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AIR CUSHION VEHICLE LECTURE SERIES

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INTRODUCTION AND BACKGROUND DEVELOPMENT

Lecture 1

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CONTENTS

INTRODUCTION AND BACKGROUND DEVELOPMENT

Lecture 1

1.0 INTRODUCTION

The following series of lectures on Air Cushion Vehicles is designed to provide an encapsulated presentation of the main design considerations in a balanced vehicle design. It is also the intent of the lectures to express the design features in fundamental parameters for general assimilation and further to identify those areas where advancing technology is improving the state of the art.

The course is directed primarily at those most concerned with the procurement, use and design of Air Cushion Vehicles as well as the management of the R&D associated with such vehicles. With this intent in mind, there is a maximum concentration on presentation of overall parameters affecting the design and a minimum concentration on theoretical development of some particular point. Where such theoretical developments are necessary for further understanding, specific references are given in the lectures as to where such treatments are provided.

This week at M.I.T. is devoted to the Advanced Marine Vehicle and within this context, Figure 1 has been prepared to aid discussion of the particular craft forms under discussion this week and how they relate to those craft using some form of air cushion support. The first day included discussion on the aerodynamic form of air cushion craft (shown in Figure 1) which will, therefore, only be briefly discussed in this lecture. The second day is devoted to the hydrofoil of which the fully-submerged type is shown in Figure 1.

The third day (today) is devoted to that particular form of air cushion craft namely the Air Cushion Vehicle which is the amphibious form. The non-amphibious form or Surface Effect Ship is the subject of the lecture series tomorrow (the fourth day). Obviously, with the similarity between certain types and with commonality of the various techniques supporting the various craft design, it will be necessary to refer to these other forms of Advanced Marine Vehicles as the lectures on Air Cushion Vehicles proceed.

HYDROFOIL & AIR CUSHION CRAFT

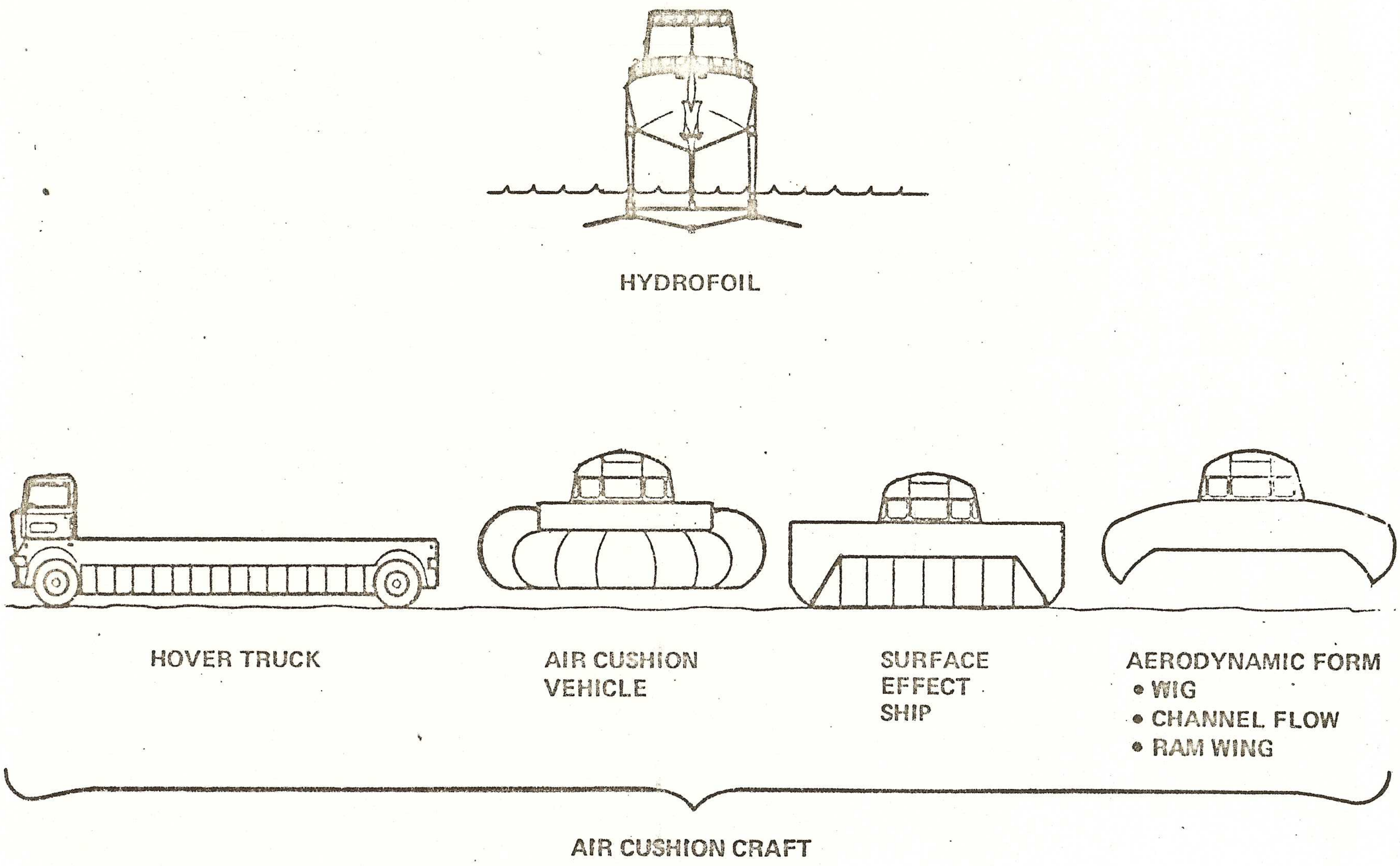


FIGURE 1

2.0 BACKGROUND DEVELOPMENT

The historical development of the air cushion vehicle has been adequately covered in earlier texts (see for example Reference 1) and only a brief overview will be given here, sufficient to identify the key developments.

Hayward (Reference 2) provides an excellent search into the past to uncover such devices as Emmanuel Swedenborg's man powered air cushion platform in 1716. Other historical research of note includes the first patent for air lubrication issued in England to another Swedish engineer, Gustav Lavalle in 1882. Lavalle's experiments were not successful however, and it was not until 1916 when Von Tomamhul built a torpedo boat for the Austrian Navy where fans were used to pump air beneath the hull to form a small air cushion. After that time various types of air cushion principles began to evolve. In 1925 a patent was issued to V. F. Casey for the use of the energy saving re-circulation principle. A principle that has been revived periodically over the last ten years but has been overshadowed by the development of skirts.

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

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

While a research of the literature will find many such examples by scientists and engineers around the world who had uncovered the various principles of the air cushion, it was not until 1955 did the modern development begin.

In 1955 Christopher Cockerell (now knighted for his achievements) was awarded a patent (Reference 3) for his annular or peripheral jet principle which because of its power saving features offered most promise for the air cushion craft. Cockerell then proceeded on a development path to build the first annular jet craft in 1959. This craft was built by Saunders-Roe, Ltd. (now British Hovercraft Corporation) by a team of engineers headed by R. Stanton-Jones and designated the SR.N 1. The trials and tribulations of such a development are best described by the words of Cockerell and Stanton-Jones themselves which may be found in the proceedings of the Princeton Symposium on Ground Effect Phenomena, October 1959 (References 4 and 5).

In this same period research was being conducted in the United States along similar lines. Melvin Beardsley narrowly missed being first with his work on annular jets in 1955. Dr. Harvey R. Chaplin (Reference 6) was responsible for most of the basic research into air cushion craft (or GEMs) at DTMB (now Naval Ship Research and Development Center) that had its beginnings in May 1957 with V/STOL research.

With the above admittedly sketchy background one can begin to group the main categories or classification of air cushion craft.

2.1 CLASSIFICATION OF AIR CUSHION CRAFT

Attention is restricted to those forms that have received serious development. Early research into, say, water-sealed curtains is not covered.

There are four basic forces of importance to a craft that operates in the interface between water and air; they are: aerostatic, aerodynamic, hydrostatic and hydrodynamic, and it is convenient to use these to classify the air cushion craft.

Figure 2 has been prepared as a family tree that shows where the various craft fit. It has been left incomplete in terms of showing a large range of craft for the sake of clarity.

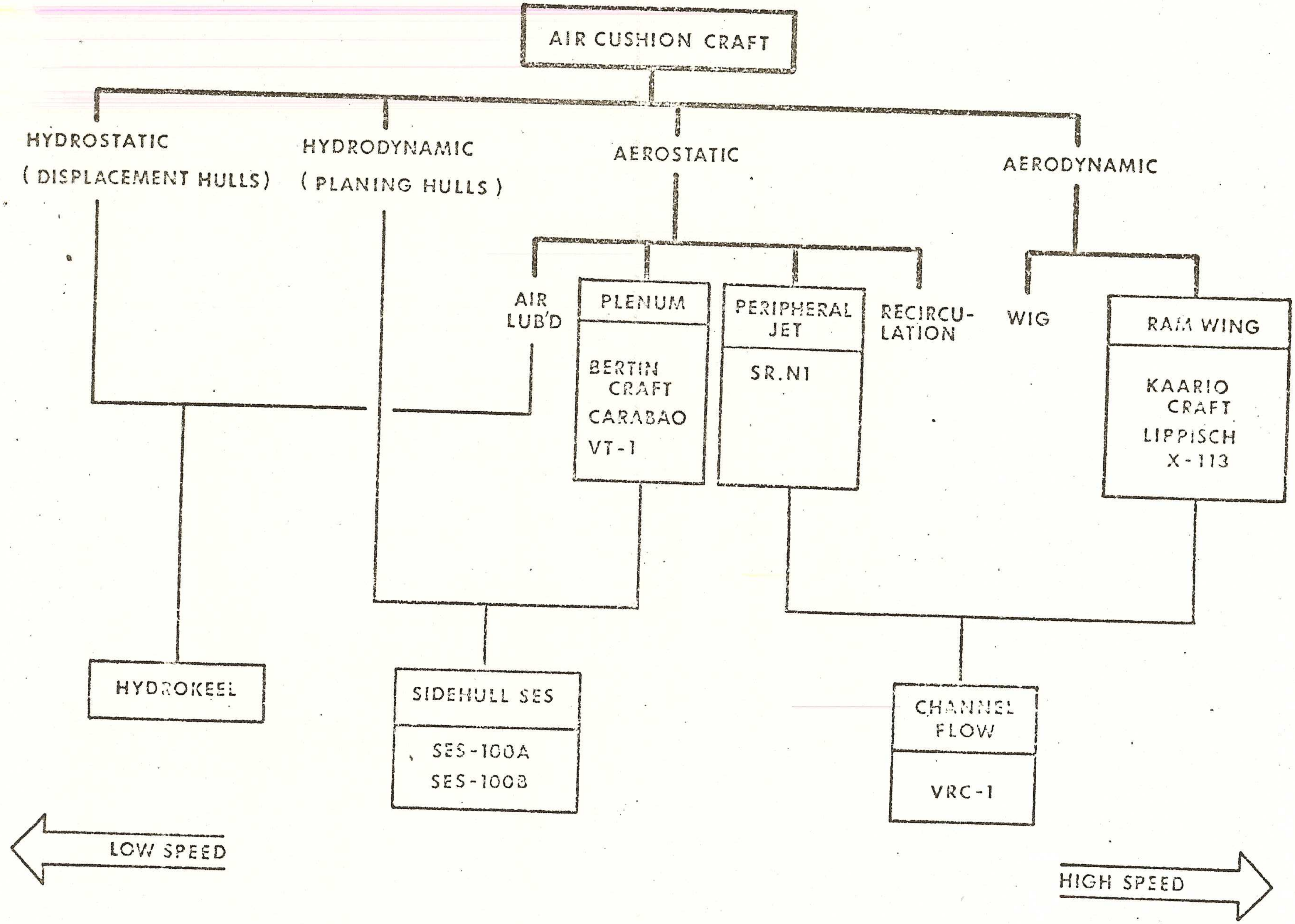


FIGURE 2 AIR CUSHION CRAFT FAMILY TREE

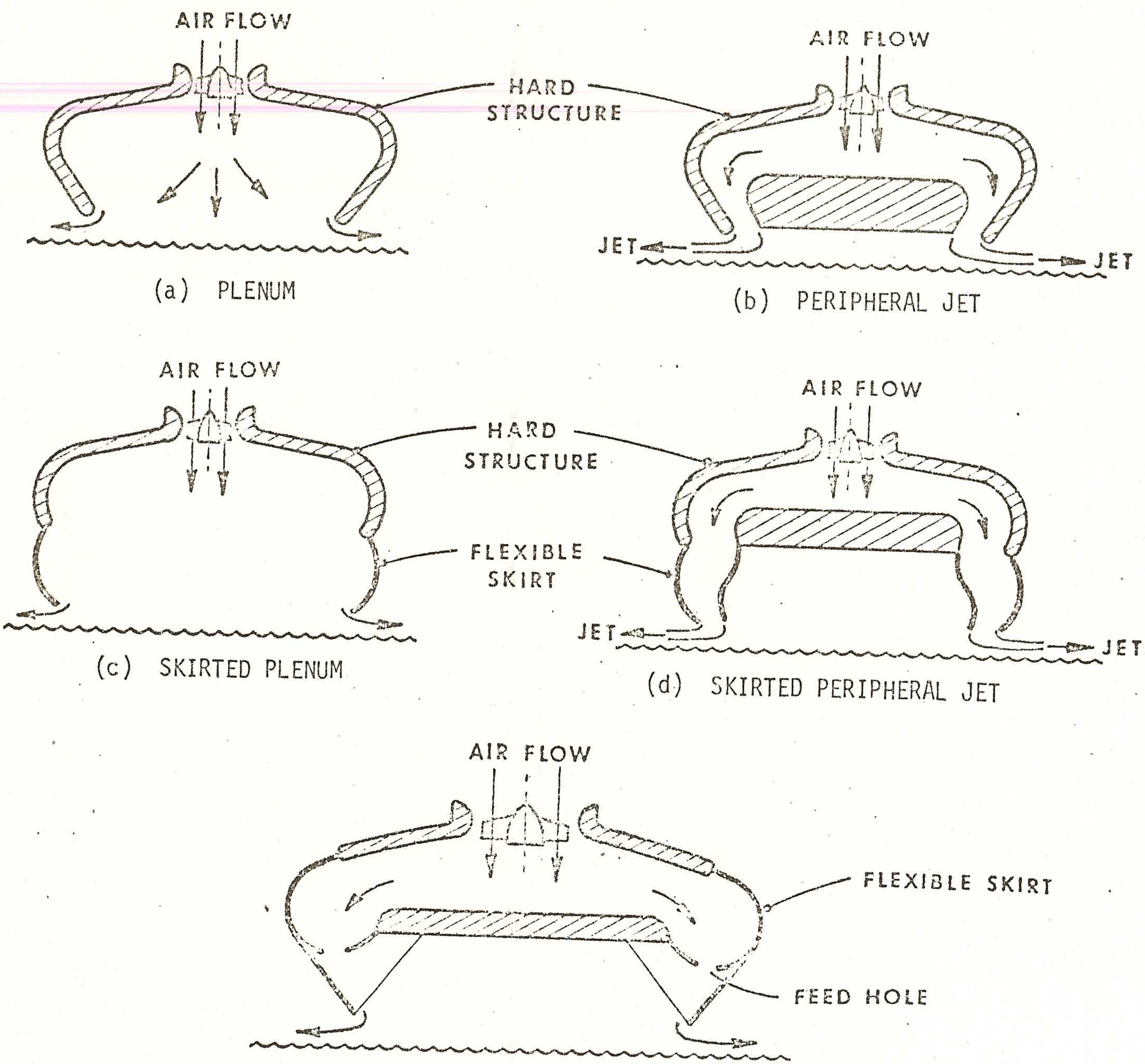
2.1.1 Aerostatic Class

The first class, and by far the largest class, is that designated 'aerostatic' and encompasses the plenum and peripheral jet forms pioneered by Cockerell as discussed above. Figure 3 illustrates the basic form of this type of air cushion craft. Two other forms of aerostatic craft would be the air-lubricated and recirculation types. These received development in the late '50s' and early '60s' by such groups as Ford Motor Company, Martin Company and Canadair, Ltd., but have not since been pursued. They are excluded here for brevity. Figure 3(a) shows the simple inverted bath tub plenum where fan air is blown into the plenum or cushion pressurizing it to generate the desired aerostatic lift. Figure 3(b) shows the simple peripheral jet where the centrifugal forces generated by the turning jets create the desired pressure rise in the cushion. This fundamental principle resulted in the SR.N 1 shown in its skirted version in Figure 4. Skirted versions where flexible extensions are added to increase obstacle (wave) clearance for the same power are shown in diagramatic form in Figures 3(c) and (d). As skirt development progressed, the pure peripheral jet gave way to a modified plenum skirt design similar to Figure 3(e). Most operational amphibious air cushion craft today are of this type and the 170-ton SR.N 4, also shown on Figure 4, is the most noted example, and the largest craft today. The British Hovercraft Corporation craft (SR.N 5, SR.N 6, SR.N 4 and BH-7) have been listed in Figure 2 as belonging to both the plenum and the peripheral jet craft because of the skirt design reasons stated.

2.1.2 Waterborne Class

The second class of craft involves some form of hydrostatic or hydrodynamic surfaces. Figure 5 illustrates the basic forms considered. These include the the Hydrokeel (Figure 5(a)) which is essentially an air-lubricated hull with low buoyancy sidehulls sealing fore and aft. There is some hydrodynamic lift from the trailing real seal at speed.

The Captured Air Bubble (CAB) craft pioneered by Al Ford (Reference 7) of which the basic form is shown in Figure 5(b) essentially sought to capture



(a) PLENUM

(b) PERIPHERAL JET

(c) SKIRTED PLENUM

(d) SKIRTED PERIPHERAL JET

(e) SKIRTED PLENUM (MODIFIED)

FIGURE 3 PLENUM AND PERIPHERAL JET BASIC FORMS

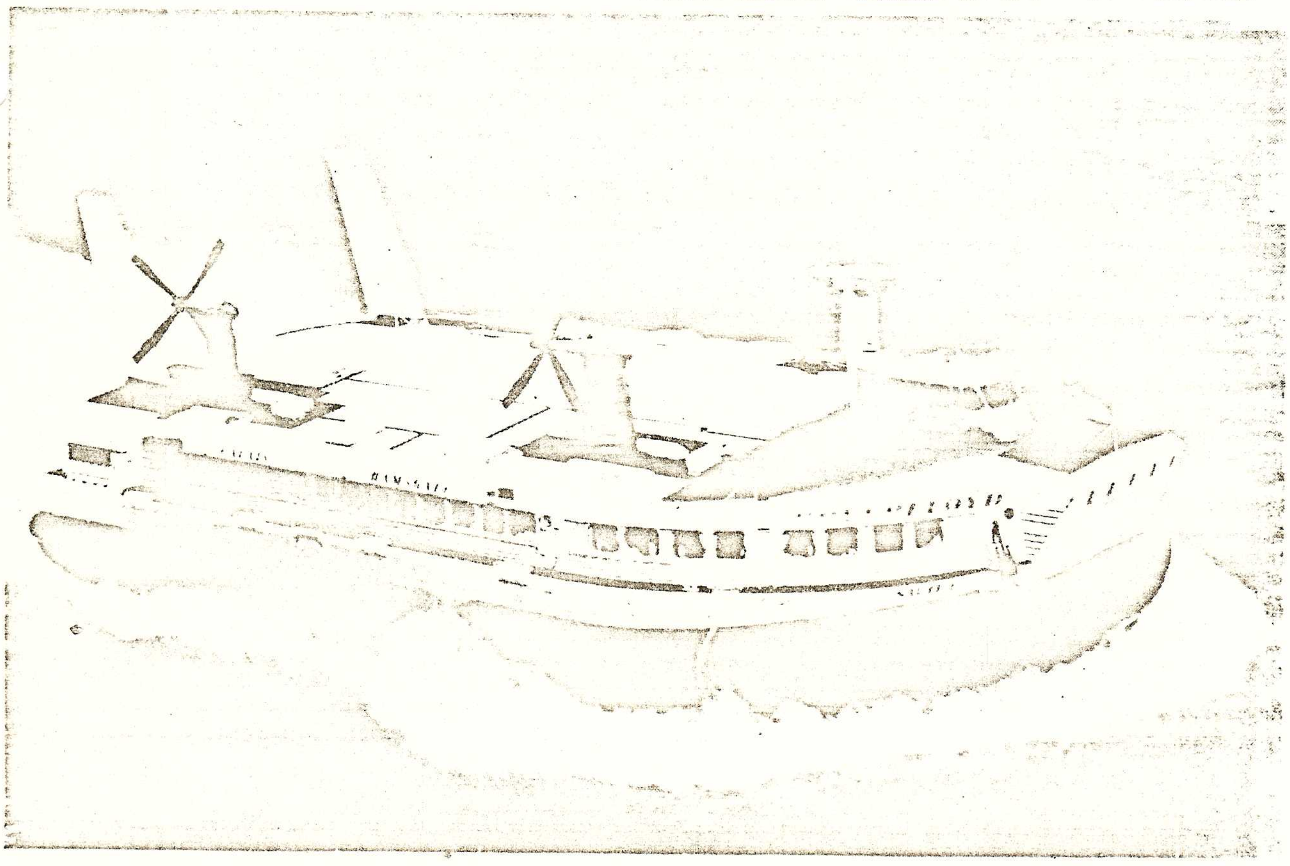


FIGURE 4 SR.N1 and SR.N4 AIR CUSHION CRAFT

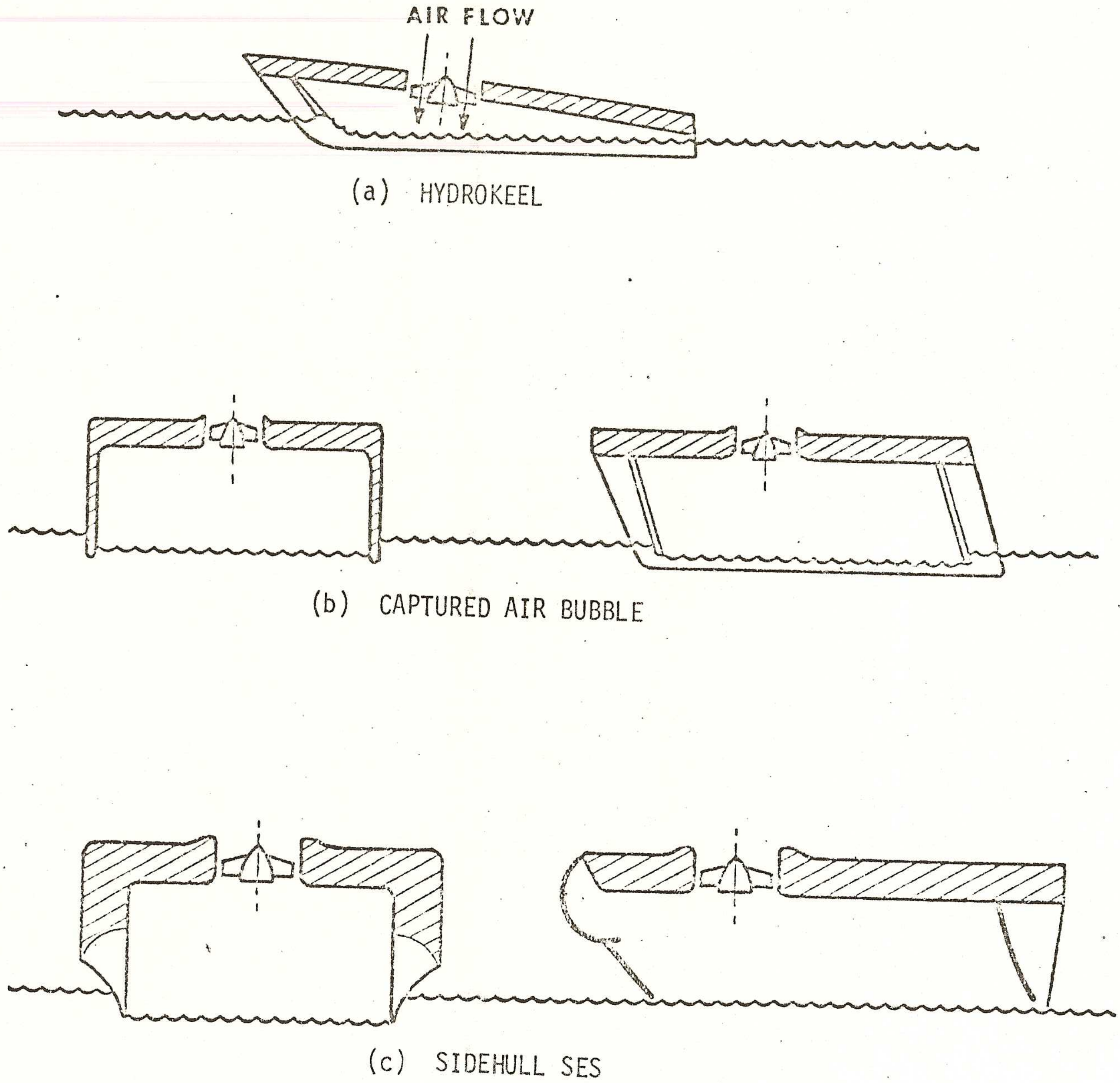


FIGURE 5 HYDROSTATIC AND HYDRODYNAMIC BASIC FORMS

the pressurized air with planing ski-like seals at the bow and stern and planing knife-edge like sidehulls fore and aft. Lateral stability was provided by the hydrodynamic forces on the planing seals.

The sidehull SES is a result of the development of the CAB and plenum/peripheral jet craft. Its basic form is as shown on Figure 5(c) and includes shaping to the sidehull* to provide stability and control. The seals at the bow and stern can be either planing surfaces or flexible skirts with their associated leakage.

Examples of these non-amphibious forms of air cushion craft can be seen in Figure 6 which shows the SES-100A, the XR-3 and the SES-100B. The adjustable planing stern seal on the XR-3 and the flexible skirt type seal on the SES-100B can be seen in Figure 6.

2.1.3 Aerodynamic Class

This third class of air cushion craft includes those craft that derive a significant amount of lift by aerodynamic means. Figure 7 shows the views in both longitudinal and transverse cross-section of the basic forms of aero-dynamic cushion craft.

The wing in ground effect (WIG) shown in Figure 7(a) is simply the application of a conventional (high aspect ratio) wing flying in ground effect. The most cited example of this is the crossing of the Atlantic in 1929 by the Dornier Do-X flying boat which flew close to the sea surface to take advantage of ground effect. There are two important gains in performance by flying in ground effect that are pertinent to the aerodynamic cushion craft.

* Early craft used the term "sidewall". Now that stability and performance benefits are found possible by shaping, it is felt that "sidehull" is a more descriptive term.

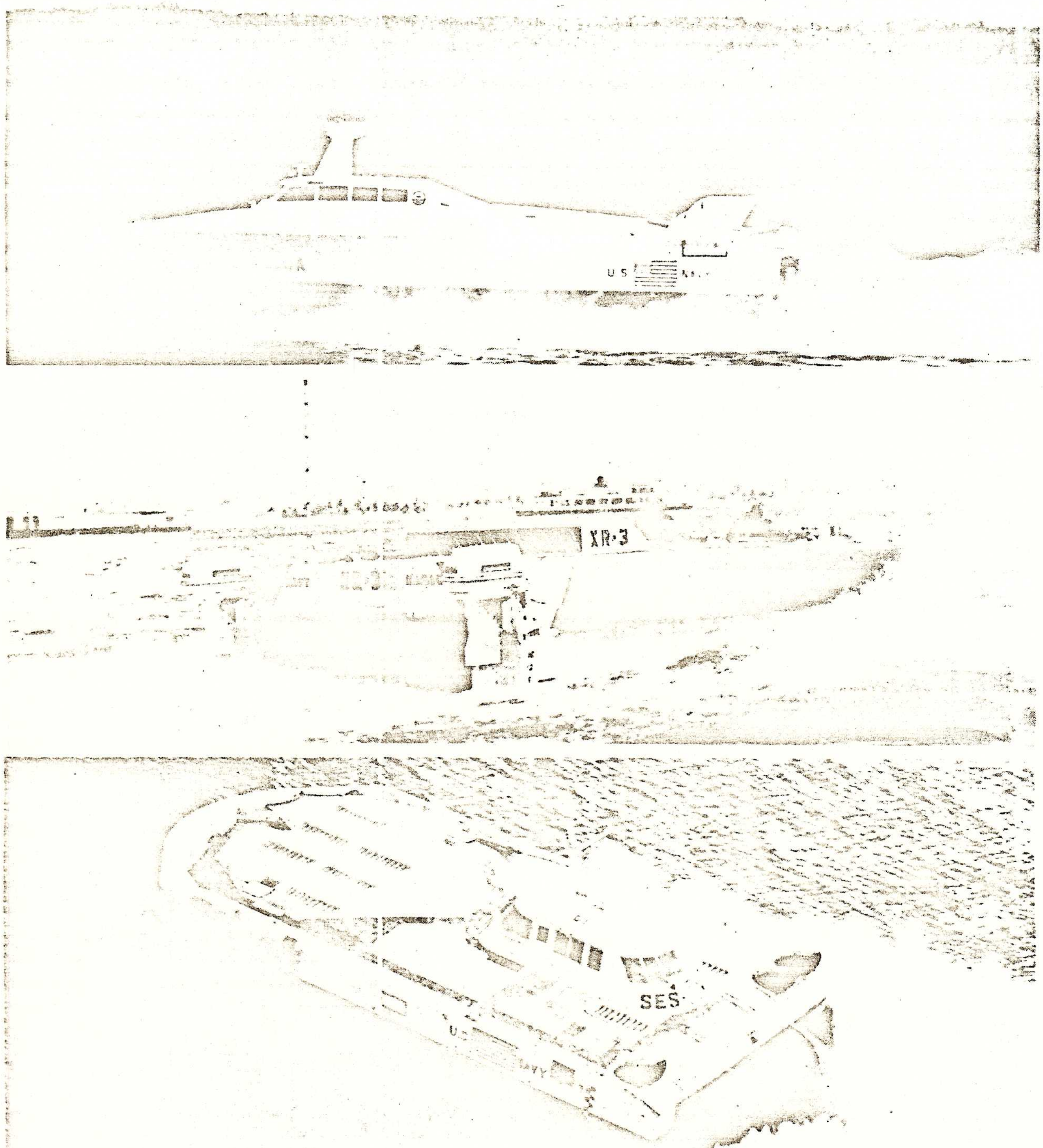
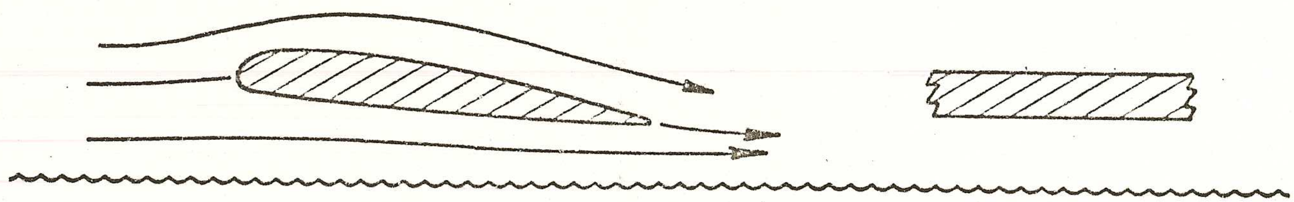
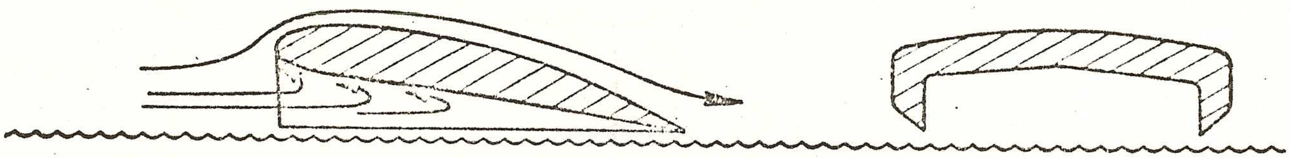


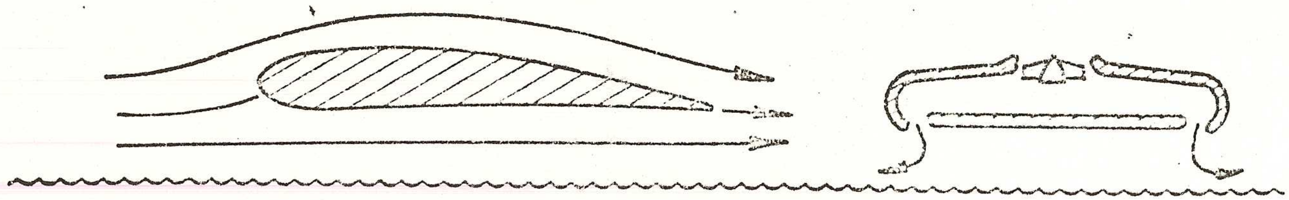
FIGURE 6 WATERBORNE AIR CUSHION CRAFT



(a) WING IN GROUND EFFECT



(b) RAM WING



(c) CHANNEL FLOW WING

FIGURE 7 AERODYNAMIC CUSHION CRAFT BASIC FORMS

The first gain in performance is that due to the increase in the bound circulation as the wing approaches the surface and distorts the streamlines. The stagnation point moves aft on the under surface and the increased curvature of the streamlines gives the experienced increased circulation and lift. The second gain in performance is that due to the partial destruction of the tip vortices. Again, as the wing approaches the surface the spanwise flow to the tip is diminished and the tip vortices weaken with the attendant reduction in aerodynamic induced drag. It was mainly due to this reduction in drag that allowed the Dornier flying boat to improve its fuel consumption and give it sufficient range to cross the Atlantic. Karl Weiland, the Swiss engineer, built a prototype of such a craft in 1963.

While gains in performance are realizable with the WIG it still required the wing aspect ratio to be of such proportions to negate its application to marine use and fit existing harbors, docks and ways.

The ram wing is a craft that removed the problem of span. It is shown diagrammatically in Figure 7(b) and is essentially a low aspect ratio wing with its trailing edge virtually touching the surface and with end plates at the wing tips to prevent the spanwise flow and to seal the pressurized ram air underneath. Since the entire lifting mechanism is provided by aerodynamic means the ram wing has no hovering ability. As mentioned earlier, the first such application of this principle was Kaario's ram wing in 1935. More recent developments include those of A. M. Lippisch (Reference 8) who perfected two prototypes, the X-112 in 1963 and X-113 in 1971. These craft were of low aspect ratio form and operated both in and out of ground effect. Figure 8 (upper photograph) shows both the X-113 flying in ground effect and Lippisch's design for a 300-ton transport aerofoil boat (upper right picture). In the latter case, it can be seen that the (passenger carrying) sidehulls provide the necessary end-plate effect for the ram wing.

The channel flow wing (Figure 7(c)) is a development that combines the hovering capability of the peripheral jet principle with the high-speed dynamic lift of the ram wing. The end plate effect is now provided by the sealing of the air jets that run fore and aft at the craft's side edges. The bow and stern jets (not shown in Figure 7(c)) retract into the main body

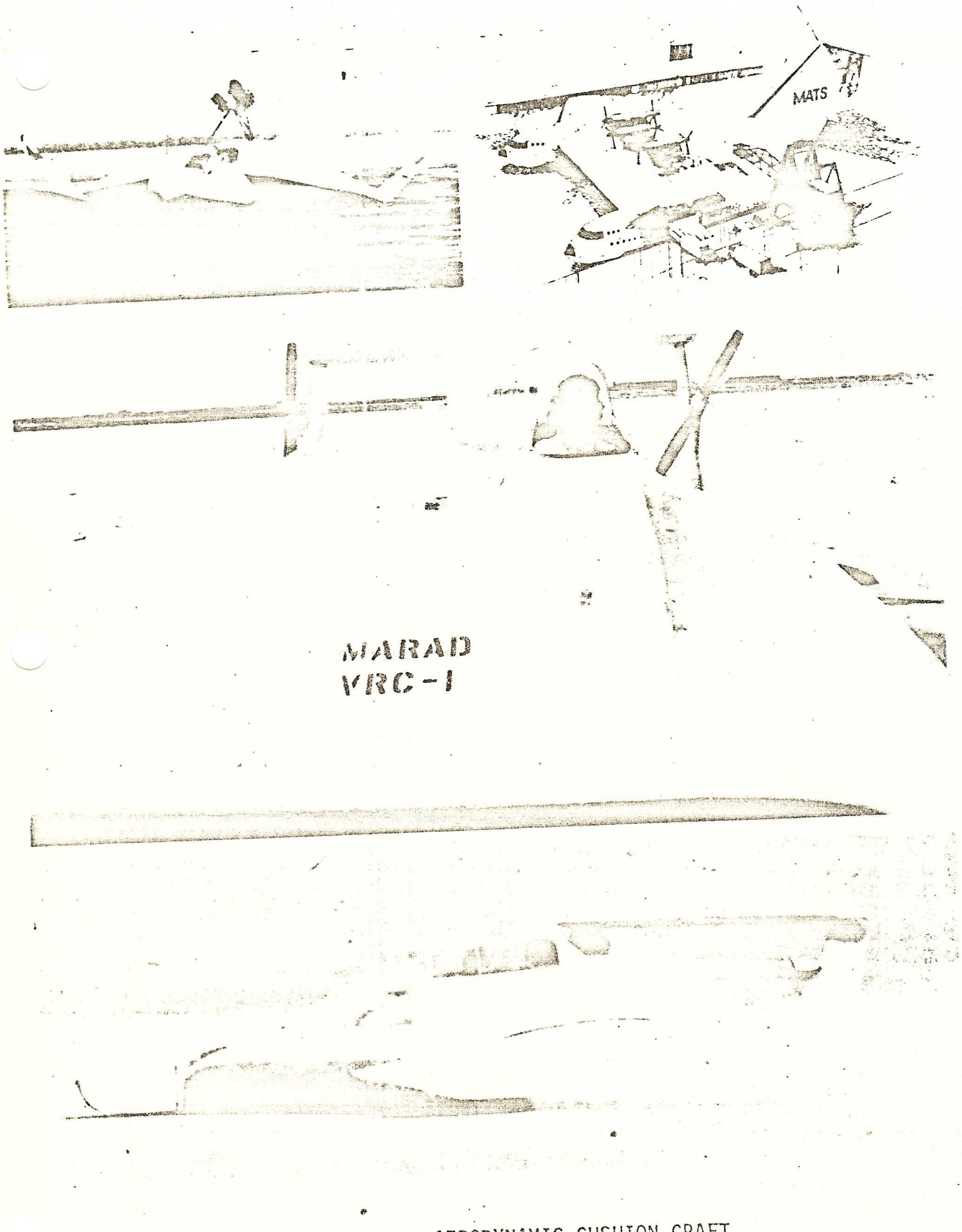


FIGURE 8 AERODYNAMIC CUSHION CRAFT

at high speed where sufficient lift to support the craft is generated by aerodynamic means. The side jets remain operating to provide the vortex drag reduction. This concept was conceived by Scott Rethorst (Reference 9) for the Columbia project. Figure 8 (middle and lower photographs) shows a prototype, the VRC-1, designed and built by the author in 1964; under test at Edwards Air Force Base, California.

It can be seen from the three main classes of air cushion craft that, all else being equal, the designer can optimize the form of craft to meet the speed region required. Generally speaking, it can be inferred from Figure 2 that a progression to the right when combining the different principles results in craft designed to optimize at higher speeds. The specific details, trade-offs and limiting factors in a real world design process as to how this is accomplished are discussed in the succeeding chapters.

2.2 MAIN DEVELOPMENT EFFORTS

With such a wide range of types and many different operating principles, it is sometimes difficult to categorize where a particular development should proceed. It is suggested that there are three main groups of development, the boundaries of each group are necessarily somewhat fluid and overlapping but at least provide a means for discussion. These are:

Low Speed Development	0 - 30 mph
Intermediate Speed Development . . .	30 - 100 mph
High Speed Development	100 - 300 mph

Figure 9 summarizes the most visible or the most active developments in the air cushion craft field as grouped by the above rather arbitrary categorization. A few comments on each are felt pertinent.

2.2.1 Low Speed Development

Until relatively recently, the bulk of the development has been in the Intermediate Speed Group spurred on by expectation of ambitious low cost operation. It is encouraging now to see in addition, the emerging development of a class of vehicles that are designed to meet a need for "low cost workhorses" that use the air cushion where its uniqueness gives it an

LOW SPEED
(0-30 mph)

- Special applications
  - Hoverpallets
  - Hovertrailers
  - Industrial uses
  - Hovertrucks
- Impassable Terrain
  - Canadian operations in Forestry work
  - Energy exploration
  - Ice pack operation

INTERMEDIATE SPEED
(30-100 mph)

- British, French, and Japanese Developments for Commercial Use
  - Channel Crossings
  - Coastal Operation
  - River Traffic
  - Inter-Island Operation
  - Hovertrains
- U.S. Development to give U.S. Navy a High Speed Capability
  - Amphibious Assault
  - High Speed at Sea (SES)

HIGH SPEED
(100-300 mph)

- Exploratory Developments Only in Western World
- Developments in USSR for Military Transport
-

FIGURE 9. MAIN DEVELOPMENT OF AIR CUSHION CRAFT.

advantage over other forms of transport. These range from the industrial application for heavy load movement that did indeed start several years ago, to the hover-trailers designed to transport heavy equipment into previously impossible territory. Figure 10 illustrates three typical uses that are indicative of the application of the air cushion principle for low speed use. The top photograph shows the movement of a large storage tank by the use of wraparound skirt system. The middle photograph shows the Bertin "Terraplane" which can operate on the road as a conventional truck and by inflating the skirts or jupes can lower the footprint pressure of the vehicle for travelling over mud or water. Propulsion in this mode is through use of paddle-type appendages to the wheels. The lower photograph typifies the latest area of development which is currently being used in the development of outlying territories of Canada. The need to explore new forms of energy and new locations for existing energy sources has hastened the need to move about in areas not presently suitable for conventional transportation. Most of the attention and interest at the present time is focused on Canada where the oil discoveries at Prudhoe Bay, to cite one example, has prompted the need to move equipment over soft or environmentally sensitive terrain. Reference 10 provides a pertinent discussion on this emerging use of the air cushion principle, where emphasis must be simplicity and payload capability.

2.2.2 Intermediate Speed Development

By far the major development work to date has been in this category. There are many excellent papers describing the historical developments in this area and will not be repeated here, other than to note in encapsulated form the main themes.

While it is certainly true that the British have developed craft designed purely for military missions such as the British Hovercraft Corporation BH-7 and have conducted military operations in such places as Borneo and Aden, it is without doubt that today they are the leaders in the commercial development of the air cushion craft. The largest majority of these craft are designed and built by British Hovercraft Corporation and operate on coastal routes ranging from 5 miles to 25 miles in length. The record is impressive as may be from the English Channel crossing statistics where

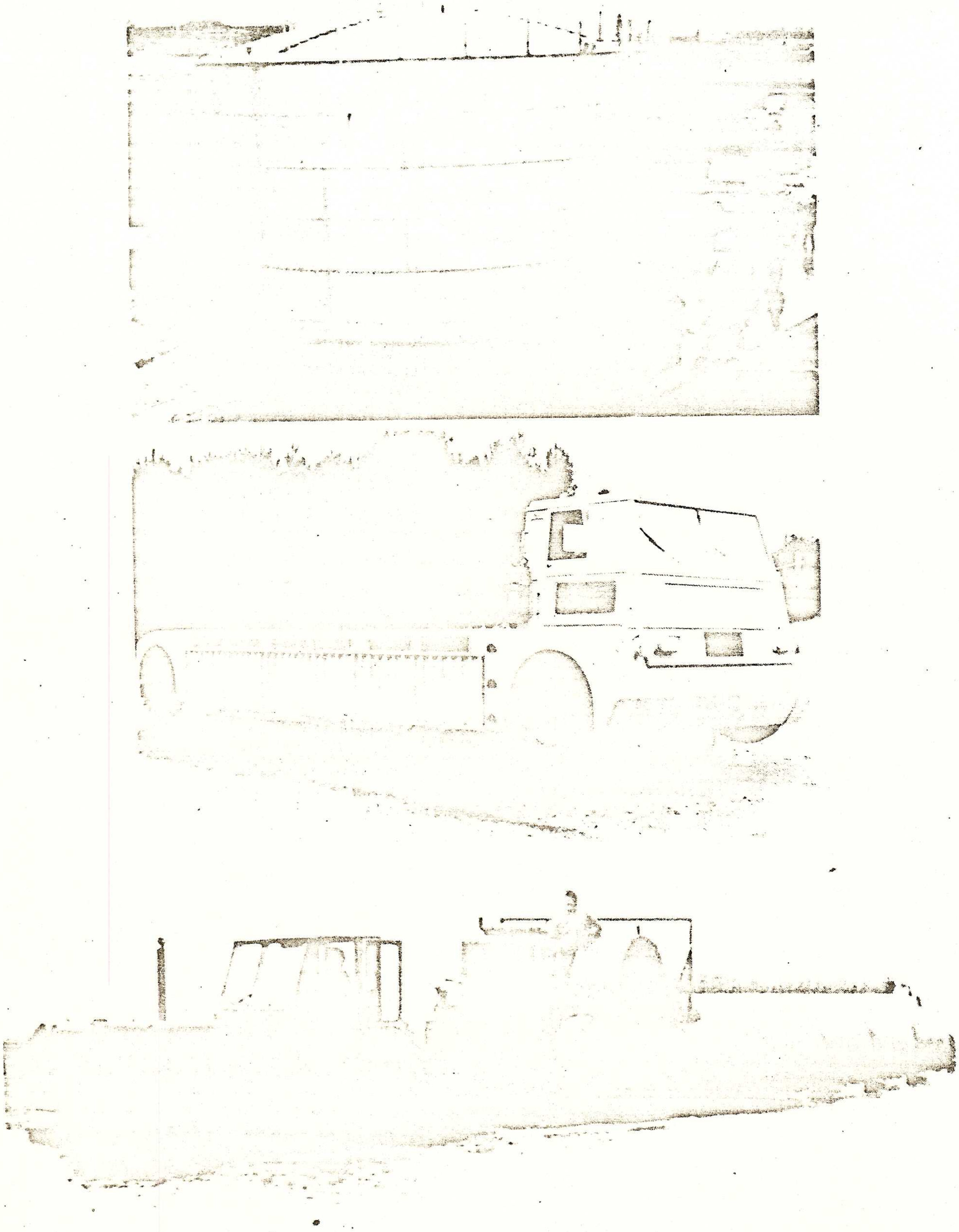


FIGURE 10 LOW SPEED APPLICATIONS OF AIR CUSHION PRINCIPLE

since 1968, when operations began, until today, the BHC SR.N4 craft (already shown in Figure 4) have absorbed over one-third of the total cross-channel traffic.* Figure 11 shows some of the British craft that are being used or have been used on commercial routes. The upper left photograph in Figure 11 shows the SR.N5 which was the first commercially successive air cushion craft and has operated on commercial routes around the world. It was constructed in 1963, has a nominal gross weight of 7 tons and carries 20 passengers. Its maximum calm water speed is 66 knots. It has been manufactured under license in the United States by Bell Aerospace and designated the SK-5, and in Japan by Mitsubishi and designated the SR.N5(M). In the case of the Bell construction, significant changes were made to the craft to make it suitable for military missions in Vietnam. The SR.N5 is now out of production and has been replaced by the SR.N6 (upper right photograph) which is a 9-ton craft carrying 38 passengers. It has a maximum calm water speed of 60 knots. The SR.N6 is currently in successful commercial operation at the present time in England and in other parts of the world. In 1973 BHC developed a twin propeller version for improved control and lower noise. BHC is developing this craft with different "Mark" versions to continue its improvements. Such improvements include a stretched variant to increase its payload capability; a deeper skirt to improve rough water performance and other variants to make it suitable for cargo missions and for military use.

Three other craft that illustrate the type of intermediate speed craft developed in England are also shown in Figure 11. The middle left photograph shows the HM-2 built by Hovermarine Transport Ltd. This company has its beginnings in the early '60's with the Denny sidewall craft and gradually developed the more successful craft shown in Figure 11. The company is now a subsidiary of Hovermarine Corporation (USA). The HM-2 is a sidehull craft again of which there are several "Mark" verions. In its standard version it has a gross weight of 21 tons and carries 65 passengers at a calm water speed of 35 knots. It has seen successful commercial operation on short naval routes in Europe and South America with plans for operation in Australia and Canada and other countries.

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* On 16 August 1974, Hoverlloyd, one of two air cushion craft operators across the English Channel, carried their 500,000th vehicle on an SR.N4. Over 3,100,000 passengers have been transported across the Channel to date.

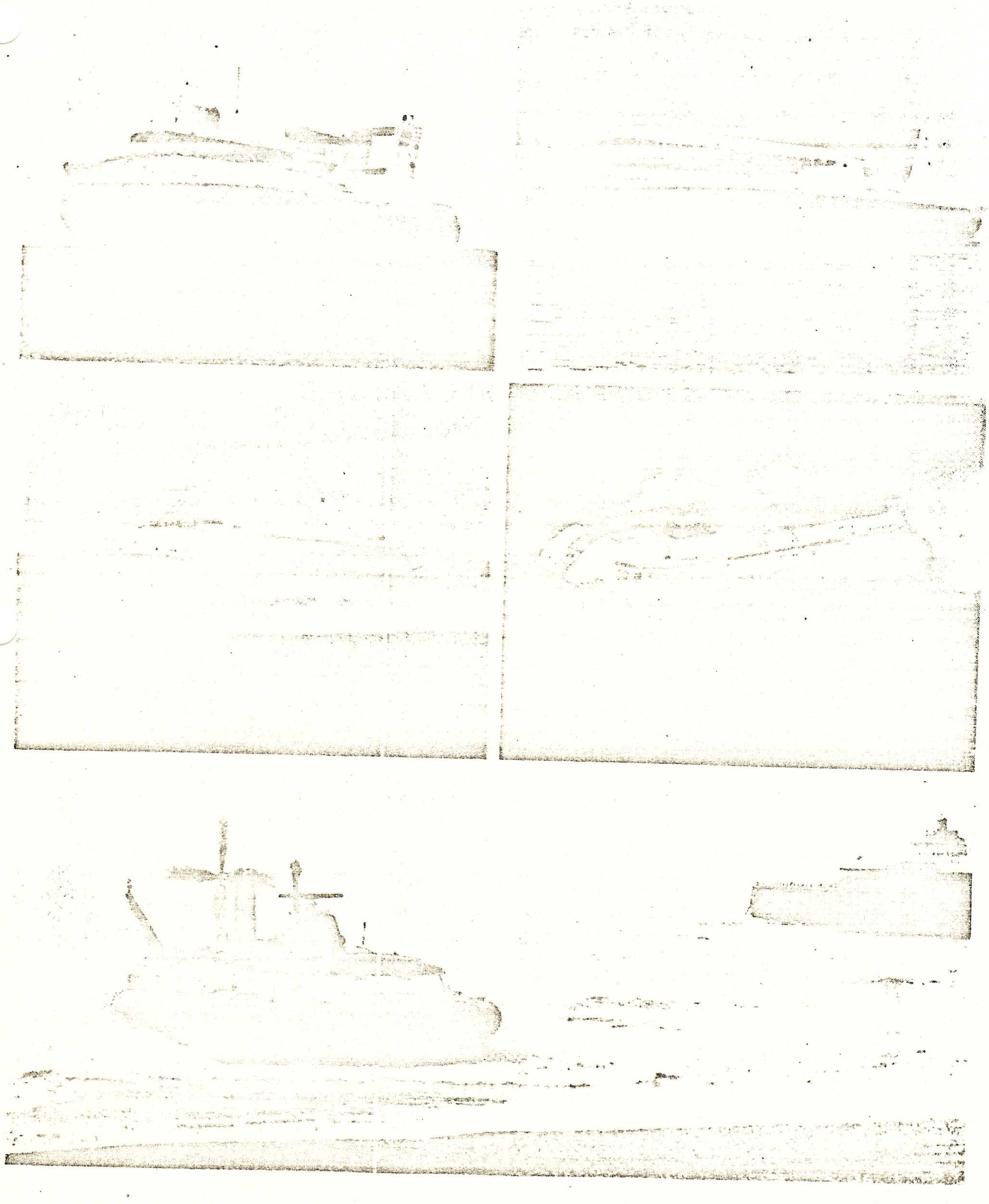


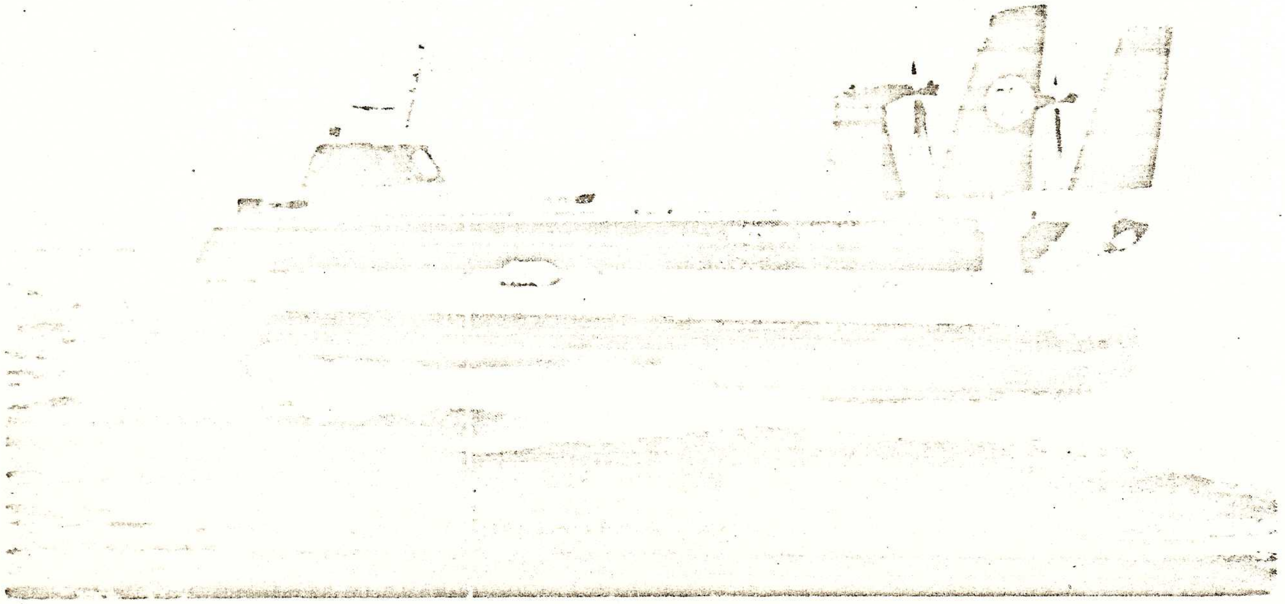
FIGURE 11 BRITISH AIR CUSHION CRAFT

The middle right photo in Figure 11 shows the Vosper-Thornycroft VT-1. Three such craft were built and were operated albeit unsuccessfully economically on commercial routes in the Channel Islands off the coast of France and in Sweden and Denmark. The reasons for the operations demise can be attributed to non-air cushion craft reasons. The VT-1 is unique in that its cushion system is that of a pure plenum as described in Figure 3 but used marine propulsion. It was argued that for its intermediate speed region of operation (30-40 knots) the quietness and high efficiency of the marine propeller gave it an economic advantage.

The lower photograph in Figure 11 shows the BH.7 on a demonstration run up to the beach at Brighton at the 1974 International Hovercraft and Hydrofoil Conference and Exhibition. The BH.7 built by British Hovercraft Corporation is specifically designed for military missions. The first of three craft was launched on 31 October 1969. It has a nominal gross weight of 45 tons and has accommodation for 70 fully equipped troops. Its maximum calm water speed is 65 knots.

Two other craft that are representative of commercial operation are the Japanese craft, the Mitsui MV-PP-15 and the French SEDAM N 300. These are shown on Figure 12. In the upper photograph can be seen the MV-PP-15 which is a 55-ton craft carrying 155 passengers. This craft with a calm water speed of 65 knots modeled after the British BHC series operates regularly among the islands in Japan. Reference 1 provides more details on the different Japanese craft either in operation or planned for the near future. A unique feature of the Japanese craft is the use of "water rods" or in the case of MV-PP-15, retractable wheels which give precise control in water by alternately dragging them in the water to generate the desired turning moment.

In the lower photograph the N300 represents the French success with its unique skirt system and is the result of development of the air cushion principle in France by the Bertin Company. It is currently operating on routes in southern France and has a gross weight of 28 tons and carries 80 passengers. Plans are underway to place a larger version, the N500,



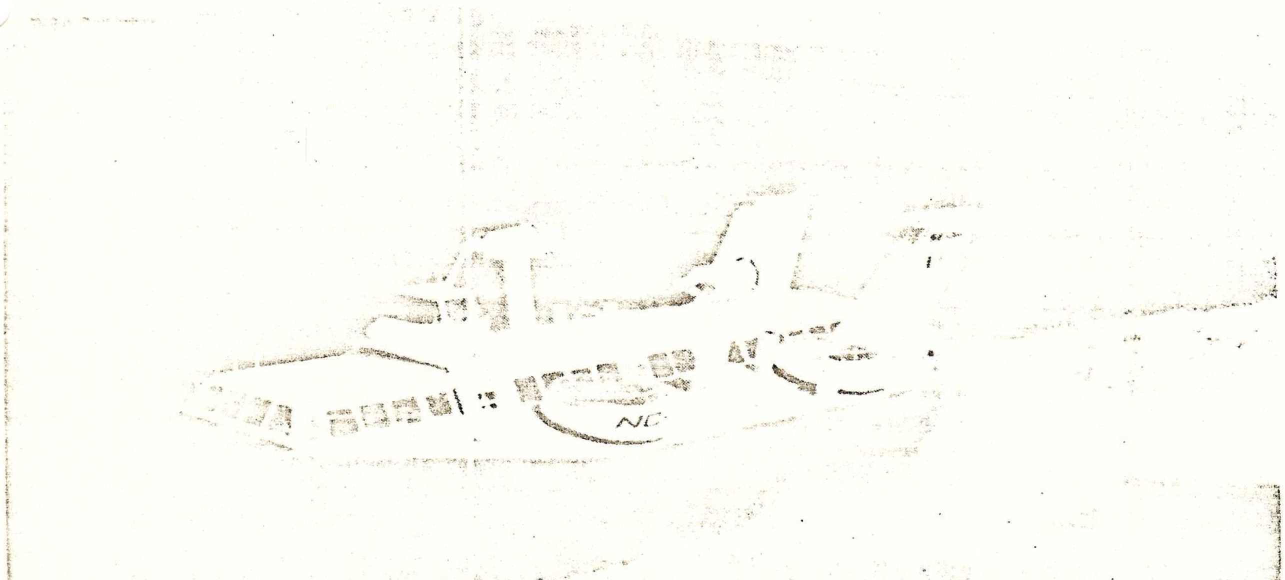


FIGURE 12 JAPANESE AND FRENCH AIR CUSHION CRAFT

which is a 236 ton craft capable of carrying 200 passengers and 60 cars at 70 knots on the English Channel operation in competition with the SR.N4. An interesting account of the history of the development of the N300 and of French air cushion craft in general was given by Monsieur Bertin to the Isle of Wight branch of the Royal Aeronautical Society in 1970 (Reference 11).

Referring to Figure 9 where the main groupings of world-wide developments have been categorized, it is felt that the above brief description summarizes the significant examples of the British, French and Japanese achievements. These craft all represent a class of vehicles designed to be economically efficient in the 30-60 knot speed range and can be categorized as low density craft (30 to 50 lb/sq ft).

In the United States almost the entire development, with some notable exceptions, have been geared to developing high speed, high density craft. Historically, it can be said that in the early 60's several companies were exploring a range of forms of air cushion craft including plenum, sidehull, recirculation, labrinth seal and other forms. Curiously, the interest in both commercial and military circles waxed and waned depending upon the success and failures of the various projects. Some of these projects were privately financed while others were the result of U. S. Government studies to determine the feasibility of air cushion craft. Both the Office of Naval Research (ONR) and the (then) Bureau of Ships, began studies for military applications. The most successful venture during this early period was the BUSHIPS-sponsored SKMR-1 designed and built by Bell Aerospace Company (then Bell Aerosystems Company) which saw its debut in 1963. At that time it was the largest craft in the United States with a gross weight of 22-28 tons depending on payload and a calm water speed of 70 knots. Figure 13 shows the SKMR-1 in both its original un-skirted form (upper photograph) and its later configuration fitted with 4-foot skirts. The SKMR-1 provided considerable basic information on both the technical aspects of aerostatic air cushion craft design as well as its use in military operations (see for example Reference 12) and much of the original military interest stemmed from this program.

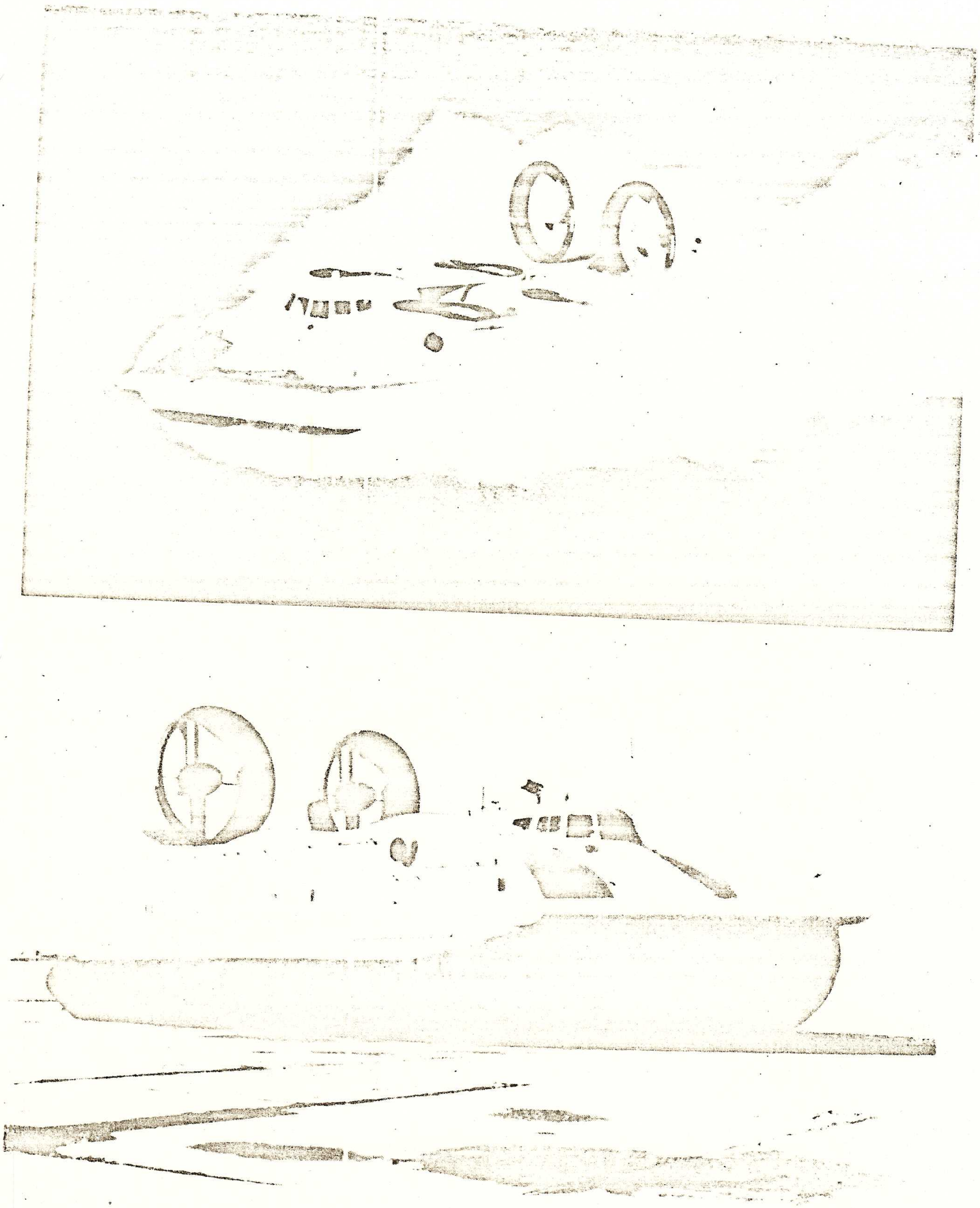


FIGURE 13 SKMR-1 WITH AND WITHOUT SKIRTS

The commercial interest in the U.S. Government began with the Maritime Administration that followed on with the original ONR studies and in 1961 began the Columbia project (Reference 13).

A key event in the development of the air cushion craft in the United States occurred in 1965 when the work being done by both industry and Government were brought together to discuss and review the different forms and basic principles and to recommend which form on which to continue development. The Surface Effect Ships for Ocean Commerce (SESOC) Committee met with industry and Government representatives at King's Point, throughout October-December 1965. The result of these reviews was the formation of a joint program between the U.S. Navy and the Department of Commerce and as a result, the Joint Surface Effect Ship Program Office (JSESPO) was set up in 1966 to develop the high-speed sidehull SES form of air cushion craft. The ultimate goal was to develop a 4000-ton class high density, high speed air cushion ship capable of cruising at 80 knots and crossing the Atlantic non-stop. Further discussion relative to this development may be found in Reference 14. By 1970 it became clear to the Maritime Administration that significant development would be required to achieve this size of craft, while it was equally clear that definite military advantage existed in the smaller sizes. Accordingly, at that time, the program became a fully U. S. Navy program administered by what then became SESPO. In mid-1974 this became PMS 304 as part of the new Naval Sea Systems Command. The two most visible products of this program are the Aerojet SES-100A and the Bell Aerospace SES-100B both high density (100 lb/sq ft), high speed (80 knots) test craft of the sidehull SES form discussed earlier.

A second key development, based on U. S. Navy and Marine Corps studies in the 1965-70 period involves the application of the air cushion principle to improved landing craft. More detailed discussion of this development may be found in References 15 and 16. Two such craft are currently under construction; they are the Aerojet JEFF(A) and the Bell Aerospace JEFF(B) again both high density craft (approximately 100 lb/sq ft) and capable of high speed. In the case of the JEFF craft, performance is stated as 50 knots in Sea State 2 on a hot day.

These four craft are shown in Figure 14 and represent the significant developments proceeding by the U. S. Navy on the amphibious form of air cushion craft.

In addition to these military developments the commercial craft, the Voyageur and Viking, built by Bell Aerospace Canada in association with the Department of Industry, Trade and Commerce of the Government of Canada are indicative of potential development in the commercial field. These craft (Figure 15) are derivatives of the Bell SK-5 craft and the original British Hovercraft Corporation designs. Since a major problem of the intermediate speed craft developed so far is one of high cost, the attempts at low cost through use of modular construction and standard components (note the conventional truck cabs for operators in both craft) can be seen in these latest developments.

2.2.3 High Speed Development

There have been sporadic developments around the world on the development of air cushion craft designed to be efficient at speeds in excess of 100 knots. The early work by Kaario in 1935 has been mentioned. Other developments include the Japanese Kawaski KAG-3 ram wing, the Lockheed winged hull, the MaRad/Vehicle Research Corporation VRC-1 and Lippisch's Aerofoil Boat. It is reported (Reference 1) that the USSR is developing a 300 mph troop transport that operates in ground effect.

From the above brief summary it is seen that by and large, the development of the air cushion craft has concentrated in providing short haul craft based on the amphibious form, with an increasing amount of development in the U.S. Navy for the large, long-haul non-amphibious craft. Further as the development, interest and funds expand, important off-shoots are beginning to form to explore other uses and forms of the air cushion craft.

FIGURE 14 U.S. NAVY HIGH DENSITY AIR CUSHION CRAFT

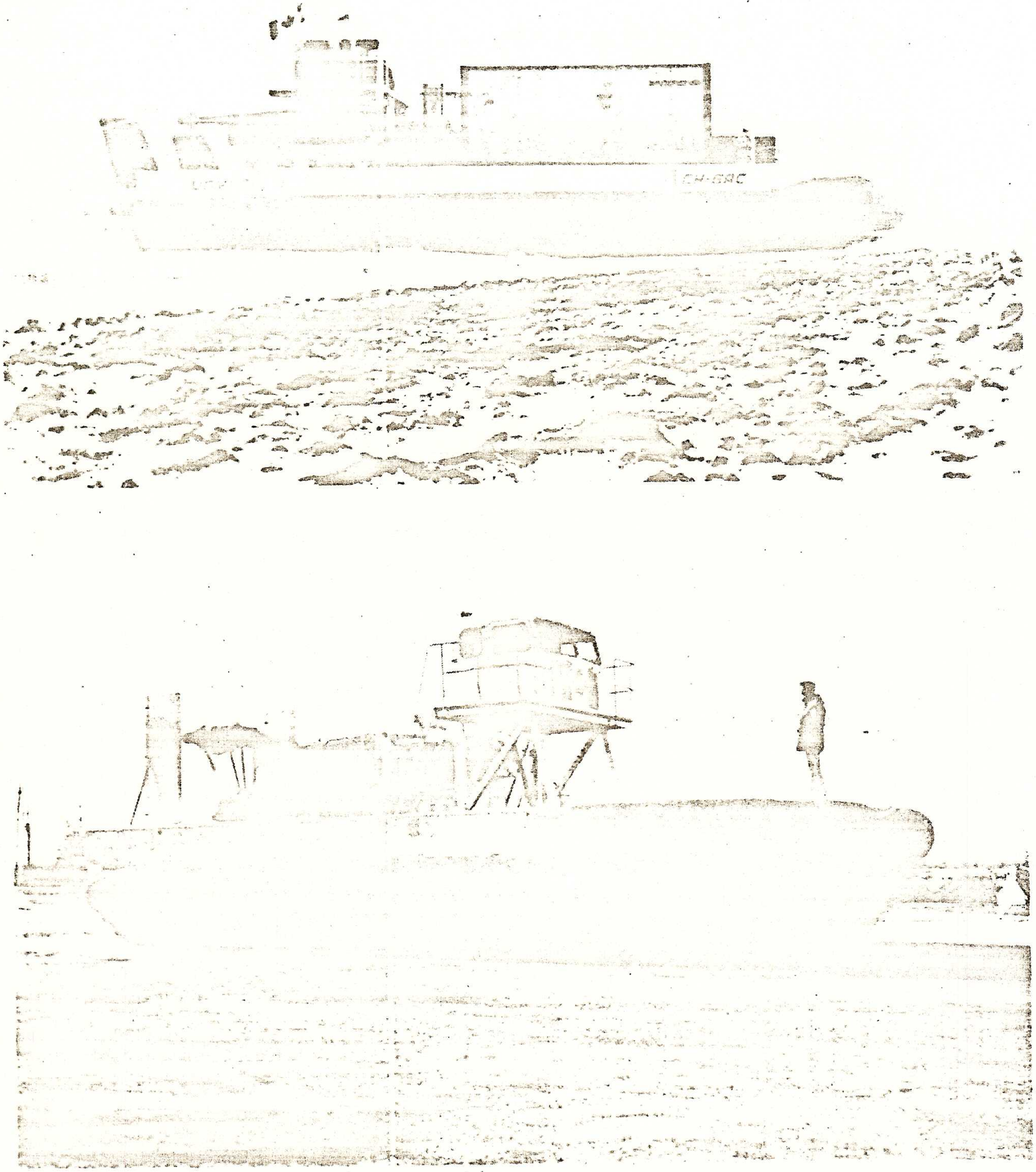


FIGURE 15   BELL CANADA VOYAGEUR AND VIKING

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