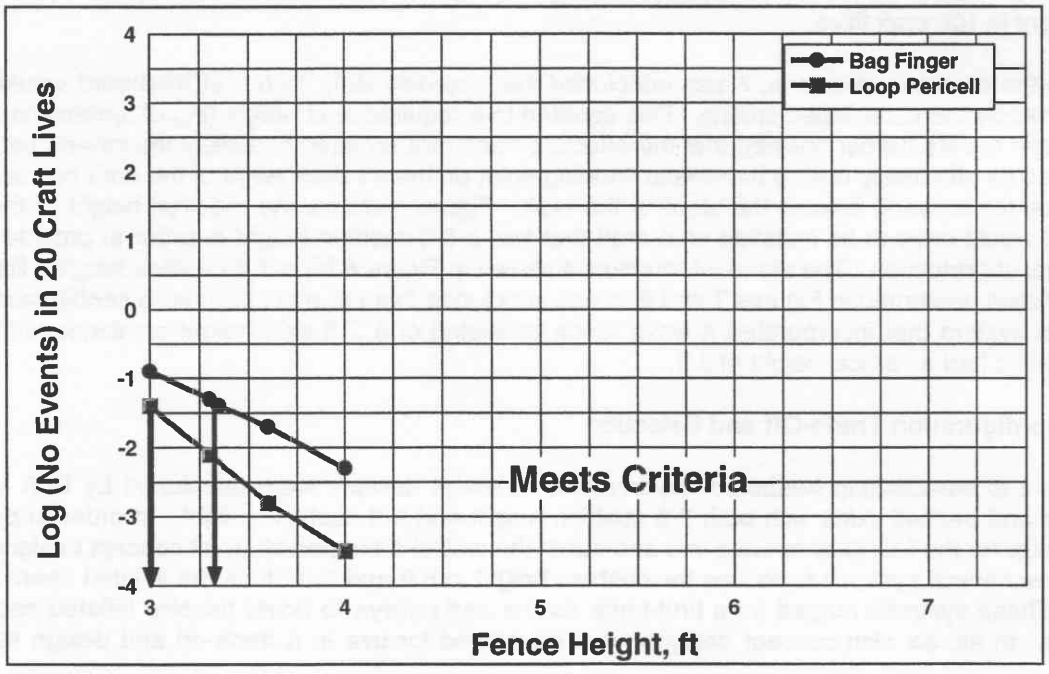


Figure 8. Fence Height to Avoid Propeller Swamping With 7-ft Skirt

The development work started with a design and trade-off phase directed at selecting the most desirable double-bubble side-seal configuration. Primary emphasis was placed on the side seal because of design issues associated with the double-bubble skirt bag. As design configurations were analytically generated, the most promising configurations were mocked-up in a simple 2-D inflation rig. In all, five different generic pericell configurations, with a total of 11 specific variants, were examined.

The concept that was ultimately selected featured a side seal that employed back-to-back fingers, as shown in Figure 9. As seen in this figure, the side seal of the deep skirt is designed as two standard open fingers which are placed back-to-back to form a type of pericell with considerable overlap of the finger tail and finger flap. With this concept, hoop tensions cannot be sustained all the way around the hemline of the cells, thus essentially eliminating drag due to scooping as with standard pericell.

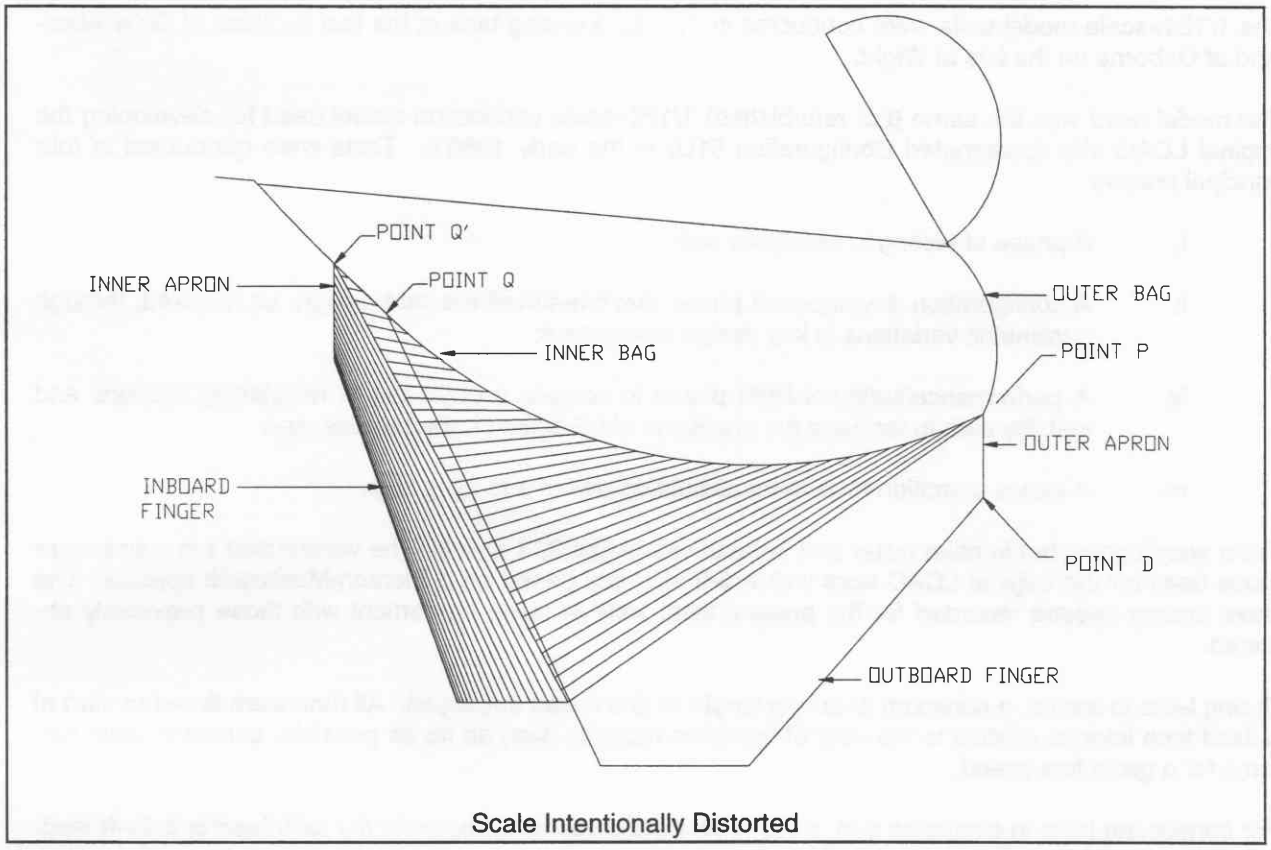


Figure 9. Section Through the Side Seal Assembly

Two 36-inch long sections of the side seal of the deep skirt were constructed and installed on the 1/10th-scale 2-D dynamic test rig for evaluation of inflated geometry and on-cushion roll stability. The roll stability of the standard 5-ft bag-finger skirt was also evaluated using a pre-existing 5-ft skirt.

The 1/10th-scale inflation tests of the deep skirt side seal showed that the double-bubble bag inflated as intended and was compatible with on-cushion operation of the LCAC in the well-deck of a support ship.

The back-to-back fingers were seen to inflate as intended and did perform in a manner which was similar to that of a standard pericell.

The roll static stability of the deep skirt was measured and compared with test data that was obtained with a standard LCAC 5-ft bag-finger skirt. The results showed that the roll static stability of the 7-ft high deep

skirt concept (without a longitudinal keel) compared very favorably with the standard 5-ft high LCAC bag-finger skirt (with a longitudinal keel) even though the craft VCG had been elevated by 2 ft.

Subsequent to these 2-D tests, design work started on the bow, bow corner, stern corner and stern of the deep skirt. The design of the bow and stern corners proved to be particularly tricky since it was necessary to blend the double-bubble side seal into a single bubble at the bow and the stern. The design development was performed by using BLA computer programs to calculate the static inflated geometry at selected longitudinal and transverse intervals and then incorporating the resulting numerical geometry into a 3-D AutoCAD drawing.

3.3 Tow-Tank Tests

The 1/12th-scale model tests were conducted in the No. 3 towing tank at the test facilities of GKN Westland at Osborne on the Isle of Wight.

The model used was the same (but refurbished) 1/12th-scale verification model used for developing the original LCAC skirt (designated Configuration 51U) in the early 1980's. Tests were conducted in four principal phases:

i. A phase of testing in simulated surf;

ii. A configuration development phase that fine-tuned the skirt design, as required, through parametric variations in key design parameters;

iii. A performance/safety-of-flight phase to compile a database of resistance, motions and stability data to facilitate the prediction of full-scale characteristics; and

iv. A series of motion tests in the simulated well of a landing ship.

Tests were conducted in calm water and in head sea-states 2, 3 and 4. The wavemaker programs were those used for the original LCAC tests with a 5-ft skirt and based on a Pierson-Moskowitz spectra. The wave energy spectra recorded for the present tests were in close agreement with those previously obtained.

During tests in waves, a minimum data trap length of 200 ft was employed. All runs were timed to start at a fixed time interval relative to the start of the wavemaker to give, as far as possible, constant wave patterns for a given test speed.

For conducting tests in simulated surf, a full width beach was constructed in the tank having a 24-ft lead-in slope of 1:10 followed by a 16-ft horizontal platform.

The simulated surf tests were conducted with the craft attached to a free-to-surge carriage via a three component dynamometer and pitch/roll trunnion plate. Thus, measurements of drag, side force, yaw moment and pitch, roll and heave motions, and vertical accelerations at three locations were available. Measurements of pressures in the bag and cushion were also available. Wave probes were located at two tank positions, one at mid tank to monitor sea state significant height and the other at the beach knuckle to measure maximum breaking wave heights. A third probe was fixed to the stern of the craft to measure water rise height above the stern deck line.

For the surf tests, the initial technique employed was to position the craft so that the stern was at the point of the breaking wave (usually at the beach slope transition knuckle). The carriage was then locked and a series of data and video runs were taken to measure forces and motions. This technique was subsequently changed in that the carriage was released just before the broken waves impacted and the slamming loads drove the craft forward over the beach platform.

Wave fences were fitted for all the surf tests.

All of the data obtained during the deep skirt tow-tank tests are presented in full-scale terms based on Froude scaling.

3.3.1 Tests In Surf

Tests with the beach in place were conducted predominantly in simulated sea-state 3 conditions. This gave:

- 4.5-ft significant wave height in deep water.
- 6.0-ft significant and 9.5-ft maximum surf height (approximately) at the location of the model.

Most of the tests were performed with the model fixed in surge at zero angle of yaw and at two weights. The LCG position was also varied.

All tests with the deep skirt were made with a 3.0-ft wave fence. It was obvious that the deep skirt gave a greatly improved surf capability which was derived from both the increase in craft freeboard and also from the larger bag section. The combined effect was to allow the surf to sweep under the craft with little "solid impact" experienced. No actual heavy fence impacts were observed and the fence really only had to deflect small amounts of broken water which had carried over the outer bag.

3.3.2 Deep-Skirt Development Tests

Twenty-five different skirt configurations were evaluated during a two-week period. These configurations included 21 changes in skirt geometry and 4 changes to the bag-to-cushion feed area. Not all of these 25 configurations were evaluated during the overwater underway part of the development tests. Overwater underway development tests started with Configuration 3B since several configuration changes were evaluated only over the ground board. After only a few tests, it was decided to incorporate a transverse seal into the skirt design. It was expected that its presence could significantly reduce craft pitch motion and resistance in rough water, based upon experience gained from testing ACV and SES models with and without a transverse cushion divider. This, in fact, was the case. However, initially, this did not result in a significant improvement in bow-down pitch static stiffness over land as expected. It was realized, however, with the help of a miniature "in-cushion" video camera, that the transverse seal was too soft to maintain an adequate pressure differential between the forward and aft compartments of the cushion. Although the static overland roll stiffness of the deep skirt was seen to be high compared to earlier configurations, the overland static pitch stiffness was decidedly inferior, particularly when bow-down (in negative trim).

Thus, the seal was quickly redesigned and manufactured to a geometry similar to that used with the current LCAC and this solved the problem. The configuration of the deep skirt was eventually frozen (at Configuration 21D) with features as follows:

- Open fingers at bow (fingers 1 through 15).
- Back-to-back fingers to form pericells along each side (fingers 16 through 36).
- Open fingers on forward side of stern corner (fingers 37 through 41).
- Raised planing fingers on stern (fingers 42 through 51).
- Full beam transverse stability seal.
- Direct cushion feed.

3.3.3 Pitch and Roll Static Stability

The static stability of the model with the deep skirt in its final configuration was measured in roll and pitch for operation at zero forward speed over both land and water. The results are compared in Figure 10 with results of tests with the original LCAC skirt configuration. The results compare very favorable despite the 2-ft increase in skirt height.

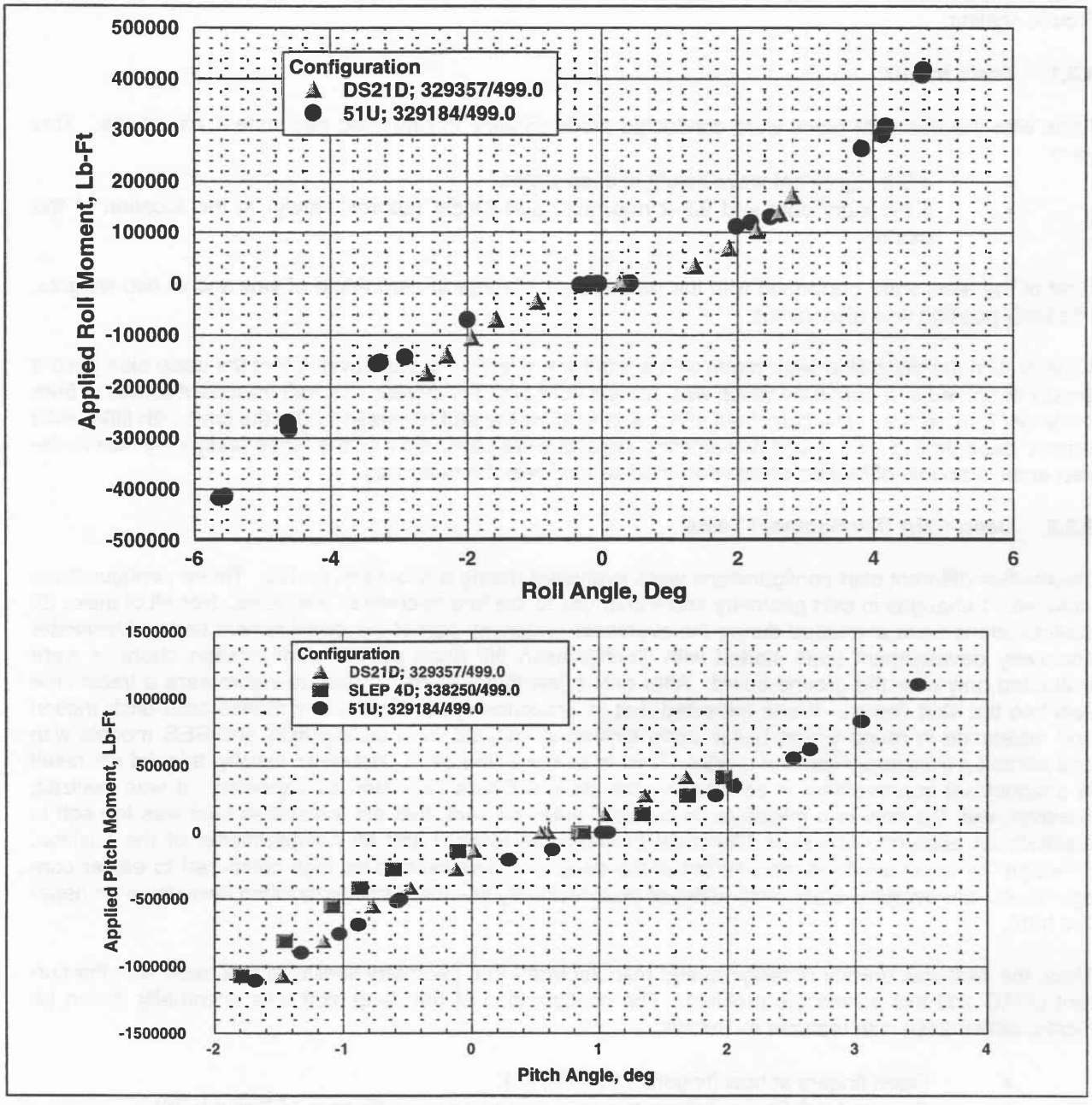


Figure 10. Overwater Roll and Pitch Static Stability Results for Final Configuration

The dynamic stability and underway stability of the deep skirt was determined as part of the subsequent plow-in boundary tests, the yaw stability and beam-sea tests, the wake crossing tests and tests of roll stability in a simulated ship's well. All of these results are discussed later.

3.3.4 Performance and Plow-In Boundary Tests

Combined resistance and dynamic pitch stability tests were conducted with the final deep skirt configuration underway with variations in forward speed, sea state, displacement and LCG. Performance was measured in terms of drag and model vertical acceleration in irregular head seas. Dynamic pitch stability

was judged on the basis of any observed tendency of the model to plow-in when operating at high speed with extreme forward LCG locations.

Measured drag at full-load weight in calm water, and in sea-states 2, 3 and 4 was compared, respectively, with the drag of LCAC for various LCG positions at essentially the same displacement. For comparable LCG positions, this comparison shows the deep skirt to have calm-water drag similar to the drag of LCAC, but significantly less drag than LCAC in sea-states 2, 3, and 4 at high speed. This difference is even more favorable for the deep skirt in the lightship condition, as shown in Figures 11 through 13, for operation in calm water, sea-state 2 and sea-state 3, respectively. Even in the overload condition, the drag of the deep skirt is at, or substantially below, the drag of LCAC as shown in Figures 14 and 15.

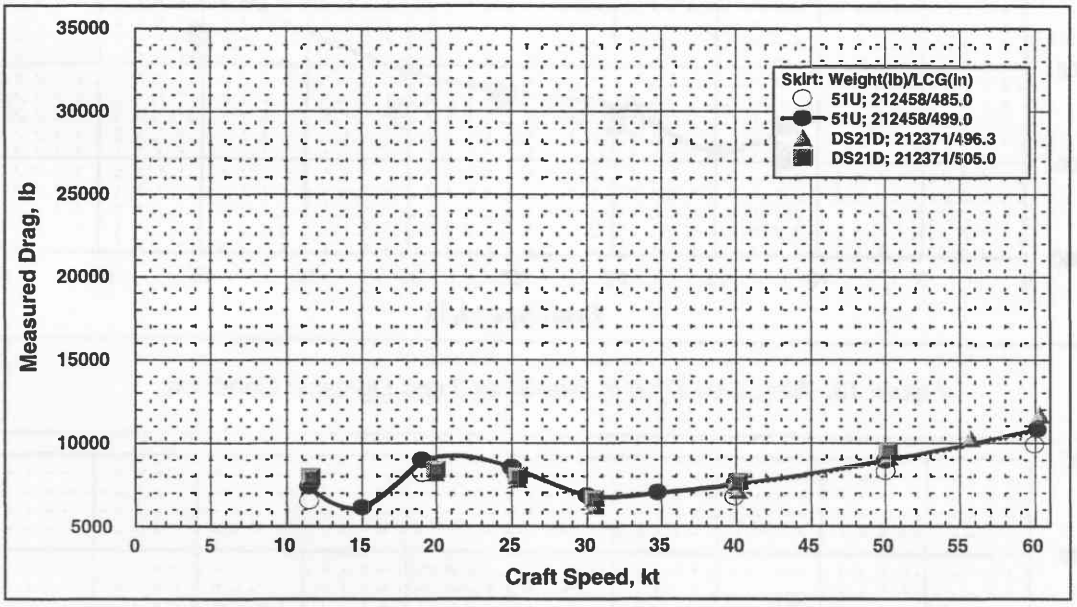


Figure 11. Measured Drag in Calm Water and Lightship Condition

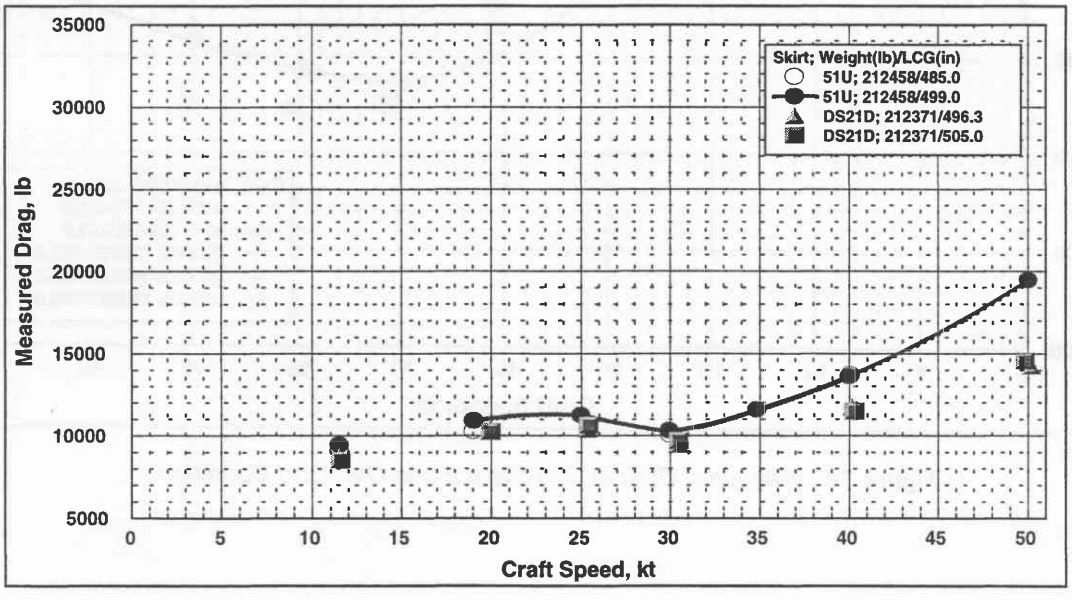


Figure 12. Measured Drag in Sea-State 2 and Lightship Condition

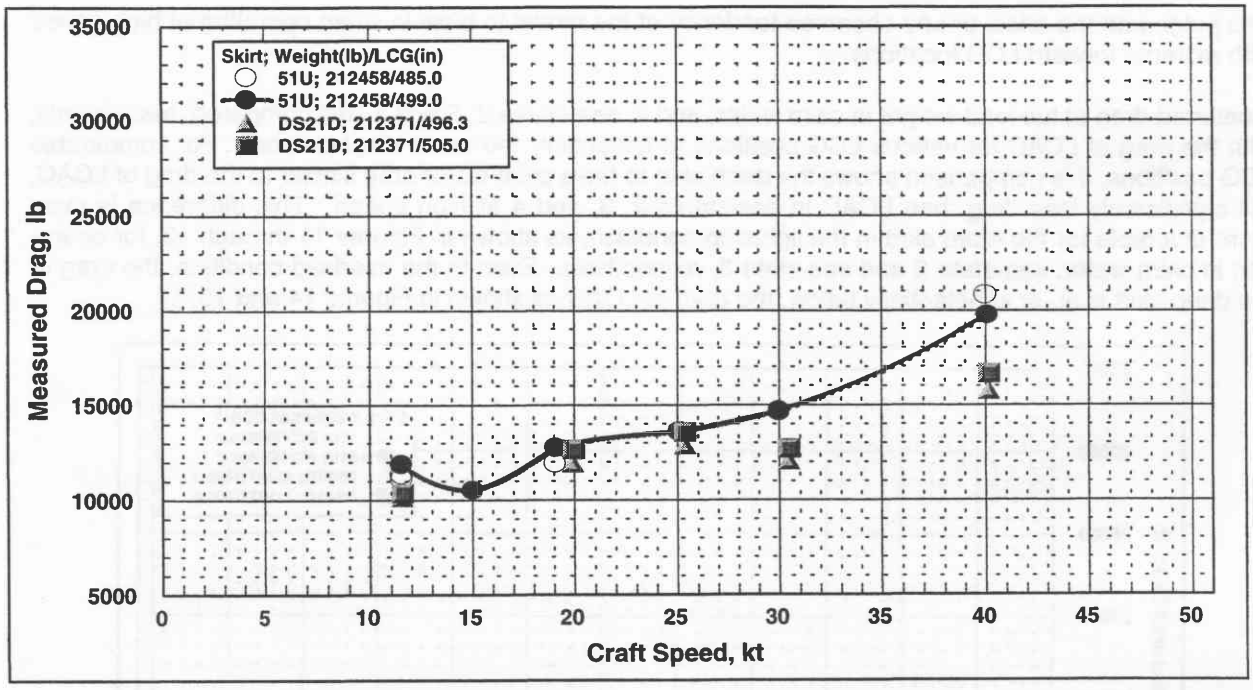


Figure 13. Measured Drag in Sea-State 3 and Lightship Condition

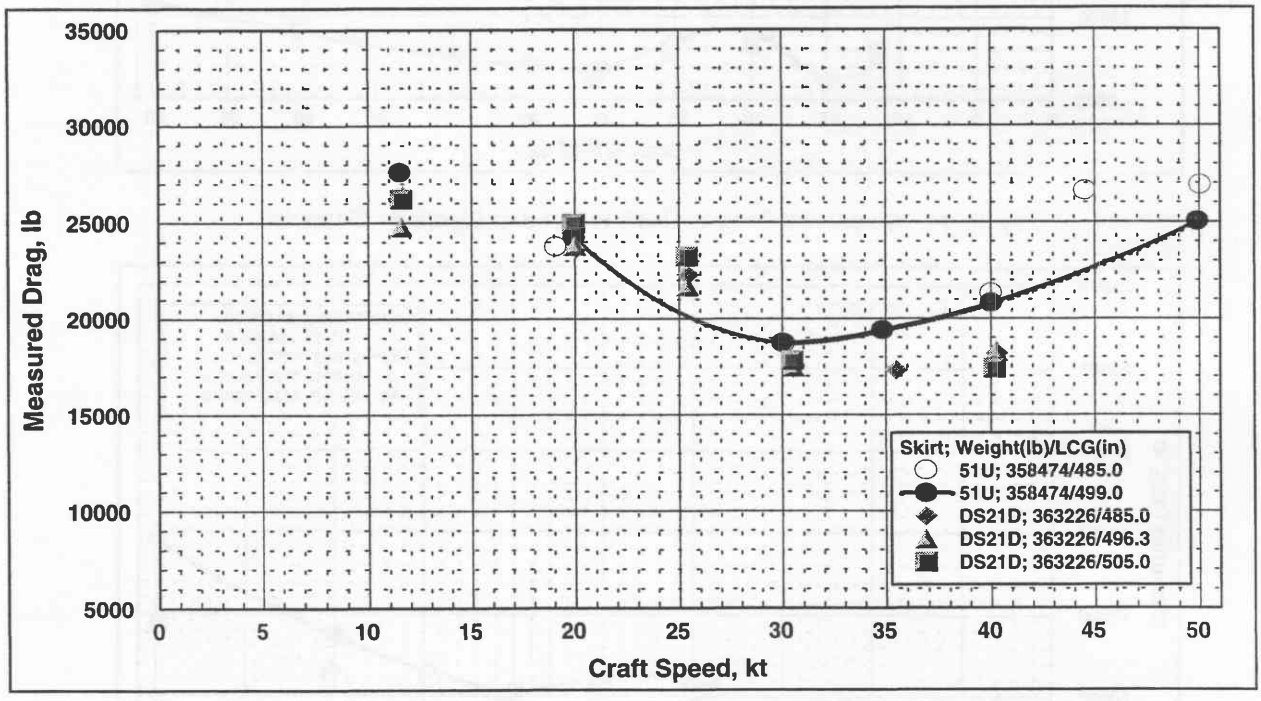


Figure 14. Measured Drag in Sea-State 2 and Overload Condition

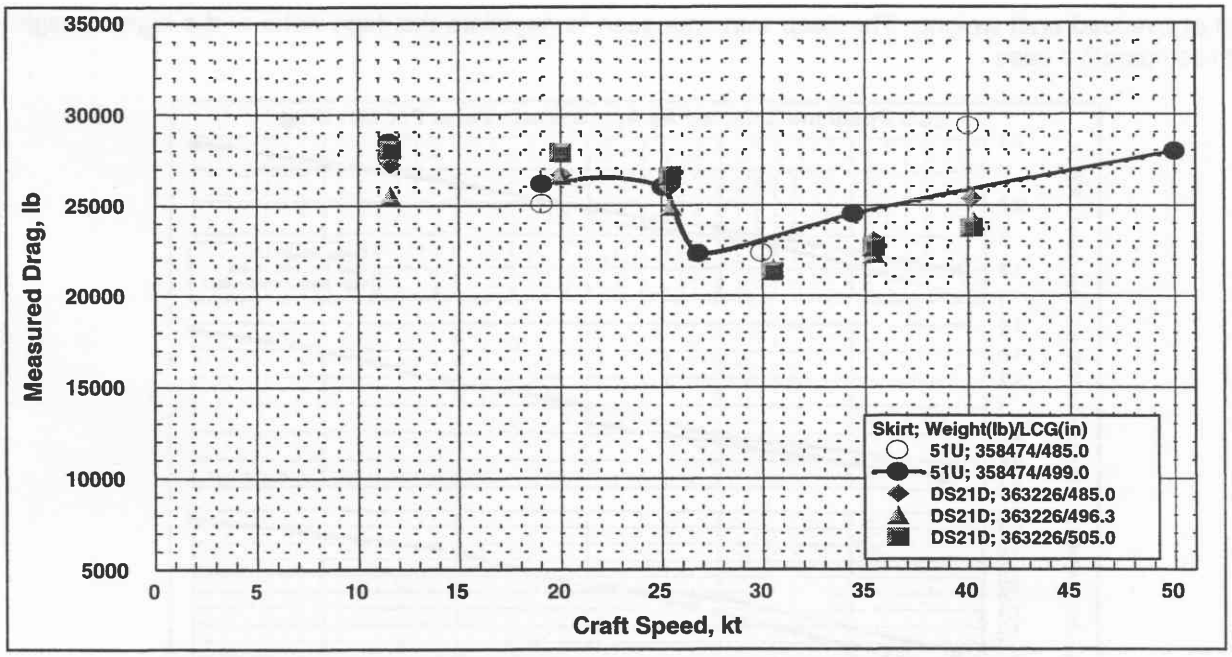


Figure 15. Measured Drag in Sea-State 3 and Overload Condition

At no condition within the range of reasonably achievable LCG locations could the model be caused to plow-in. However, in sea-state 3 at 40 kts with the LCG forward to station 475, there was some evidence of "skirt nibbling" during bow-down pitch excursions which suggests that this combination of speed, LCG and sea state was possibly close to a plow-in boundary.

3.2.5 Seakeeping

Seakeeping results for the deep skirt and LCAC are summarized in Figure 16. Here, the significant (4 x rms) vertical accelerations at the bow, stern and amidships are plotted against forward speed for operation in head seas. The accelerations of LCAC are slightly less than those for the deep skirt.

3.2.6 Stability Beam-On and at Angles of Yaw

Beam-on tests were conducted with the model fixed in yaw with various fixed angles of roll leading side down and the model free to heave and trim.

Beam-on tests were conducted at constant speed over calm water with the craft locked at 90 degrees yaw and starboard side leading. The tests were conducted to determine the critical overturning speed and to establish the variations in roll moment, drag, cushion pressure and bag pressure with roll angle.

Similar tests with the same test fixture were also conducted at -30 and -45 degrees of yaw. The results of these tests show that, in all cases, the trends exhibited by the deep skirt match fairly closely the trends exhibited by the LCAC.

3.2.7 Wake Crossing Stability

These tests were conducted with the free-to-surge rig to measure craft pitch response and the stability of the craft and its skirt upon encountering, at high speed, specified isolated waves representative of a ship's wake in otherwise calm water.

In general, it was found that the deep skirt has significantly reduced excursions in pitch compared to LCAC. Note that in 1982, no attempt had been made to have LCAC cross a wake of 4.5 ft at high speed

and at overload craft weight. The deep skirt was seen to negotiate this high wake at the higher weight with comparative ease.

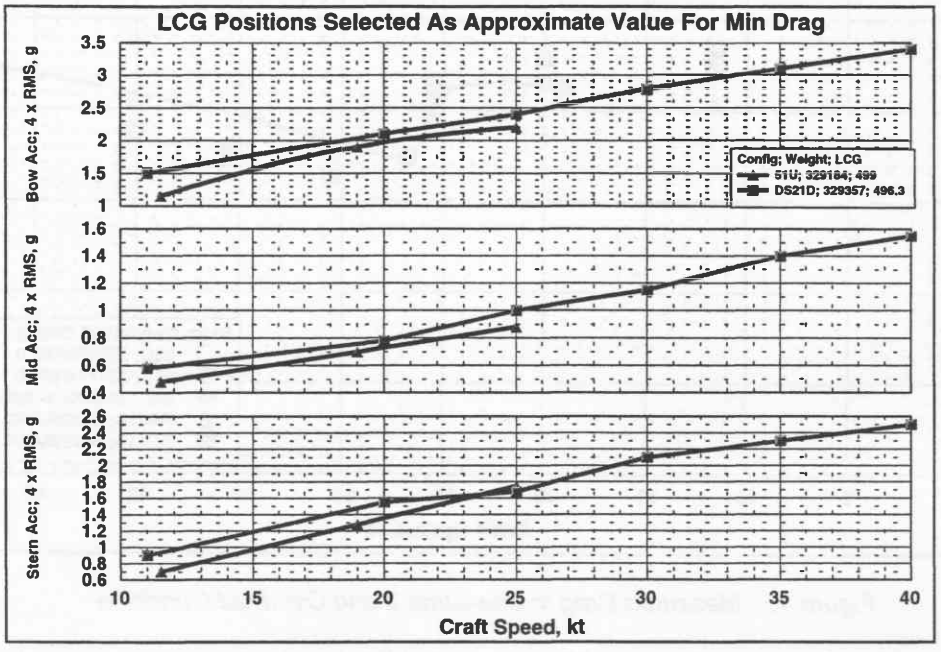


Figure 16. Comparison of Sea-State 4 Vertical Accelerations

3.2.8 Stability in Simulated Ship's Well

The full-scale LCAC has had a tendency to oscillate predominantly in roll and sway when hovering in the well of a landing ship. This has, at times, caused damage to the fenders and hard structure of the craft. To alleviate this problem, a Well-Deck Entry System (WDES) was developed, a principal feature of which is the installation of vertical tubes (referred to as ribs) spaced at intervals along the sidewalls of the ship's well. The presence of the tubes vents high pressure cushion air that gets trapped beneath the skirt bag when the bag makes contact with the sidewall of the well. This prevents a build-up of pressure beneath the skirt bag which would otherwise cause a large rolling moment and sway force to build-up as the mechanism for forced oscillation of the craft.

With the introduction of a new skirt of greater cushion height, it was questioned whether the ribs would be as effective in alleviating craft motion as they are for the existing 5-ft skirt. Thus, a mock-up of a ship's well was created, with and without ribs of the appropriate height, and tests conducted to examine their effectiveness. Tests were conducted for a range of weights, fan speeds, and well-deck widths from 48 to 51 ft. Some conditions simulated resulted in free oscillation of the model without ribs in place. With the ribs in place, the oscillations were always eliminated.

4.0 CONCLUSIONS

4.1 Performance

In calm water and still air with a normal payload, there is little to choose between the performance with a 5-ft skirt compared to a 7-ft skirt.

In sea-state 2 in head seas, craft performance with the deep skirt becomes significantly superior to craft performance with the existing LCAC skirt.

In sea-state 3 head seas, again, the performance of the LCAC with the deep skirt is superior to that of the LCAC with the existing skirt.

These differences are even more favorable for the 7-ft skirt in the lightship condition for operation in calm water, sea-state 2 and sea-state 3.

Even in the overload condition, the drag of the deep skirt is at, or substantially below, the drag of the existing 5-ft skirt.

The combination of a 7-ft deep skirt, transverse stability seal, and back-to-back fingers to form pericells was responsible for this improvement compared to the existing skirt. The transverse stability seal helped to dampen pitch motions and reduce drag, particularly near hump speed, while at high speed it reduced drag by helping to impede the loss of cushion air due to wave pumping.

4.2 Stability and Safety-of-Flight

Roll and pitch stiffness of the 7-ft deep skirt over land and water was found to be the same as for the LCAC despite the extra 2 ft of skirt height.

At no condition within the range of reasonably achievable LCG locations and forward speeds could the model be caused to plow-in.

The results of tests beam-on and at angles of yaw showed that in all cases the trends exhibited by the deep skirt match fairly closely the favorable trends exhibited by the LCAC.

With the 7-ft skirt, the model exhibited far superior wake-crossing capability.

Tests at low speed in following surf confirmed the predictions of relative motions that indicated that a combination of a 7-ft skirt and a 3-ft bulwark would be the best choice to:

i. Eliminate the likelihood of the propeller being damaged by green water and
ii. Minimize craft maneuvering-plane motions induced by the action of surf.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the sponsor of the project, NAVSEA PMS 377J, and the valuable contributions made by the organizations listed at the end of the introduction to this paper.

The views and opinions expressed in the paper are, however, those of the authors and do not necessarily reflect the official views and opinions of the U.S. Government.

REFERENCES

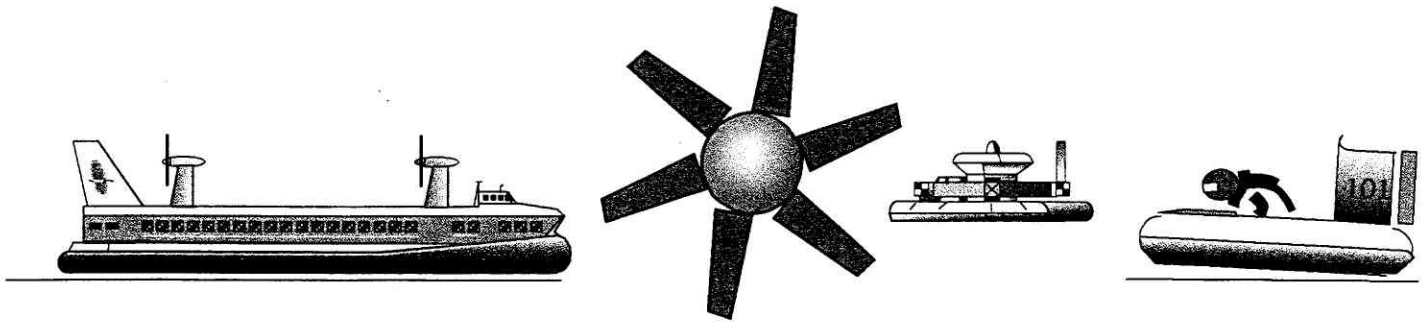
1. Lavis, D.R, et. al., "On the Prediction of Acceleration Response of Air Cushion Vehicles to Random Seaways and the Distortion Effects of the Cushion Inherent in Scale Models," presented at the Ship Control-System Symposium, U.S. Naval Academy, Annapolis, Maryland, July 1972, AIAA Paper 72-598.

2. Forstell, B.G. and Harry, C.W., "The Use of Model-Test Data for Predicting Full-Scale ACV Resistance," Joint International Conference on Air Cushion Technology, Rockville, Maryland, 24-25 September 1985.

3. Lavis, D.R., Forstell, B.G. and Jiang, C., "Advanced Hovercraft - Skirt Technology," RINA, London, UK, December 1997.

LES VÉHICULES À COUSSIN D'AIR
Amélioration de la poussée

par G.J.VERNIER



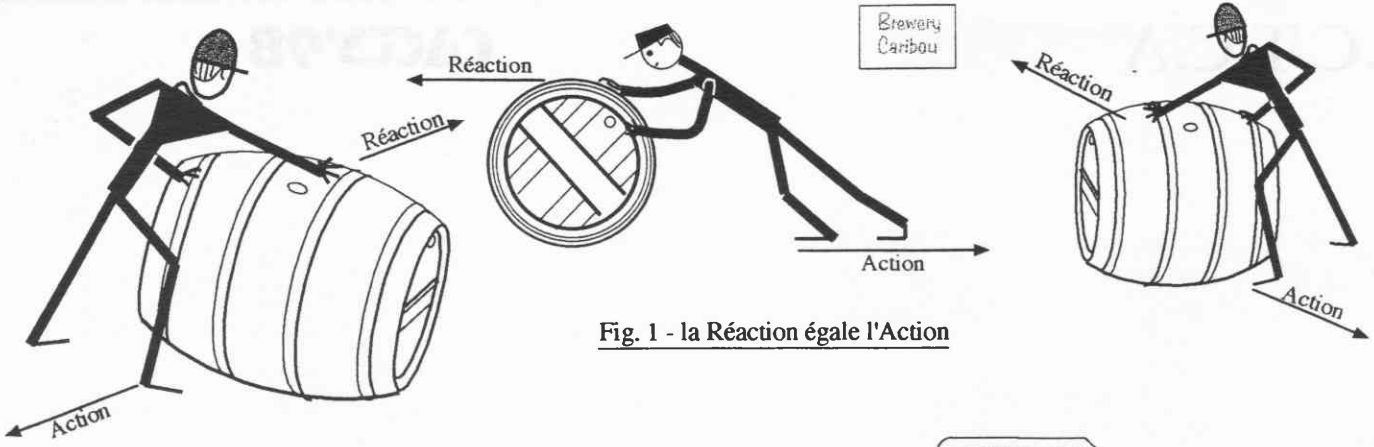


Fig. 1 - la Réaction égale l'Action

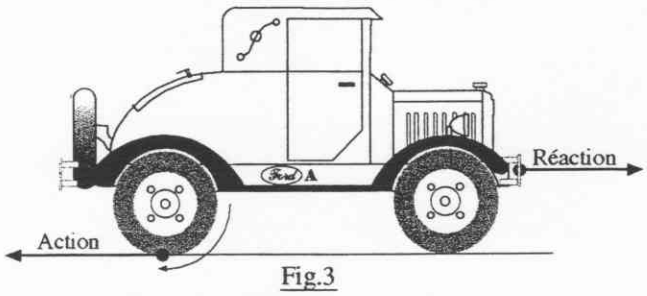


Fig.3

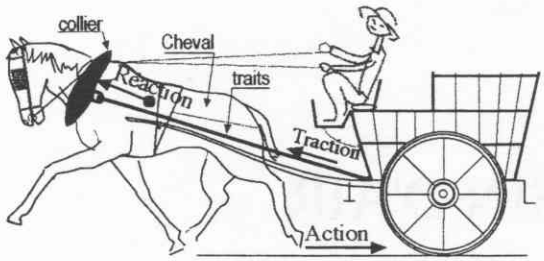


Fig.2 - Le cheval pousse en tirant la charrette.

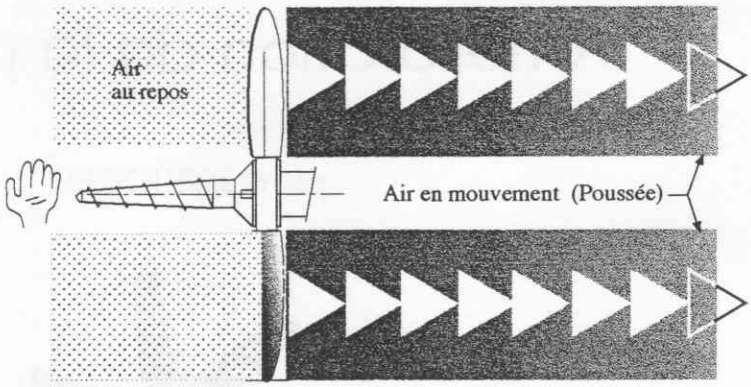


Fig.4 - l'Hélice ne se visse pas dans l'air.

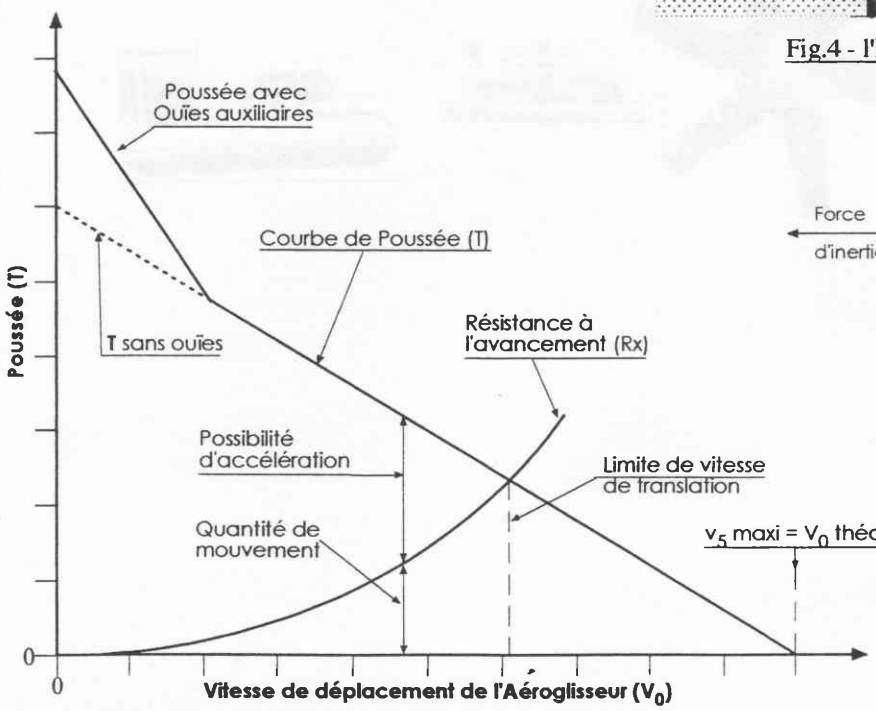


Fig.5 - Courbes de Poussée & de Résistances.

Fig.6 - Équilibre des Forces en mouvement.



Rx = Forces de Résistance à l'avancement
m.v = Quantité de mouvement



G.J.VERNIER CACD 98

Amélioration de la poussée

Afin de profiter entièrement des extraordinaires possibilités de l'Aéroglisseur amphibie (survol indifférent de la terre ou de l'eau) et pour préserver faune et flore lacustres, fluviales ou marines, la propulsion de ce véhicule s'effectue par voie aérienne. Hélices libres ou carénées, ventilateurs carénés (duct fan) représentent les principaux propulseurs adaptés au but recherché.
Une hélice immergée réduit l'Aéroglisseur à un bateau, très rapide certes, mais ralenti ou arrêté par tous les obstacles (bancs de sable, rapides, épaves, roches affleurantes). De plus elle découpe tout ce qu'elle rencontre (de nombreux cétacés souffrent de plaies dorsales) et elle engendre un tourbillon d'eau important qui affouille les fonds et les berges.

La propulsion par "Waterjet" n'est qu'un palliatif qui diminue le tirant d'eau sans permettre le franchissement de bancs de sable ni de rapides. Il a une fâcheuse tendance à aspirer les algues et les sacs plastiques et à se boucher. Le sable en suspension dans l'eau abrase rapidement le rotor dont le rendement, déjà faible comparé à celui d'une hélice, chute très vite.

Propulsion - Ce mot vient de "propulsus" participe passé latin de "propellere" qui, comme chacun sait, signifie "pousser en avant". Un tonnelier ou un brasseur propulse un tonneau en le poussant (Fig.1). Un cheval pousse sur son collier (Fig.2) dont les traits tirent la charette. L'automobile exerce, par adhérence, avec la roue motrice, un effort tangentiel sur le sol qui, par réaction, propulse la voiture en sens opposé. (Fig.3)
Une hélice ne se visse pas dans l'air ou dans l'eau, elle met en mouvement une masse de fluide (air par exemple) primitivement au repos, qu'elle dirige à l'opposé du sens de déplacement du véhicule. (Fig.4)
Le propulseur éprouve , en retour, une réaction (T = m.v) qui constitue la force de propulsion que l'on nomme " Poussée" ou " Traction".

$$\text{Réaction} = \text{Action}$$
$$M.V_o = m.\ v_5$$

M = masse de l'Aéroglisseur — m = masse du fluide en mouvement
V_0 = vitesse de déplacement Aéroglisseur — v_5 = vitesse du jet de fluide

La puissance utile pour la propulsion sera : $m.\ v.V$
La force vive perdue dans la transformation : $1/2\ m.v^2_5$

Poussée (thrust) - symbole $\mathbf{T}_{\text{Newton}} = m.\ v$. C'est une force . Elle égale la quantité de mouvement transmise au fluide par le propulseur.
La poussée max. se situe au point fixe $V_0 = 0$. (Fig.5) Elle décroît lorsque la vitesse V_0 augmente. La vitesse V_0 maxi du véhicule est atteinte lorsque la résistance totale à l'avancement (Rx) coupe la courbe de poussée. La poussée est nulle lorsque $V_0 = v5$.

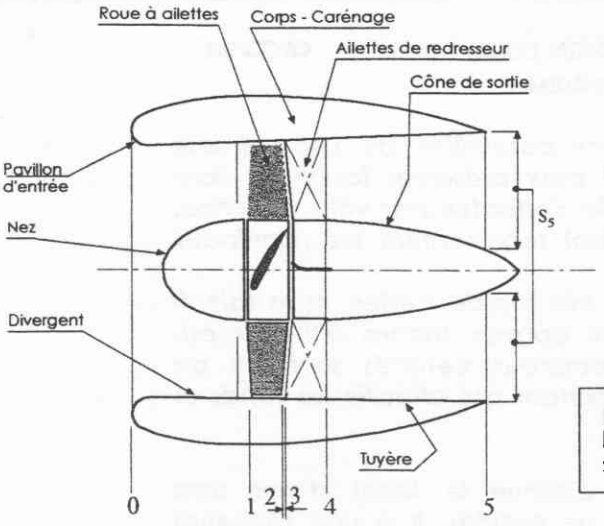
L'aéroglisseur étant immobile, le ventilateur aspire l'air extérieur, au repos (Débit au point fixe).

En translation, le ventilateur, se déplaçant vers l'air au repos, doit traiter une quantité de fluide plus importante, fonction de la vitesse du véhicule (Débit à V_0 positive). L'efficacité du traitement fera varier positivement l'angle de la courbe de poussée.

$$T_{\text{point fixe}} = m.v_5 \qquad T_{\text{translation}} = m.(v_5 - V_0)$$

Force d'inertie et quantité de mouvement. - (Fig.6) Pourquoi l'Aéroglisseur continue-t-il à accélérer alors que les valeurs de la courbe de poussée diminuent avec la vitesse du véhicule ?
Le propulseur doit équilibrer deux forces en présence : la quantité de mouvement $M.V_0$) qui égale les forces de résistance en vitesse de déplacement stabilisée et la force d'inertie ($1/2\ m.v^2$) que le propulseur doit vaincre pendant les accélérations.

Pour une vitesse V_0 donnée, la droite, reliant la ligne d'abscisses et la courbe de résistance à l'avancement (Rx), indique, en valeurs de poussée, la quantité de mouvement. La droite, complémentaire, reliant la courbe de résistance à l'avancement à la courbe de poussée, représente la valeur possible des accélérations (Fig.5).



0 - Entrée de pavillon

1 - Bord d'attaque de pales du rotor

2 - Bord de fuite de pales du rotor

3 - Entrée des pales fixes du redresseur

4 - Sortie des pales fixes du redresseur

5 - Sortie tuyère.

Les caractéristiques du fluide à la section (5) déterminent la Poussée et permettent le calcul dimensionnel des éléments situés en amont de ce plan.

Fig.7 - Nombres repères de références des différentes sections de la veine d'air.

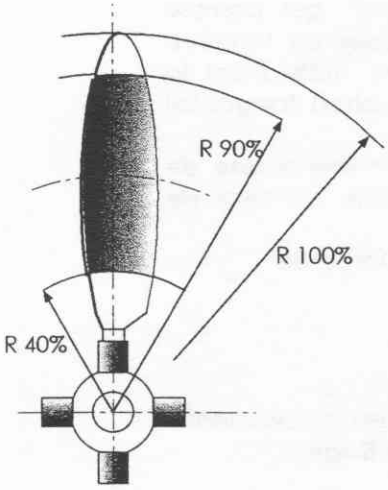


Fig.8- Hélice libre à quatre pales

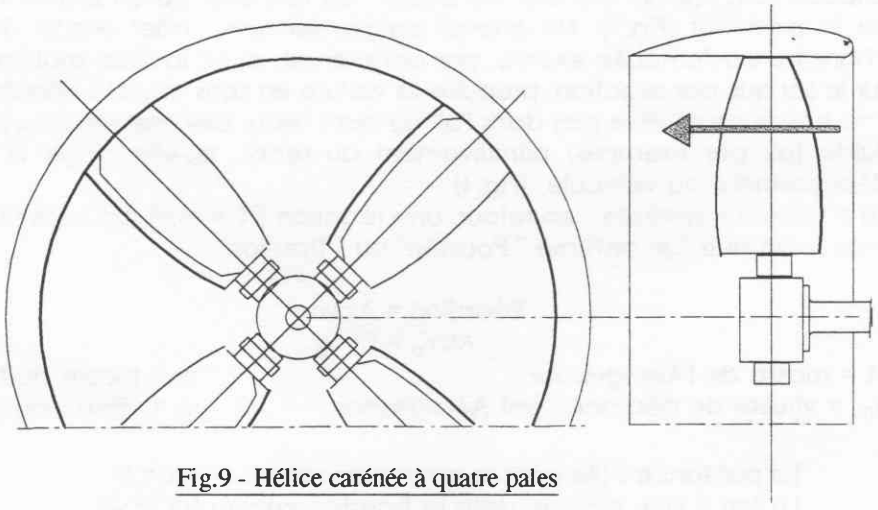


Fig.9 - Hélice carénée à quatre pales

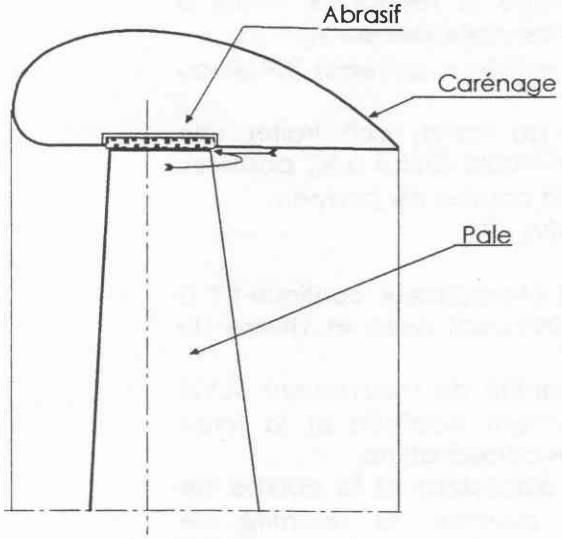


Fig.10 - Abrasif périphérique d'étanchéité

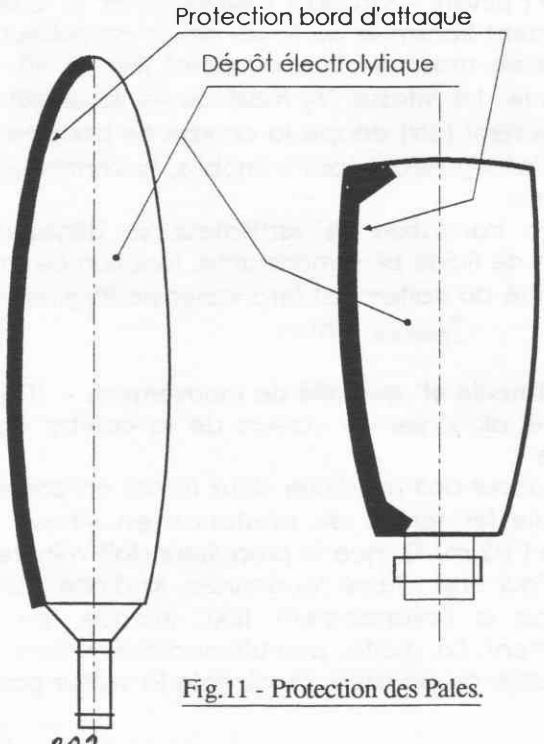


Fig.11 - Protection des Pales.

G.J.VERNIER CACD 98

Amélioration de la poussée

Augmentation de la puissance - C'est le premier réflexe pour augmenter la poussée , il est simple et moins coûteux que l'étude d'un ensemble propulsif nouveau. Mais la variation de poussée en fonction de l'augmentation de puissance est faible et le rendement de propulsion chute, les autres paramètres restant identiques. Pour une augmentation de puissance de 50% le gain de poussée sera de 30%, mais le rendement de propulsion diminuant de 20%, la poussée devient à peine suffisante pour compenser l'augmentation de masse du moteur, des transmissions et des accessoires.

Augmentation de la surface de passage d'air (Φ roue, S_0 & S_5) - En doublant le diamètre utile du passage d'air c'est à dire en multipliant ces surfaces par 3, la poussée augmente de 68% et le rendement de propulsion évolue positivement de 0,537 à 0,7. Le rendement de propulsion ($2.V_0 / V_0 + v_5$). est d'autant plus élevé que le rapport V_0/v_5 (vitesse du véhicule / vitesse de l'air à la sortie de la tuyère) est plus petit). Nous avons donc intérêt à réduire au maximum la variation de vitesse de l'air à la traversée de l'hélice. La poussée (T) du propulseur étant égale à (m.v) il est nécessaire pour conserver sa grandeur, d'augmenter (m) ,ce qui nécessite d'attaquer une masse d'air plus importante (débit massique kg/sec.) en augmentant le diamètre de l'hélice et de la tuyère. En vertu de l'égalité des quantités de mouvement lorsque le débit massique augmente, la vitesse (v_5) du flux diminue, toutes conditions restant égales par ailleurs.
Rendement de propulsion: 0,5 = passable, O,6 = bien, 0,7 = excellent, 0,8 parfait, 0,9 but.
Poussée: T = mv : 2,5/ 3 kg / kw = passable - 4 = bien, 5 = très bon, 6 = but.

Hélice libre - Comme vous le constatez sur la figure (Fig.8), toute la surface totale balayée par l'hélice en rotation n'est pas acfive. Seule la zone située entre les rayons 0,4 et 0,9 communique à la masse d'air une quantité de mouvement utile.
Un bras (de 0 à 0, 40) éloigne la partie active des obstacles situés en aval (capot moteur ou autres) afin d'en éviter les interférences. Elle permet en outre à la surface active de travailler à des vitesses linéaires efficaces (100 à 225 m/sec).
A la périphérie des pales, une forme élliptico-triangulaire s'oppose aux pertes marginales en évitant que les filets d'air de l'intrados, sous pression, ne viennent combler la dépression de l'extrados.
L'hélice possède une fonction importante : la variation possible du pas des pales (hélice à pas variable) qui adapte leur angle d'incidence aux variations du débit d'air (petit pas au point fixe et aux basses vitesses, grand pas aux vitesses élevées). En limite de rotation des pales, l'hélice assure le freinage du véhicule par reverse, tout en conservant son sens de rotation.
Ses défauts majeurs: très grand diamètre, danger pour l'environnement et bruit.

Hélice à carénage extérieur - (Fig.9) L'hélice semi-carénée tourne dans un anneau dont le but consiste à diminuer les pertes marginales à la périphérie des pales, lorsque le jeu de fonctionnement est suffisamment réduit. Seule, une couche d'abrasif (Si C) en agloméral grains fins + gros grains collés à la paroi du carénage, peut réduire la fuite à pratiquement zéro (Fig.10). La veine fluide épouse la forme du carénage pendant la transformation d'énergie, évitant les tourbillons d'interférence, ce qui autorise l'emploi de pales larges à grande efficacité.
A puissances fournies, sensiblement égales, le diamètre d'une hélice à carénage extérieur est réduit pratiquement de moitié par rapport à celui d'une hélice libre.

Construction - Les hélices des aéroglisseurs souffraient principalement des dommages causés por les embruns et par les projecfions d'eau douce ou salée qui érodaient le bord d'attaque et l'intrados des pales.
Actuellement, les pales se composent d'un longeron interne en métal léger situé sur l'axe neutre, de mousse à cellules fermées donnant la forme, le tout enveloppé d'une coquille en résine époxy et fibre de verre, revêtu d'un dépôt électrolytique de nickel. Une protection multicouche de fibres de verre longues , de caoutchouc synthétique et de polyuréthane protège le bord d'attaque. Ce procédé réduit considérablement l'érosion tout en supprimant la cause d'oxydation (Fig.11).

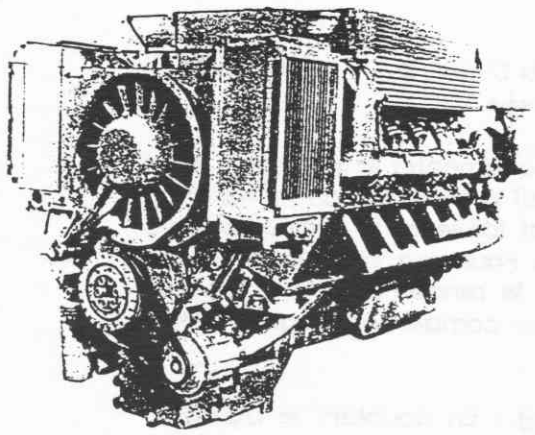


Fig.12 - Moteur Diesel DEUTZ V.12 - 1440 kw - air cool.

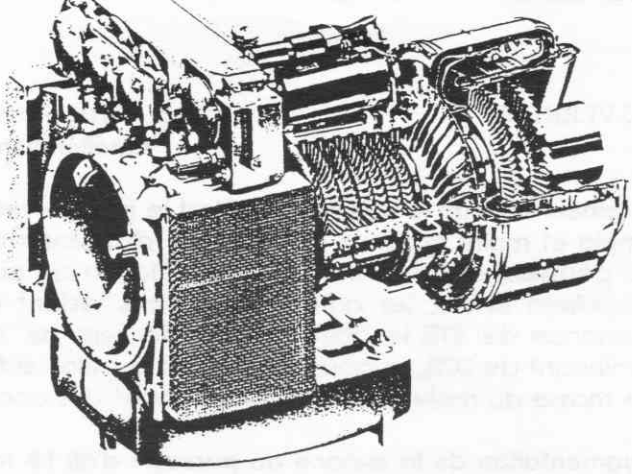


Fig.13 - Turbine à gaz AVCO LYCOMING TF 25 - 1800 kw.

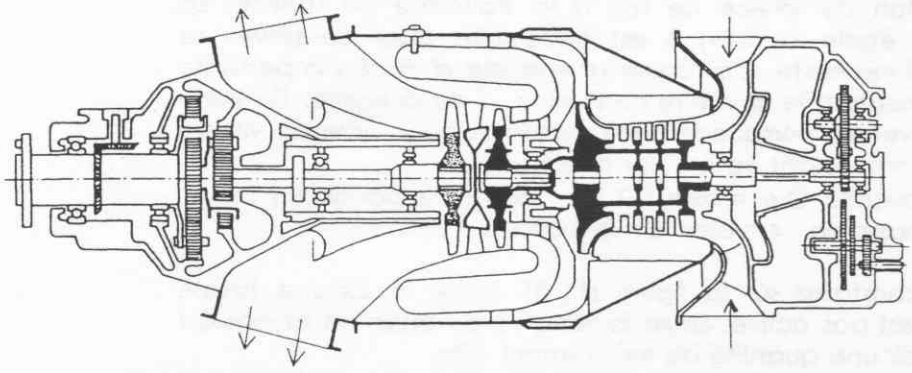


Fig.14 - Turbine à gaz P. &W. of Canada - 560 kw.

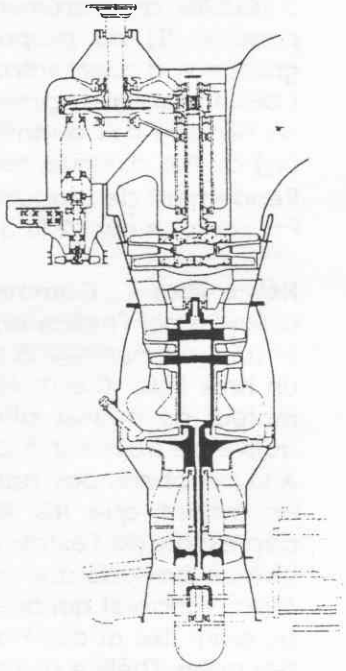


Fig.15 - Turbine à gaz TURBOMÉCA (F) "Turmo" - 1115 kw

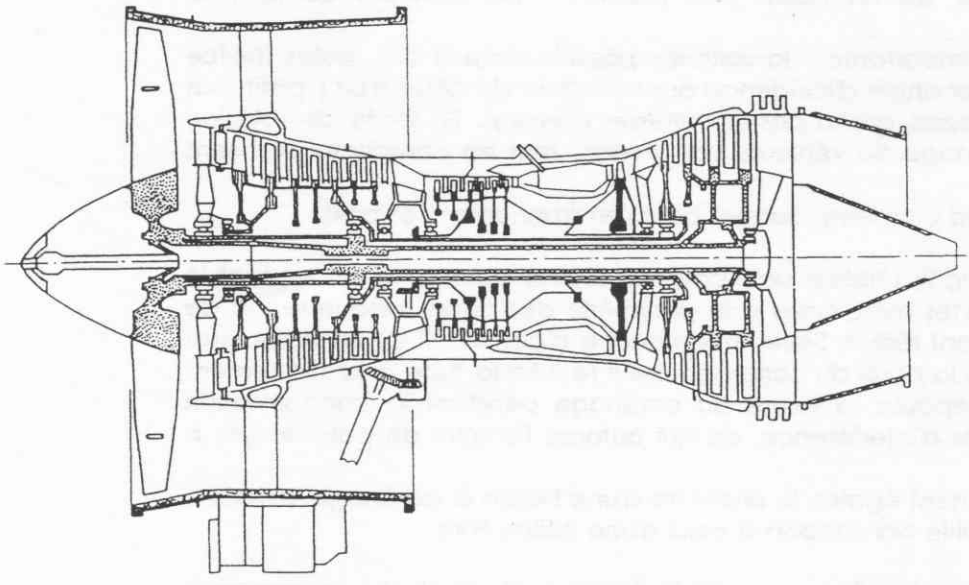


Fig.16 - Turbo-Fan - R.R. RB 211 524 - T = 22 700 kgf.

3 corps = (3 arbres concentriques)
Turbine BP (3 roues) → Ventilateur principal.
Turbine MP (1 roue) → Compresseur BP.
Turbine HP (1 roue) → Compresseur HP.

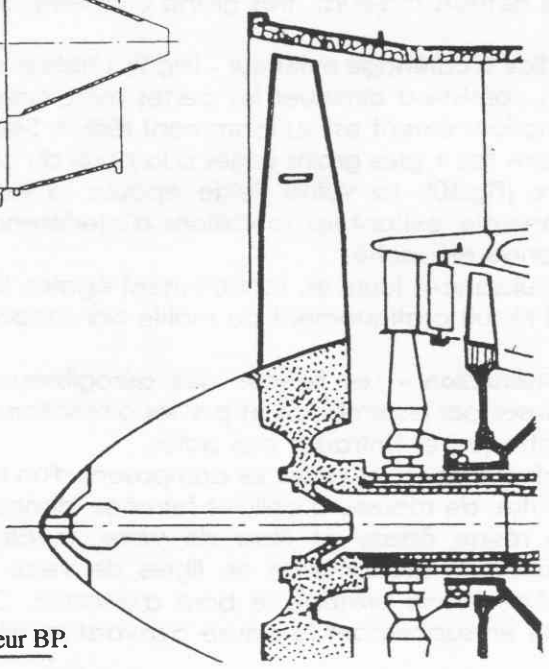


Fig.17 - Détail du Ventilateur & 1er étage compresseur BP.

Motorisation - tous les moteurs courants sont utilisés dans la motorisation des Aéroglisseurs : moteurs à pistons à explosions ou à combustion et turbines à gaz. Le turbo réacteur ou turbo jet, en évaluation, n'a pas encore d'utilisation pratique sur ce véhicule.

Moteurs à pistons à explosions - spécification : (0,5 à 1,5 kg/ch.)=(O,36 À 0,75 Kg/ kw). Le carburant essence est interdit sur les véhicules de transport. Seuls les aéroglisseurs de tourisme et de compétition utilisent ce type de moteur.

Moteurs à pistons à combustion (Diesels)- (Fig.12)
masse spécifique: 2,5 à 5kg /ch (3,4 à 6,8 kg/kw)
Consommation spécifique: 0,18 à 0,185 kg/ch. h.
En égalisant les puissances fournies à la propulsion et au coussin d'air, l'emploi de moteurs "Diesels rapides" (1800/2700t/m) sur aéroglisseurs se révéla un bon compromis et une standardisation des unités motrices. Longtemps, la masse importante du moteur diesel, quoique robuste et économique, l'écarta de l'aéroglisseur. Quatre moteurs de 750 kw grèvent le devis de poids d'au moins 10 tonnes, auxquels il convient d'ajouter la masse des réducteurs contre 900 kgs pour 4 turbines à gaz de puissance identique.
Parmi les techniques utilisées nous trouvons, soit 4 motreurs entraînant chacun une hélice de propulsion et un ventilateur de sustentation ou 2 moteurs affectés à la propulsion et 2 à la sustentation.

Turbines à gaz (turbo shaft) - Masse spécifique: 0;15 à 0,30 kg/ch. (0,20 à 0,40 kg/kw)
Consommation spécifique: 0,200 /0,300 kg /ch.h.
L'avantage de masse des turbines à gaz (Fig.13 - 14 - 15), les désigne, à priori, comme indispensables à l'aéroglisseur. La vitesse de rotation de leurs turbines libres, entraînant l'arbre de travail, leur impose un réducteur de l'ordre de 20/1 intégré d'origine à la structure.
Notons qu'une hélice libre, accouplée à une turbine à gaz affiche une masse souvent supérieure à celle-ci (O,25 à 0,35 kg/kw).

Turbo réacteurs à ventilateur (Fan-jet ou Turbo-fan) - **(Fig.16)** Actuellement ce moteur n'a aucune raison d'être cité dans cet exposé car aucun aéroglisseur commercial ne l'utilise.
Dans ce type de moteur, 80 à 85% de la poussée provient du ventilateur ; 15 à 20% seulement sont fournis par les gaz chauds du générateur. En simplifiant, nous pourrions dire que nous sommes en présence d'un ventilateur entraîné par un moteur qui pourrait être quelconque à la condition qu'il fournisse la puissance requise.
L'avant dernière génération développait une poussée de 20 à 25 tonnes. Les plus récents sont tarés à 40/50 tonnes. Ce qui permet l'emploi de 2 moteurs là où 4 s'avéraient nécessaires. Dans le cadre de cet exposé, seule la technique de l'ensemble ventilateur nous intéresse. Nous allons en examiner les constituants pour les transposer, en similitude, aux Aéroglisseurs.

Le ventilateur de Turbofan - Possibilités pour l'aéroglisseur - (Fig.17) Le calcul et les applications le confirment. Ce type de ventilateur, extrêmement étudié, dépasse de loin les performances et les rendements des hélices.
Son installation, telle qu'elle, est impensable sur un aéroglisseur dont la vitesse de translation reste, encore, très éloignée de celle des avions de transport (100km.h/850 km.h). Par suite la vitesse d'éjection du flux de poussée doit être harmonisée pour conserver un rendement de propulsion élevé (1020 km.h. / 200 km.h).
Le ventilateur "type avion" travaille en régime supersonique et comprime l'air à un taux de 2,5/1 environ qu'il faut détendre pour le transformer en vitesse.

Une étude en similitude, prenant en compte les données de fonctionnement d'un aéroglisseur, permettra l'adaptation de ce modèle de ventilateur sur véhicules à propulsion aérienne à vitesse de translation lente (100 à 300km/h).
Ainsi, rendement de propulsion et poussée seront améliorés. Le bruit sifflant de l'hélice se transformera en sons graves ,moins agressifs à l'oreille. Une grille à larges mailles, de surface importante pour limiter les pertes de charge, protégera l'environnement tout en évitant l'ingestion de corps étrangers.

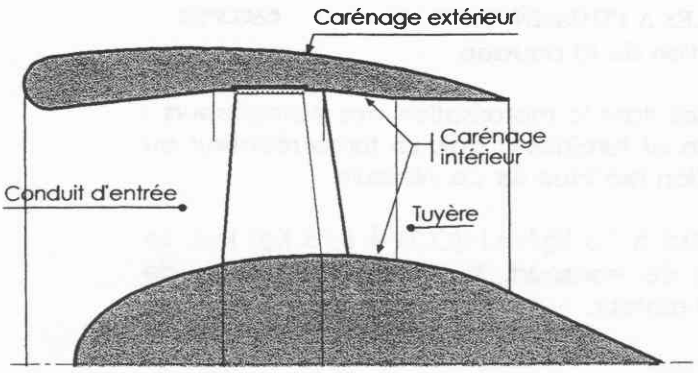
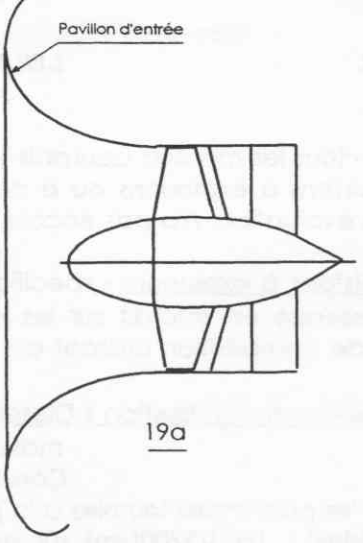


Fig. 18 - Carénage de la veine d'air - 1/2 vue en coupe.



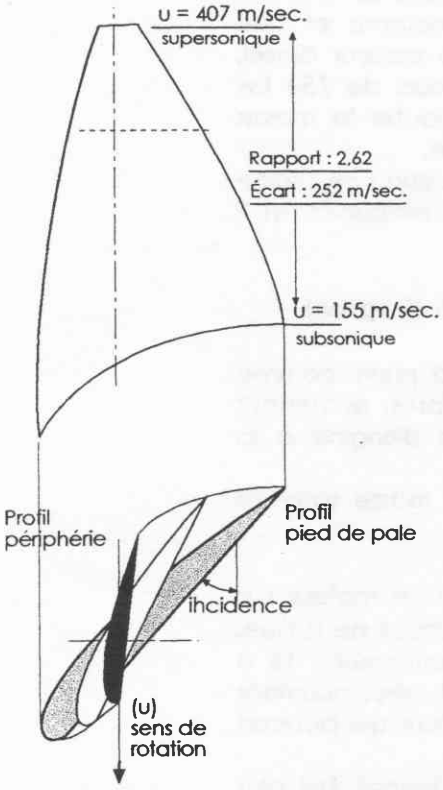


Fig.20 - Écart de vitesses circulaires & variation de l'incidence.

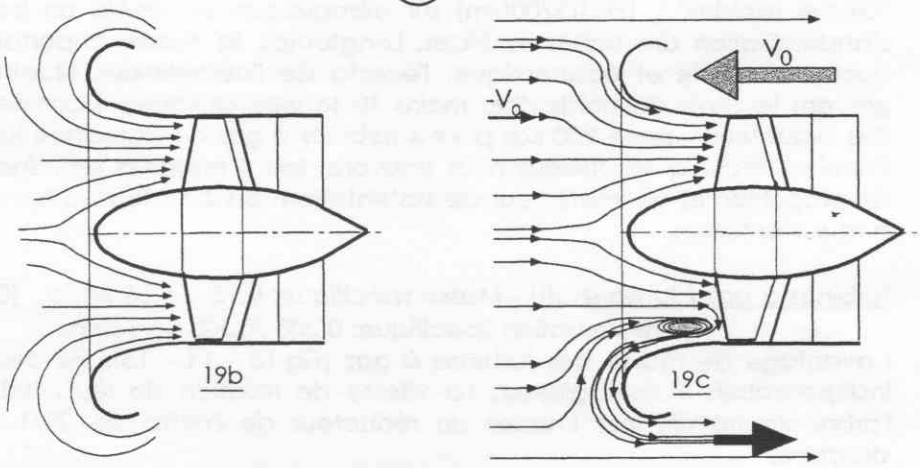


Fig.19 - Influence du Pavillon d'entrée sur la veine d'air.

19a - Pavillon pour mesure de poussée statique au Banc d'essai.
19b - Pavillon réduit. Aéroglisseur au point fixe et à basse vitesse.
19c - Vitesse de translation élevée. Saturation de la veine d'air.

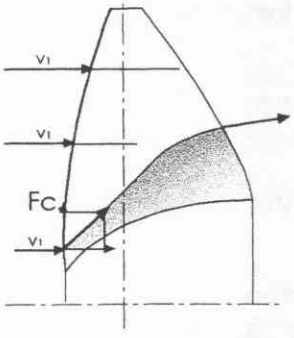


Fig.21 - Déflexion de l'air au pied de pale par centrifugation.

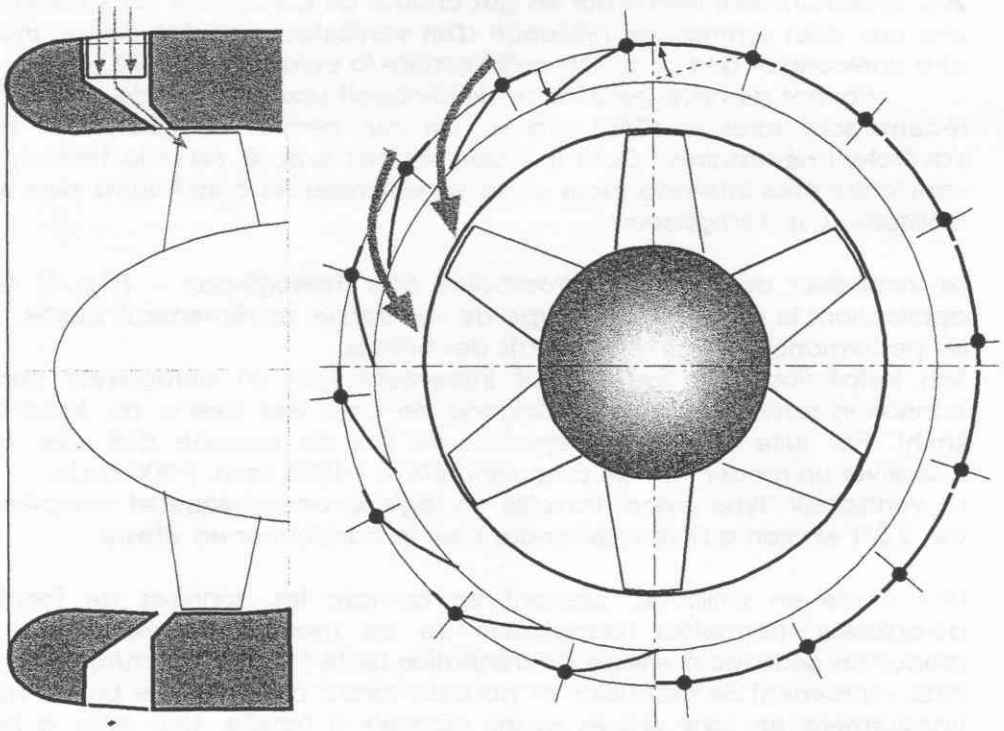


Fig.22 - Ouïes d'entrée d'air auxiliaires, par clapets mobiles, pour augmenter la Poussée au point fixe & aux vitesses moyennes en remplacement du pavillon d'entrée.

Examen du ventilateur de TurboFan -

Le carénage - Un carénage intérieur et extérieur, sans rugosité, maîtrise étroitement la veine d'air dans ses configurations successives (compressions et détentes) sans possibilité d'actions non prévues, créatrices de vortex néfastes et de pertes de charge.

La roue - Multipales (40 pales environ) à faible charge par pale, sans interférence entre elles. Les logiciels de calcul et de modélisation sont actuellement bien définis, de même la technique de fabrication est au point.

Le rapport des vitesses linéaires entre pied de pale et périphérie (2,6 environ), de valeur normale quoiqu'un peu élevée (*voir ci dessous pied de pale*).

Le pied de pale - La rotation d'une roue, physiquement idéale,(mouvement continu, absence de vibration, faible résistance de palier...) présente un défaut que l'on trouve sur toutes les turbo machines: la vitesse linéaire, circulaire varie en fonction du rayon considéré .

Ainsi une roue de diamètre Φ 2,10m/ 0,80m tournant à 3700 t/m aura une vitesse périphérique de 407 m/sec et une vitesse de pied de pale de 105m/sec c'est à dire un rapport de 2,62, proportionnel au rapport des diamètres.

Afin que chaque élément de pale, le long du rayon, transforme l'énergie de façon identique, nous augmenterons l'incidence des pales et la largeur de celles ci, de la périphérie vers le moyeu (Fig.20). Si théoriquement l'augmentation d'incidence augmente la force de sustentation (Rz), elle accroît en revanche la résistance (Rx) jusqu'à une limite où l'élément de pale décroche et ne produit qu'un tourbillon de résistance négative d'où l'intérêt d'un rapport de diamètres le plus faible possible.

Un deuxième phénomène s'ajoute au précédent : les molécules d'air à vitesse axiale faible (comme au pied de pale) sont projetées radialement le long de la pale par la force centrifuge Fig.21).

Pour pallier ces défauts, le premier étage du compresseur BP, situé immédiatement en aval du ventilateur, intervient et ajoute son action aux éléments de pales de Φ inférieur du ventilateur pour homogénéiser le débit d'air.

Le conduit d'entrée d'air - (Fig.18) Le calage des pales et le conduit d'entrée d'air, d'un Turbofan, sont définis pour obtenir le meilleur rendement à la vitesse de croisière (850/900km/h par vent nul) à une altitude donnée. Pendant le décollage l'ensemble turbo réacteur fonctionne à pleine charge sous une poussée considérable avec un rendement déplorable. Cette action ne dure que 30 secondes pour un temps total de vol de 5h à 15 h, ce qui n'influence guère le bilan énergétique.

Deux formes sont habituellement utilisées pour définir l'entrée d'air.

-1 /- Le pavillon d'entrée -

(Fig.19) - Pour point fixe et déplacement lent (O à 5O km/h)

(Fig.19a) - Pavillon de diamètre égal à 3 diamètres de roue pour mesure de la poussée max. au point fixe, sur banc d'essais.

(Fig.19 b) - Pavillon réduit convenant aux basses vitesses. A noter que le maillage des filets d'air s'étend en arrière du pavillon, lieu où la dépression s'exerce encore.

(Fig.19c) - Lorsque la vitesse de translation augmente, donc la vitesse d'entrée d'air, le ventilateur n'absorbe plus le débit total et sature. Un tourbillon-bouchon se crée, aggravant l'écoulement et l'air excédentaire reflue.

-2 /- Le carénage de "section fuselée", suivi d'un divergent (Fig.18).Il convient pour les vitesses élevées (> 50 km.h.) et doit être adapté à la vitesse d'utilisation max.

Dans ce cas, le véhicule accélère lentement vers sa vitesse max. Il faut alors adjoindre, à l'ensemble ventilateur, un dispositif d'appoint d'air au point fixe et aux faibles vitesses : les "ouies auxiliaires" (Fig.22).

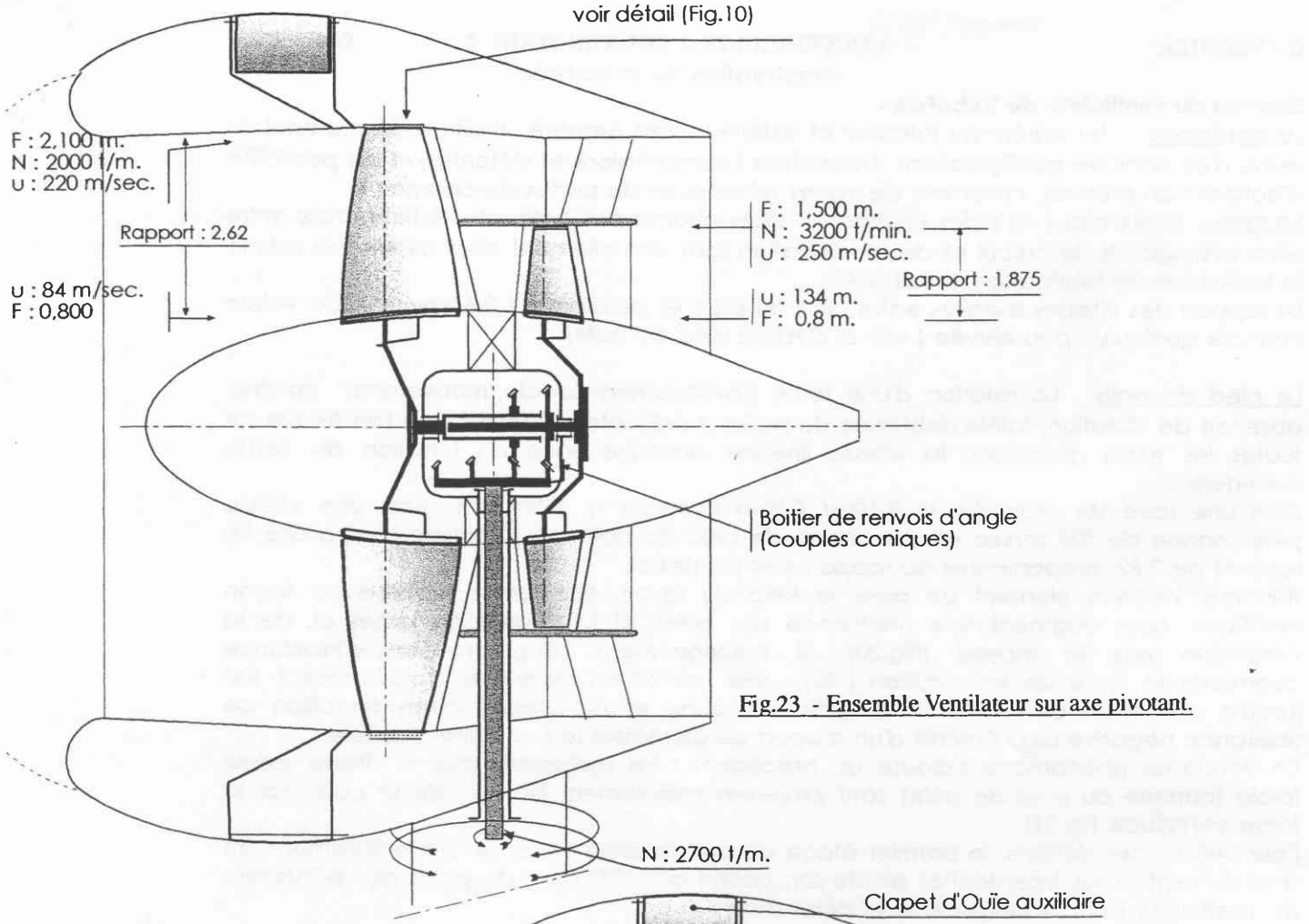


Fig.23 - Ensemble Ventilateur sur axe pivotant.

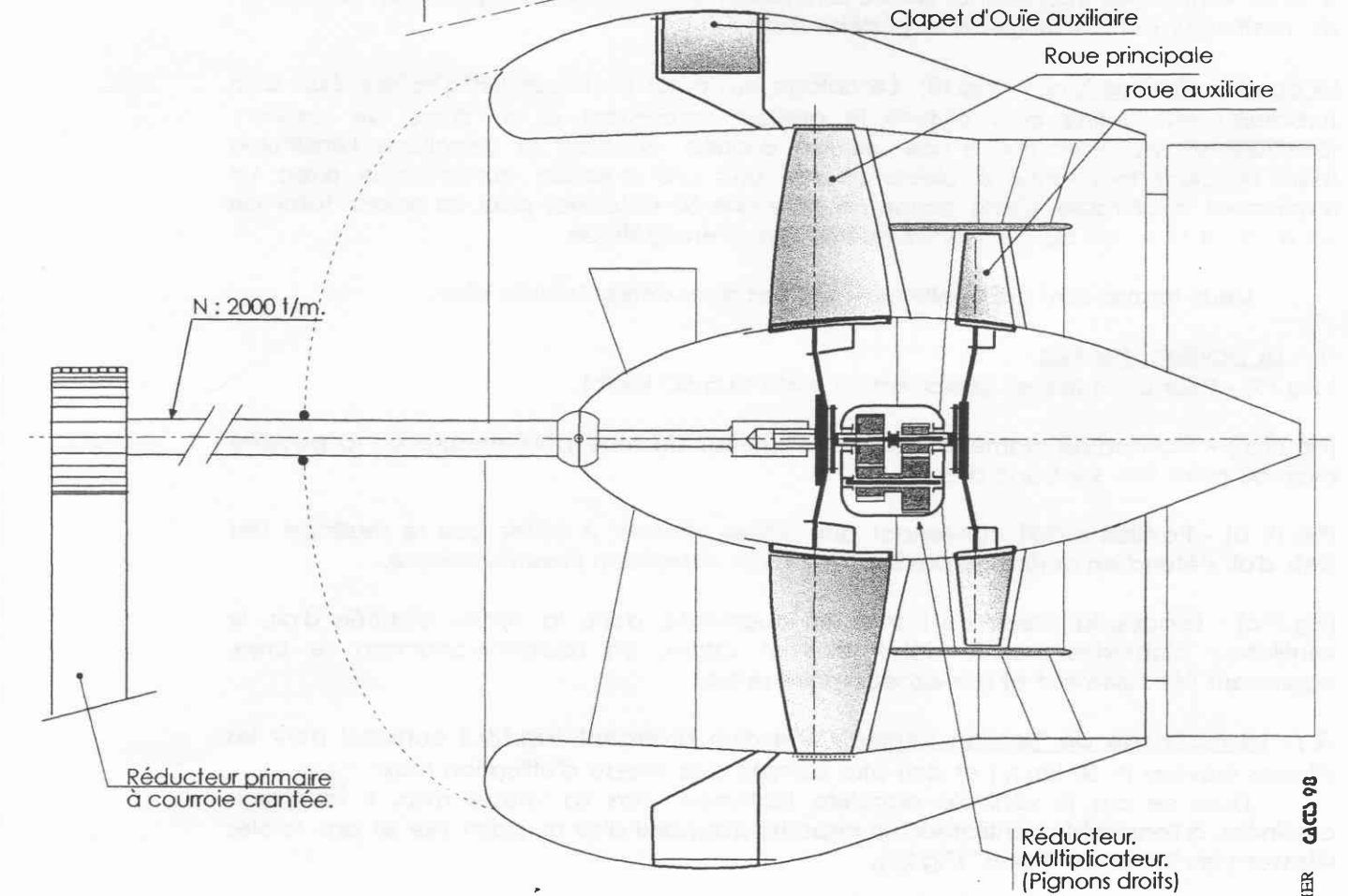


Fig.24 - Ensemble Ventilateur sur support fixe.

G.J.VERNIER

Ventilateur adapté à l'aéroglisseur - Si l'avion commercial n'accélère qu'une fois, sur son trajet de 2000 à 15 000km, l'aéroglisseur se comporte différemment. Il doit pouvoir manoeuvrer à tout moment et accélérer rapidement pour atteindre sa vitesse max.

Le calage des pales du ventilateur et le dessin du conduit d'entrée sont définis pour une vitesse de translation rapide de l'aéroglisseur. Le débit d'air s'accroît alors en fonction de l'augmentation de vitesse du véhicule.

Après un ralentissement, l'accélération sera modeste puisque le débit d'air au point fixe et à faible vitesse sera pénalisé par le diamètre d'entrée, dimensionné pour les vitesses élevées.

Pour rétablir les conditions de bon fonctionnement et donner de la vivacité aux déplacements lents, l'appoint de débit sera fourni par des entrées d'air auxiliaires, automatiques ou commandées (Fig.22).

L'air additionnel, aspiré par la dépression du ventilateur, sur la périphérie extérieure du carénage, s'introduit par des conduits de section dégressive dans la zone de dépression juste en amont des pales du ventilateur.

Il importe que l'air, considéré à vitesse nulle à l'entrée des ouïes, sur le carénage extérieur, accélère dans les conduits pour acquérir la vitesse débitante prévue en configuration "vitesse" au bord d'attaque des pales.

Les (Fig.23 24) montrent deux "ensembles ventilateurs" identiques quant à la transformation du flux d'air. Seuls les cinématiques de motricité diffèrent.

(Fig.23) - L'ensemble pivote sur un axe vertical. Ce module constitue l'élément directionnel de l'aéroglisseur par orientation du vecteur " poussée" . *(voir Wärtsilä Larus).*

Le boîtier contient deux renvois d'angle à pignons coniques. L'un, réducteur, diminue la vitesse de l'arbre de transmission (N = 2700 t/m) à (N = 2100 t/m), vitesse de rotation du ventilateur principal dont les vitesses circulaires évoluent de (u = 220m/sec) à la périphérie des pales à (u = 84 m/sec) au pied des pales. L'autre multiplie la vitesse de l'arbre vertical par le rapport 1,185 pour entraîner le ventilateur auxiliaire à N = 3200t/m).

(Fig 24)- le montage mécanique représente une motricité classique pour moteur "Diesel" dont la réduction primaire s'effectue par courroie crantée. L'arbre de transmission tourne à la vitesse du ventilateur principal (N = 2100 t/m) Un train d'engrenages droits multiplie la vitesse de rotation par 1,52 pour entraîner le ventilateur auxiliaire à (N = 3200 t/m) dont les vitesses circulaires vont de (u = 250 m/sec) à (u= 134 m/sec) au pied de pale.

Evolution du flux d'air

Les filets d'air traversent en premier lieu une toile métallique à grande surface développée et larges mailles pour la protection rapprochée et le blocage de corps étrangers. Eventuellement, elle est chauffante afin d'éviter le givrage par temps froid.

Le carénage, profilé extérieurement, débute par un rayon, signe d'adaptation aux vitesses élevées. Il se poursuit intérieurement par un divergent qui ralentit la vitesse débitante.

A proximité du bord d'attaque des pales, débouchent les ajutages des ouïes auxiliaires dont les entrées sur le carénage extérieur sont ouvertes ou obturées par des clapets mobiles. Ils pourraient être automatiques, munis seulement d'un ressort taré à une valeur inférieure à la dépression, lorsque le débit d'air est insuffisant. Cependant nous avons constaté des battements aux périodes transitoires qui plaideraient en faveur d'une commande positive.

Le ventilateur principal comporte des pales larges semi- elliptiques, à profil bi-convexe subsonique, de construction mixte (mousse interne, coquille en composite et longerons en alliage léger).

A la sortie du bord de fuite des pales une cloison circulaire divise la veine d'air et délimite la surface d'action du ventilateur secondaire.

Un redresseur, extérieur à la cloison, joue le rôle d'anticouple.

Le redresseur, intérieur à la cloison, infléchit les filets d'air pour leur entrée dans le ventilateur secondaire dont le supplément de dépression active la zone de pied de pale du ventilateur principal.

Un redresseur de sortie harmonise la vitesse débitante des filets d'air à celle de la veine sortant du redresseur extérieur à la cloison.

les deux flux se rejoignent qui, éjectés au travers de la tuyère, engendrent la poussée.

C'est en observant les Aéroglisseurs de compétition et en pratiquant des essais sur eux que mes connaissances à ce sujet se sont précisées. Je tiens à remercier pilotes et constructeurs qui se sont prêtés à mes recherches et particulièrement Michel Soulabail du Club Aéroglisseurs d'Ile de France ainsi que Jean Pierre et Patrick Godicheau du Club Anjou Aéroglisseurs.

Je suis très sensible à l'accueil de S.C.T.C.A et particulièrement à celui de Monsieur J.E. LAFRAMBOISE qui m'a permis de m'exprimer sur un sujet dont la technique me passionne depuis de nombreuses années.

Gabriel J.VERNIER