FORTY-PLUS YEARS OF HOVERCRAFT DEVELOPMENT

By

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ABSTRACT

The paper discusses the current world-wide state of development of hovercraft including Air Cushion Vehicles (ACVs) and Surface Effect Ship (SES) in their commercial and military applications. Included are accounts of developments of historical importance, with descriptions of current designs and subsystem technologies. Technologies discussed include those concerned with hull structure, resistance, propulsion, cushion seals, lift systems, stability, wake, seakeeping and maneuvering.

After more than 40 years of dedicated development, the design and construction capabilities can be considered mature. While much of the technology was developed in North America, Europe and the Far East have established the competitive viability of commercial applications.

The military applications have been well recognized here and in both Europe and Russia and perhaps it is not too late for North America to also realize the commercial potential of the ACV and SES technology that we helped to introduce.

1.0 INTRODUCTION

Air cushion supported craft, referred to as hovercraft, include amphibious Air Cushion Vehicles (ACVs) and non-amphibious Surface Effect Ships (SES). After more than 40 years of dedicated development, hovercraft technology can now be considered to be mature. The established techniques for design, performance prediction and model testing are credible and reasonably well documented. This development has occurred during the period of extensive expansion in electronic computers and computational techniques that have benefited our understanding of the technology of both conventional and advanced craft alike. Thus, both conventional and advanced craft have emerged from the dark ages together.

Although variants and hybrids have been successfully demonstrated, least risk hullforms or configurations have been established for both ACVs and SES. A consistent pattern for the selection of seals, lift systems, and propulsors has emerged, while the feasibility of steel, aluminum and single-skin or cored FRP construction has been amply demonstrated.

The U.S. Navy's program for the quantity production of Landing Craft, Air Cushion (LCACs) is a good example of ACV technology that has been successfully applied. Here the ACV was chosen to perform a function for the Marine Corps that virtually no other craft could perform. Similar examples exist with the Canadian Coast Guard's use of SR.N6s and AP.1-88 ACVs, and the UK's SR.N4 cross-channel ferries which have been in service for 30 years.

The recent examples of ACV technology, the ABS M10, the Textron C-7, the Griffon 400TD and the Westland Dash 400 are clearly very impressive examples of where the development has taken us.

Similarly, for SES has been the success of the Hovermarine HM series of passenger ferries of which over 100 were built. Focus for SES today is more towards larger sizes with the Royal Norwegian navy's MCM vessels and Japan's Techno Superliner, TSL A70 leading the way. However, in proposing applications, military or commercial, risks must be realistically assessed. Today, state-of-the-art is 1500 tons displacement for SES. Based on world experience, it would be reasonable to propose development of military or commercial SES, of up to 20,000 tons if the design and all components are essentially state-of-the-art and the potential benefits, economic or military, justify the risk associated with simply increasing size (and cost).

SES and ACVs can achieve very high speeds economically. This is possible because of the much lower power required for such speeds compared to conventional craft, but this entails a somewhat higher initial cost. This economy of operation will improve further as the size of these craft increases.

2.0 HISTORY OF CRAFT DEVELOPMENT

2.1 Early Endeavors

There have been numerous attempts over the years to utilize pressurized air, in one form or another, to reduce the resistance of marine vessels and land vehicles. Many of these attempts have been documented by way of patents. Some of these were reduced to practice with varying degrees of success. Some were in the form of improvements made on the works of earlier inventors while others were isolated developments that faultered often due to a lack of funding.

Table 1 is a list of some of the more significant inventions derived from a patent search of prior art or otherwise derived from the information reported in References 1 through 12. The dates shown are the dates of the first application of the patent in each case. Therefore, several, if not many, years of development would have likely to have taken place before the date shown for the inventor's first patent in each case.

The earliest entry in this table is 1716 and there are a total of 30 entries preceding the significant pioneering developments of Sir Christopher Cockerell which were the impetus for modern development and which were first patented in 1955.

Not all of the inventors are listed here (Table 1), since many did not patent their hovercraft or air lubricated hull ideas. Names such as Ivanov (1853), Froude (1865), Kabachinski, Labshin, Loitsyanski, Fedyaevski, Tsiolkovski (1927), Levkov (1927), & Turkin (1953) have been mentioned (Reference 12) in this regard and add another nine to the list of 30 occurring before 1955.

Perhaps, some of the more intriguing contributions were those that featured flexible seals or skirts to help contain the cushion of pressurized air. There were at least eight inventors, starting in 1908 as shown in Table 1, who had this idea long before the British SR.N1 was fitted with a flexible seal in 1960. Of, perhaps, particular interest are the patents by Worthington, USA, 1908; Porter, UK, 1908, Breguet, France, 1922; and Cristadoro, USA, 1942.

Worthington (U.S. Patent 936,395) described an air cushion support for a streetcar and used "flexible" end seals to contain the air cushion at the front and rear of the car. Porter (U.S. Patent 1,123,589) on the other hand, devised a flying machine with an inflated flexible peripheral curtain to surround and trap air supplied to the underside of the machine. Breguet (British Patents 187,627 and 193,005) also used flexible fore and aft seals to trap pumped air for a double hull/fuselage flying boat to assist take-off and landing over land and water. The arrangement is illustrated in Figures 1 and 2. Cristadaro, out of Ventre, California, (U.S. Patent 2,322,790) also presented a vehicle with flexible end seals. In this case, it was an air-screw-propelled marine vehicle with rigid sidehulls that also featured an inflatable transverse flexible seal amidships to divide the cushion and improve longitudinal stability. The inflated bow seal was also said to protect the hullform from slamming loads. The description given about the operational behavior of the vessel in calm and rough water would strongly suggest that the concept had actually been reduced to practice.

Others who considered flexible seals included Fletcher, USA, 1953; Beardsley, USA, 1957 (U.S. Patent 3,342,280), Figure 3; Bertelsen, USA, 1958, Reference 11; and McCreary, USA, 1960 (U.S. Patent 3,532,179).

Table 1. Early Hovercraft-Related Patents

Date of Patent	Name and Location	Subject
1716	Swedenborg, E., Sweden	Plenum Craft Illustration
1876	Ward, J., San Francisco, USA	Plenum Machine Idea
1880	Girard, L., France	Rail Car
1882	De Laval, G., Sweden	Air Lubricated Hull
1888	Walker, J. Texas, USA	Air Lubricated Hull Idea
1889	Barre, M.C.A., France	Rail Car
1897	Culbertson, USA	Sidewall Craft Idea
1902	Therye, C., France	Rail Car
1906	Schroeder, F.W., Germany	Air Lubricated Hull Design
1907	Clark, J., USA	Craft With Annular Ducts
1908	Worthington, C. USA	Rail Car With Flexible Seals
1908	Porter, J.R., UK	Annular Jet Craft With Flexible Skirt
1909	Wunderlich, A., Germany	Plenum Craft
1912	Alcock, A.U., Perth, Australia	Levapad Craft
1913	Eells, A.F., USA	Rail Car
1916	Von Thomamhul, D.M., Austria	Air Lubricated Torpedo Boat
1921	Gambin, M.A., France	Sidewall Craft
1922	Breguet, L., Paris, France	Plenum Craft With Flexible Seals
1922	Trask, F.G., North Dakota, USA	Rail Car
1925	Casey, V.F., Minneapolis, USA	Air Lubricated Hull With Air Recirculation
1927	Tsiolkovski, K.E., Russia	Rail Car
1928	Nicin, V., Dresden, Germany	Plenum Car Giving Reduced Wheel Load
1928	Warner, D.K., Sarasota, USA	Sidewall Craft
1935	Birrard, J., France	Sidewall Craft Design
1935	Kaario, T.J., Finland	Plenum/Ram Wing Craft
1942	Cristadoro, C.C., Ventre, CA, USA	Sidewall Craft With Flexible Seals
1944	Brian, W.S. & Birk, F.J., Owensboro, KY, USA	Sidewall Craft
1952	Bondat, A.J., France	Snow Skis With Multi-Plenum Air Cushions
1954	Seck, W.G., Canton, Ohio, USA	Hovering Vacuum Cleaner by Hoover Co.
1955	De Lima, R.A., Brazil	Peripheral Jet and Aircraft Landing Gear
1955	Cockerell, C., UK	Peripheral Jet and Sidewall Craft
1955	Roe, A.V., Canada	Peripheral Jet Craft
1957	Beardsley, M.W., Severna Park, MD, USA	Craft With Peripheral Jet & Membrane Sheet
1957	Weiland, C., Switzerland	Craft With Labyrinth Seal
1957	Bertin, M., France	Craft With Multi-Cell Plenum
1958	Jay, D.J. & Pelthman, H.W., USA	Craft With Multi-Plenum
1958	Latimer, C.H., Needham, UK	Craft With Flexible Skirt
1958	Petersen, T.K. & Smith, P.L., Tulsa, OK, USA	Cargo Handling Conveyor
1959	Gaska, C.W., Michigan, USA	Craft With Flexible Skirt
1959	Vaughen, J.F., Irving, Texas, USA	Hover Pallet With Flexible Seals
1960	Ford, A., USA	Sidewall SES
1960	Hurley, R.T. & Agni, E.S., USA	Sidewall Craft
1960	Mackie, H.A. & Veryzer, R.W., USA	Wheel Barrow With Flexible Skirt
1960	McCreary, N.B., Arkansas, USA	Plenum Craft With Flexible Skirt
1962	Lewis, N.W., USA	Craft With Finger Skirt - Vertical
1962	Bliss, D.S., UK	Craft With Finger Skirt - Inclined

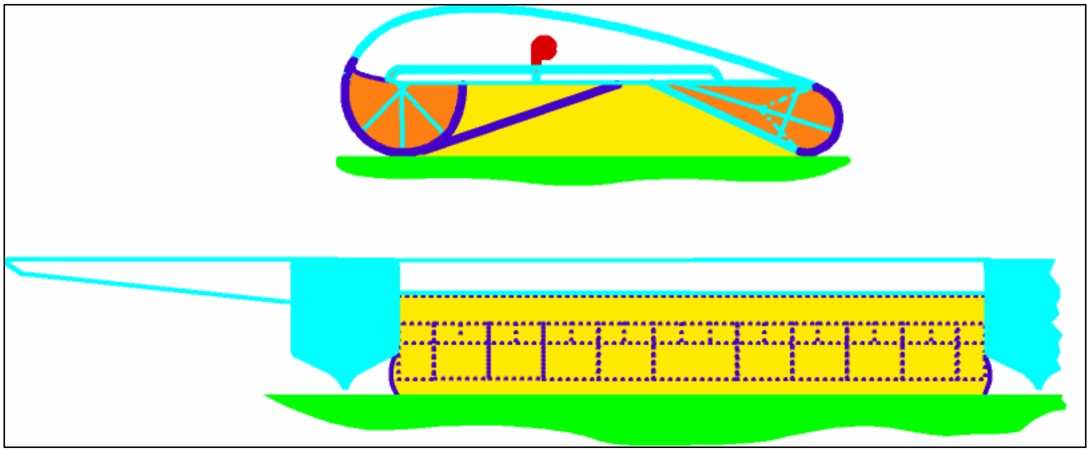

Figure 1. Flexible End Seals by Breguet, France, 1922

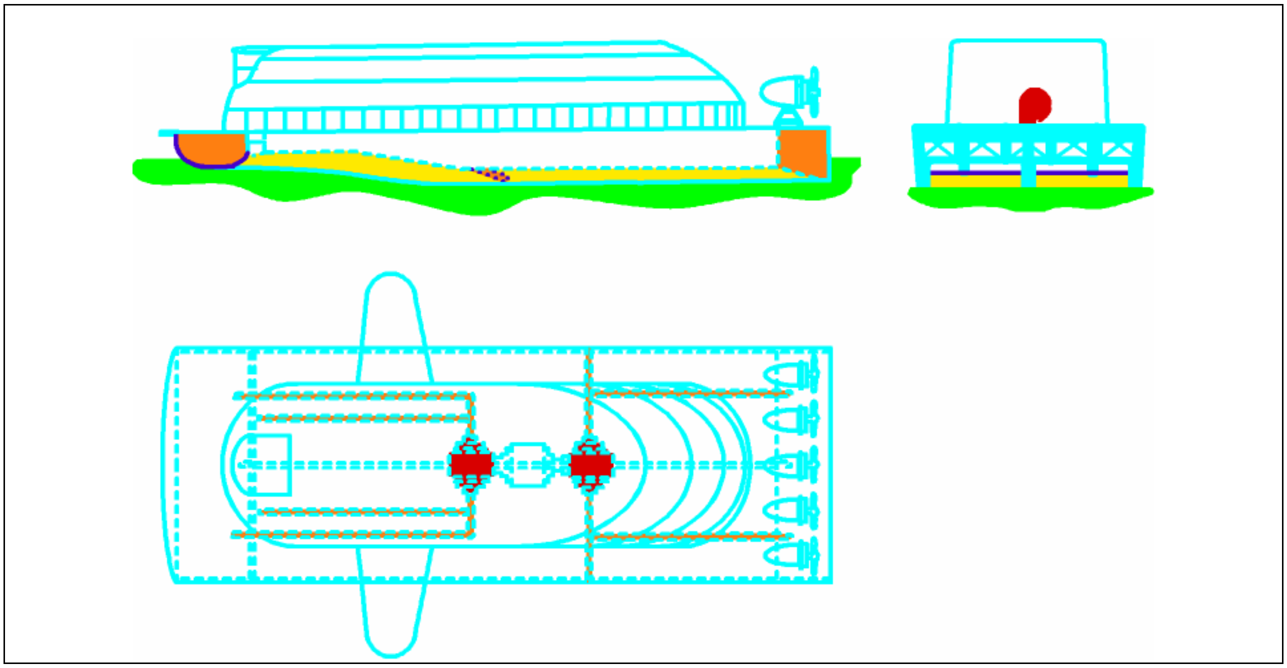

Figure 2. Flexible End Seals and Cushion Divider by Cristadoro, USA, 1942

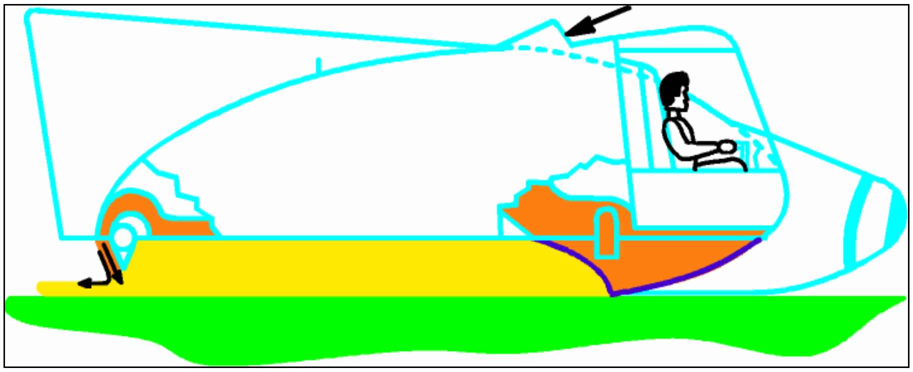

Figure 3. Flexible Bow Seal by Beardsley, USA, 1957

By 1955, there had already been considerable interest in VTOL aircraft, particularly, in the USA and Canada. The effect of the proximity to the ground on the vertical thrust of an ordinary jet and of an annular jet when directed vertically had been explored and led naturally to the development of the GEM or Ground Effect Machine.

Many large North American companies including General Motors, Ford, Curtis-Wright, Convair, Martin and Bell in the U.S. and A.V. Roe in Canada, saw the potential of the commercial exploitation of this effect and, by 1959, the Curtis-Wright Company had already built a prototype air car and that even featured an 8-inch flexible skirt.

2.2 Modern Craft Developments

In this next section of the paper some of the major developments are reviewed to illustrate the wealth of technology and operational experience that has now been gained worldwide since these early days in the commercial and military applications of ACVs and SES. Estimates of total craft constructed to date vary with the sources, the highest being over 1000 SES and ACVs combined. Tables 2 and 3 show, respectively, the leading particulars of 442 of the most prominent ACVs and 318 of the most prominent SES, that have been built.

2.2.1 Commercial ACVs

Modern developed of amphibious ACVs stemmed from the research, starting in 1953, of the British inventor Sir Christopher Cockerell who, in conjunction with Saunders-Roe Ltd and with sponsorship of the British Government, built the SR.N1 in 1959.

In 1961, Saunders-Roe, which became the British Hovercraft Corporation♦ (BHC) and much later GKN Westland, produced the 76-seat, 27-ton, SR.N2 research craft/passenger ferry which reached a speed of 70 knots.

The early ACVs (British SR.N1 and U.S. Bell Hydroskimmer XHS-4, for example), operated initially without flexible skirts, but the advantages of these skirts quickly became evident. The evolution of the skirt was extremely rapid, with numerous configurations being evaluated. Some of the earlier skirt designs were far more complex than those in use today.

The first full-scale series production of ACVs began with the 18-seat SR.N5 in 1964 and serious commercial operations first became feasible when the British 38-seat SR.N6 entered service in 1966. The SR.N6 was produced as a stretched version of the SR.N5. Sixty-five of these craft were built.

By the late 1960's, two more British companies were developing commercial ACVs: Britten-Norman, who produced the very-low-noise-level, lift-fan propelled, CC-5 and CC-7 series of small craft and Vosper Thornycroft, who produced the large, marine-screw propelled, VT-1 passenger ferry, which was later converted to airscrew propulsion.

By the early 1970's, Japan, France, Canada and several additional British companies were involved in commercial ACV development.

The British Hovercraft Corporation's SR.N4 series of passenger/car ferries, first launched in 1968, were the largest commercial self-propelled ACVs built. Six of these have been in operation across the English Channel with over 27 million passengers carried in the first 17 years. Two of the six SR.N4 MK2s were stretched to a 300-ton MK3 configuration in 1978.

By the late 1970's, France had produced their two large 285-ton N500 ferries for the English Channel route. One has since been destroyed by fire and the other deactivated.

The introduction in 1982 of BHC's diesel-powered AP.1-88 represented a milestone in the ACV industry's efforts to produce a cheap and commercially viable ACV. While BHC was the design authority, a joint agreement, between BHC, Hovertravel Ltd, and the British Government, resulted in a pooling of considerable ACV technology and experience. Recently the design has been enlarged to produce the DASH 400, the latest ACV built, now in service this year with the Canadian Coast Guard, Figure 4.

Development of commercial ACVs in Russia, starting in the 60's, has concentrated on large, heavy-lift hoverbarges and on small utility craft for the transport of 5 to 15 passengers or light cargo.

These developments have been driven by requirements for vehicles capable of operating on

♦ A division of Westland Aerospace, Ltd, Yovel, UK.

the ice, snow and vast marsh areas of the Russian North, Far East and Siberia. Russia's main sources of minerals, oil and natural gas are located in these regions. Some 80% of the gas and petroleum sites in Western Siberia are located amidst swamps, salt marshes, tundra and shallow water which are impassable to conventional vehicles.

Finland also produced the prototype PUC-22 amphibious mixed-traffic ferry, designated Laurus. This craft was ordered by the Finnish Board of Roads and Waterways from the Oy Wartsila Helsinki shipyard in 1980. The craft was delivered in 1982.

Table 2. Leading Particulars of Prominent ACVs

Name	Builder	Country	Launch Year	No. Built	Hull Material	Length Overall (ft)	Beam Overall (ft)	Max. Speed (kts)	Role
SR.N1	Saunders Roe (BHC)	UK	1959	1	Al Alloy	31.40	25.00	23.00	Experimental
SR.N2	Saunders Roe (BHC)	UK	1961	1	Al Alloy	65.25	29.50	70.00	Experimental, Ferry
VA-3	Vickers Armstrong	UK	1962	1	Al Alloy	55.00	27.00	55.00	Experimental
SK-3	Bell	US	1963	1	Al Alloy	18.70	16.00	52.00	Experimental
HD-1	Cowes Boatyard	UK	1963	1	Wood/Polyfoam	50.00	23.00	35.00	Experimental
SR.N3	BHC	UK	1963	1	Al Alloy	77.00	30.50	79.00	Military
SKMR-1	Bell	US	1963	1	Al Alloy	65.50	27.00	70.00	Experimental, Military
SR.N5	BHC	UK	1964	8	Al Alloy	38.75	23.00	60.00	Ferry, Military
SORMOVICH	Sormovo Shipyard	Russia	1965	1	Al Alloy	96.00	32.80	75.00	Ferry
SR.N6	BHC	UK	1965	57	Al Alloy	48.40	23.00	52.00	Ferry, Military
BC-8	Bertin (Sedam)	France	1965	1	Al Alloy	33.00	16.50	43.00	Crash Tender
SK5	Bell	US	1966	6	Al Alloy	38.83	23.75	60.00	Ferry, Military (Patrol, SAR)
CC5	Cushion Craft	UK	1966	1	Wood,/Al/ GRP	30.30	15.20	40.00	Experimental
HD-2	Hovercraft Dev.	UK	1967	1	Al Alloy	30.75	19.00	45.00	Experimental
SR.N4 Mk 2	BHC	UK	1968	4	Al Alloy	130.20	78.00	70.00	Ferry (Passengers, Cars)
N300 Mk II	Sedam	France	1968	2	Al Alloy	76.10	36.40	57.00	Ferry
CC7	Cushion Craft	UK	1968	Unknown	Al Alloy/GRP	25.80	15.20	40.00	Light Utility, Trainer
MV-PP5	Mitsui	Japan	1968	19	Al Ally	52.50	27.30	55.00	Ferry
LACV-30	Bell	US	1969	26	Al Alloy	76.30	36.30	40.00	Military (Cargo Trans, Patrol)
BH-7 Mk2	BHC	UK	1969	1	Al Alloy/GRP	78.33	45.50	58.00	Military (Patrol, MCM)
GUS	Leningrad Shipyard	Russia	1969	31	Al Alloy	72.11	26.40	60.00	Military
N102C	Sedam	France	1969	10	Al Alloy/GRP	33.50	25.30	60.00	Ferry, Utility Craft
T4	TTI	US	1970	1	Al Alloy	35.00	17.50	35.00	Experimental
AIST	Leningrad Shipyard	Russia	1970	16	Al Alloy	155.00	65.00	70.00	Military
VOYAGEUR	Bell	Canada	1971	4	Al Alloy	65.70	36.70	64.00	Cargo Transport
MV-PP 15	Mitsui	Japan	1972	4	Al Alloy	86.60	45.60	60.00	Ferry
EM2	Enfield	UK	1973	1	Al Alloy	40.00	21.00	45.00	Experimental
LEBED	Leningrad Shipyard	Russia	1973	35	Al Alloy	81.40	35.40	70.00	Military
VIKING	Bell	US/Canada	1974	1	Al Alloy	44.50	26.00	57.00	Patrol
VT2	Vosper Thorneycroft	UK	1975	1	Al Alloy	101.00	43.50	65.00	Military (Patrol, MCM)
N500	Sedam	France	1977	2	Al Alloy	164.00	75.50	75.00	Ferry
AALC JEFF(A)	Aerojet General Corp.	US	1977	1	Al Alloy	96.10	47.80	65.00	Experimental, Military
AALC JEFF(B)	Bell	US	1977	1	Al Alloy	86.70	47.00	70.00	Experimental, Military
PRC 711-IIA	Liu Zhou Shipyard	PRC	1978	1	Al Alloy	43.60	19.60	40.00	Experimental
SR.N4 Mk3 (Super 4)	BHC	UK	1978	2	Al Alloy	185.00	92.00	65.00	Ferry (Passengers, Cars)
PRC 722	Dagu Shipyard	PRC	1979	1	Al Alloy	89.30	45.30	55.00	Experimental
TIGER 12	Air Vehicles Ltd	UK	1980	5	Al Alloy	27.00	13.00	35.00	Military (C&R), Utility Craft
LARUS PUC 22	Wartsila	Finland	1981	1	Al Alloy	108.30	48.20	23.30	Ferry
UTENOK	Feodosiya Shipyard	Russia	1982	2	Al Alloy	88.90	44.00	65.00	Military
TSAPLYA	Feodosiya Shipyard	Russia	1982	2	Al Alloy	87.90	44.00	50.00	Military
SAVR-2	MTI	Russia	1982	Unknown	Al Alloy/GRP	33.10	15.20	27.00	Utility Craft
AP.1-88	BHC	UK	1982	10	Al Alloy/GRP	80.00	36.10	50.00	Ferry, Trainer
PRC 7210	Wu Hu Shipyard	PRC	1983	2	Al Alloy	34.50	15.20	22.00	Utility Craft
G1000 TD	Griffon Hovercraft Ltd	UK	1983	5	Al Alloy	28.20	15.00	35.00	Utility Craft
G1500 TD	Griffon Hovercraft Ltd	UK	1984	3	Al Alloy	34.30	15.00	33.00	Ferry, Utility Craft
PRC 716 II	Hudong Shipyard	PRC	1984	1	Al Alloy	60.70	11.20	43.20	Ferry, Cargo Transport
LCAC	Bell/Avondale	US	1984	93+	Al Alloy	88.00	47.00	50.00	Military
2500 TD	Griffon Hovercraft Ltd	UK	1985	2	Al Alloy	49.20	23.00	40.00	Ferry
PELIKAN	Unknown	Russia	1985	2	Al Alloy	288.40	144.90	50.00	Military (MCM)
G2500 TD	Griffon Hovercraft Ltd	UK	1985	2	Al Alloy	48.70	19.50	31.00	Ferry, Workboat
PUMA	V/O Sudoexport	Russia	1985	5-10	Al Alloy	41.25	17.58	35.00	Ferry, Ambulance
SAVR-3	MTI	Russia	1985	Unknown	Al Alloy	Unknown	Unknown	27.00	Agriculture
TIGER 16	Air Vehicles Ltd	UK	1985	3	Al Alloy	38.10	13.90	33.00	Ferry, Utility Craft
SAH 2200	Slingsby Aviation	UK	1986	25+	GRP/Kevlar	40.60	Unknown	40.00	Supply, Logistic Support, Ferry
POMORNIK	Leningrad Shipyard	Russia	1986	3	Unknown	183.50	72.00	55.00	Military
VCA 36	Chaconsa	Spain	1986	1	Al Alloy	82.60	36.20	60.00	Military
SURVEYOR 12D	Air Cushion Enter.	N. Zealand	1986	2	Al Alloy	31.10	18.00	41.00	Ferry, Utility Craft
TIGER 40	Singapore Shipbldg	Singapore	1987	1	Al Alloy	52.49	19.69	35.00	Varied
TAIFUN	UFA Aviation Inst.	Russia	1987	Unknown	Al Alloy	Unknown	Unknown	Unknown	Ferry, Utility Craft
TURK IV Mk1	KTMI	S. Korea	1988	1	Al Alloy	45.10	25.20	50.00	Ferry, Ambulance
IRBIS	V/O Sudoexport	Russia	1988	1	Al Alloy	59.16	20.96	31.00	Ferry, Utility Craft
G2000 TD	Griffon Hovercraft Ltd	UK	1989	3	Al Alloy	35.80	15.20	31.00	Ferry
TURK IV Mk2	KTMI	S. Korea	1989	2	Al Alloy	51.70	25.80	40.00	Ferry
PH 11	Hovertrans BV	Netherland	1990	2	GRP	37.20	19.30	40.00	Utility, Fire Fighter
MV-PP 10	Mitsui	Japan	1990	2	Al Alloy	78.10	37.20	50.00	Ferry
SIBIR	Gorkavski Philial CNII	Russia	1990	1	Al Alloy	82.70	38.40	43.00	Cargo Transport
4000 TD	Griffon Hovercraft Ltd	UK	1992	2	Al Alloy	58.70	24.00	38.00	Ferry
COLIBRIE	Hovertrans BV	Netherland	1993	2	FRP	37.70	18.70	37.00	Multi-Role
ABS M-10	ABS Hovercraft Ltd	UK	1994	2	FRP	61.80	28.90	50.00	Military/Workboat
C-7	Textron Marine	US	1994	2	FRP	52.50	31.20	40+	Ferry, Fire & Rescue
DASH 400	GKN Westland	UK	1998	1	Al Alloy	93.50	39.40	50.00	Coast Guard

Table 3. Leading Particulars of Prominent SES

Name	Builder	Country	Launch Year	No. Built	Hull Material	Length Overall (ft)	Beam Overall (ft)	Max. Speed (kts)	Role
D1	Denny	UK	1961	1	Wood	66.00	12.00	17.6	Experimental
D2	Denny	UK	1962	4	GRP	81.50	19.00	27 to 34	Ferry
XR-1	NAEF	US	1963	1	Wood, Al Alloy	49.00	13.50	40	Experimental
ZARYA (OPTNYE-1)	Moscow Ship	USSR	1963	Several	Al Alloy	72.30	12.90	20	Experimental
XR-1B	USN	US	1965	1	Wood, Al Alloy, GRP	49.00	19.00	35	Experimental
XR-3	USN	US	1967	1	Al Alloy	24.00	12.00	25	Experimental
HM-216	Hovermarine	UK	1968	30+	GRP	51.00	20.00	35	Ferry
GORKOVCHANIN	KSSG	USSR	1969	1	Al Alloy	73.00	13.20	19	Ferry
100B	Bell	US	1972	1	Al Alloy	77.70	35.00	94	Experimental
100A	Aerojet	US	1972	1	Al Alloy	81.90	41.90	76	Experimental
ZARNITSA	Sormovo	USSR	1972	100+	Al Alloy	73.00	13.30	33	Ferry
XR-5	USN	US	1973	1	Al Alloy	46.75	8.25	25	Experimental
XR-1D	Rohr	US	1974	1	Wood, Al Alloy, GRP	50.00	19.00	43	Experimental
ORION-01	Sosnovska	USSR	1974	Large	Al Alloy	84.60	21.30	32	Ferry
RASSVET	Sosnovska	USSR	1974	30	Al Alloy	87.00	23.30	36	Ferry
HM-218	Hovermarine	UK	1976	50+	GRP	60.00	20.00	35	Ferry]
BH-110	Bell Halter	US	1978	6	Al Alloy	110.00	39.00	30	Crew Boat
HM-2 Mk4	Hovermarine	UK	1978	5	GRP	60.00	20.00	35	Ferry and Crew Boat
TURT-II	KTMI	Korea	1978	1	Unknown	27.00	Unknown	Unknown	Experimental
RODOLF	Bell	US	1979	1	Al Alloy	48.00	24.00	33	Survey
PLAMYA	CDB	USSR	1980	1	Al Alloy	85.60	21.30	27	Fire Boat
HM 221	Hovermarine	UK	1981	6	GRP	70.00	20.00	30	Fire Boat
WR-901	Chaohu	China	1981	4	GRP	63.30	13.00	21	Ferry
MOLENES	French Navy	France	1981	1	Wood, Al Alloy	39.70	11.30	18	Experimental
HM-527	Hovermarine	UK	1982	5	GRP	89.30	33.50	40	Ferry
SES-200	Bell Halter	US	1982	1	Al Alloy	160.00	39.00	32	Experimental
TYPE 7203	DAGU	China	1982	1	Unknown	73.00	22.60	30	Ferry
KTMI-8M	KTMI	Korea	1982	1	Al Alloy	39.40	15.10	30	Ferry
LUCH	Astrakhan	USSR	1983	2	Al Alloy	75.00	12.60	24	Ferry
HALTER YACHT	Halter	US	1984	1	Al Alloy	70.00	20.00	36+	Pleasure
MARIC-717-2 and -3	DFS	China	1984	Unknown	Al Alloy, GRP	70.00	16.20	24	Ferry
MARIC-719	WS	China	1984	1	Steel, GRP	116.00	25.00	30	Ferry
CIRR-105P	Brodrene AA	Norway	1984	1	GRP	106.00	36.00	46	Ferry
KTMI-18M	KTMI	Korea	1985	5	Al Alloy	59.40	30.00	40	Ferry
KTMI 26M	KTMI	Korea	1986	3	Al Alloy	84.00	33.50	35	Ferry
CIRR-115P	Brodrene AA	Norway	1986	1	GRP	106.00	36.00	47	Ferry
CIRR-120P	Brodrene AA	Norway	1987	11	GRP	116.00	37.70	50	Ferry
JET RIDER	KkrV	Sweden	1987	2	GRP	110.00	34.00	48	Ferry
DERGACH*	KBS	USSR	1987	1	Unknown	211.60	55.80	45	Patrol*
BES 16	Bazan	Spain	1988	1	Al Alloy	55.00	17.70	35	Experimental
MARIC-719-2	Hu	China	1988	1	Steel	131.00	27.00	28	Ferry
HARPOON	Brodrene AA	Norway	1988	1	GRP	59.00	23.60	52	Experimental
KTMI-17M	KTMI	Korea	1988	1	Al Alloy	57.00	16.50	30	Ferry
AIR-RIDE 109	Avondale	US	1989	2	Al Alloy	109.00	34.00	30	Ferry
WESTAMARIN 4000	Westamarin	Norway	1989	2	Al Alloy	131.00	41.00	52	Ferry
MEKAT 150 (CORSAIR)	Blohm & Voss	Germany	1989	1	GRP	118.00	42.70	52	Patrol/Ferry
AGNES 200	CMN	France	1990	1	Al Alloy	167.30	42.60	44	ASW
SEASWIFT 23	Royal Schelde	Holland	1990	1	GRP	80.00	26.00	37	Ferry
SES-200A	Bell	US	1990	1	Al Alloy	160.00	42.60	43	Experimental
MTG - MOSES	Lurssen	Germany	1990	1	GRP, Wood	33.00	8.50	25+	Experimental
TESTRIGG (SMYGE)	KkrV	Sweden	1991	1	GRP	100.00	37.40	50	Experimental
UT 904 ACC	Ulstein	Norway	1991	4	GRP	128.00	39.40	45+	Ferry
MANTO	Scheepswerf Polyship	Belgium	1993	2	FRP	97.10	35.40	40	Ferry
OKSOY & ALTA Classes	Kvaerner Mandal A/S	Norway	1993	6	FRP	181.10	43.60	20+	Military MCM
Type 7217	Bei Hai Shipyard	China	1993	2	Steel	144.40	27.20	25	Ferry
DONG YANG GOLD	Samsung Heavy Industries	Japan	1994	1	FRP	119.80	40.00	50	Ferry
TSL-A70 HISHO (KIBO)	Mitsui Tamano & Mitsubishi	Japan	1994	1	Al Alloy	229.70	61.00	54.4	Experimental
UT 928	Ocean Fast Ferries Pty Ltd	Australia	1996	2	Al Alloy	126.00	38.70	48.0	Ferry

The People's Republic of China (PRC) launched the PRC 722, (DAGU-A) at Tianjin in 1979. The design was undertaken by the Shanghai Shipbuilding Research Institute, and built at the DAGU Shipyard with the assistance of some 52 other specialist engineering, technical and military groups.

The skirt configuration of the DAGU-A is very similar to that used on British hovercraft designs, and some technology has been obtained from the UK. The large loop in the bag portion has been found to give better seakeeping, improved ride, and extended skirt life. The DAGU-A is similar to a scaled-down BHC SR.N4. Four craft of the DAGU-A type are believed to have been constructed.

Commercial ACV development in the U.S. has been minimal. An exploratory SR.N5 ferry service was conducted in San Francisco Bay during the mid 60's and attempts have been made to use SR.N6s on several other routes in the U.S. However, commercial success has resulted from the development of large, heavy-lift hoverbarges and of small utility craft capable of carrying 5 to 13 passengers.

Figure 4. Canadian Coast Guard, Dash 400, by Courtesy of GKN Westland Aerospace Limited, UK

The first U.S. hoverbarge, the ACT-100, was built in 1971 by Global Marine Development, Inc. for year-round Arctic transport operations across tundra, marshland, offshore ice and open water.

The self-propelled hoverbarge D-PAAC was built in 1980 by Hover Systems, Inc. The D-PAAC was engaged in commercial transport operations in Alaska in 1980-1981, and again in 1984, over land, ice and open water. The D-PAAC was purchased in 1985 by the U.S. Army for experimental operation. In July 1985, the D-PAAC was used successfully by the Army to retrieve a Chinook helicopter which had crashed on mud-flats in New Jersey.

In terms of sheer numbers and variety, the light hovercraft industry worldwide has been phenomenal. Pindair Ltd., for example, had at one time their small inflatable hovercraft operating in 67 countries. There have been many builders of light hovercraft along the way, world-wide. UK companies who have remained in business include Air Vehicles Ltd (1968) with their Tiger series of light hovercraft; Griffon Hovercraft Ltd (1976) with their successful TD-series of small to medium size craft (their largest, the 4000 TD is shown in Figure 5), and Ingles Hovercraft Ltd with their River-Rover series. In the U.S., Textron Marine & Land Systems (TM&LS) the principal builder of the U.S. Navy's LCAC, also entered this market in 1994 with the C-7 Executive Transporter, Figure 6. Another version has entered service as a fire-fighting/rescue craft at Changi International Airport, Singapore. Applications of these and other inexpensive craft have included police duties, fire-fighting duties, airport crash-rescue, hovering doctor services, military firing range bomb disposal duties, geological surveying, seismic surveying, logistics, passenger ferries, construction site personnel carriers, pest control, agricultural spraying activities and oil rig support duties, etc.

Figure 5. Griffon 4000 TD, Courtesy of Griffon Hovercraft Ltd, UK

Figure 6. C-7 Executive Transporter, Courtesy of Textron Marine & Land Systems, USA

An even much larger number of recreational ACVs have been built both commercially and privately. There are at least 24 independent hoverclubs throughout at least ten countries, while the Hoverclub of America Inc., headquartered in Foley, Alabama, 36436, (P.O. Box 980), has 12 branches in the U.S. and three more overseas. Hoverclubs exist to encourage the construction and operation of light, recreational ACVs by private individuals, schools, colleges, universities, and other youth groups. In the United Kingdom and the United States, local and national race meetings are held each year at which as many as 60 or more light ACVs compete for championship points. According to "Jane's High-Speed Marine Transportation," [6], a growing activity within the various hoverclubs has been the pastime of hovercruising which involves traveling by single, or more usually, multiseat light ACVs along rivers, canals, lakes or coastlines, thus offering the ability to explore areas which are not accessible by other means of transport.

By virtue of the numbers of craft involved, it is not surprising that many innovative ideas are explored and valuable experience gained from a very large number of operating hours each year. The ACV industry would do well to monitor this activity closely.

2.2.2 Military ACVs

The development of military ACVs in North America can be traced back to Harvey R. Chaplin, who published the first mathematical description of the peripheral jet phenomenon in 1957 at the David Taylor Model Basin (DTMB).

In 1963, Bell launched the SKMR-1 for the U.S. Bureau of Ships. This craft was the largest ACV then built (68 ft by 32 ft) and was operated at 70 knots. Using twin shrouded propellers for the first time on an ACV, SKMR-1 successfully interfaced with a landing ship's dry well.

The first employment of ACVs in combat by the U.S. was in Vietnam in 1966 (Figure 7). These were Bell-modified British SR.N5s, designated SK-5s. Three were deployed by the Navy and three by the Army. Three were later used by the USCG for search and rescue duties.

Figure 7. Army SK-5 (PACVs) Deployed to Vietnam, 1966

SKMR-1 and SK-5 provided the basis for the Navy Amphibious Assault Landing Craft (AALC) program, which produced the JEFF(A) and JEFF(B) as prototypes for the LCAC [22] of which over 90 were constructed (Figure 8).

The Viking, produced by Bell Aerospace Canada Textron in 1974, evolved from the Voyageur (1971) to meet the need for a smaller but similar multi-purpose craft. Both used the integrated lift and propulsion system concept developed for the SR.N5 and SR.N6.

In 1975 the U.S. Army bought two prototype 30-ton payload LACV-30s from Bell, Canada for the LOTS (Logistics-Over-The-Shore) mission. These craft were also developed from the Voyageur. Twenty-four LACV-30 production units were delivered, in addition to the two prototype craft.

The U.S. Army considered a heavy lift hover-barge, designated PACK (Pontoon Air Cushion Kit), developed by Band, Lavis & Associates, Inc. to complement the LACV-30 in the LOTS mission [13 to 15]. The baseline PACK had 80-ft by 32-ft hard-structure dimensions and carried a 140-ton payload (Figure 9). The PACK had a modular steel structure and a skirt that could be easily installed in segments. The size of the craft could, therefore, be easily varied by multiples of the dimensions of the standard pontoons. The PACK has been operated and evaluated in four JLOTS exercises since 1990.

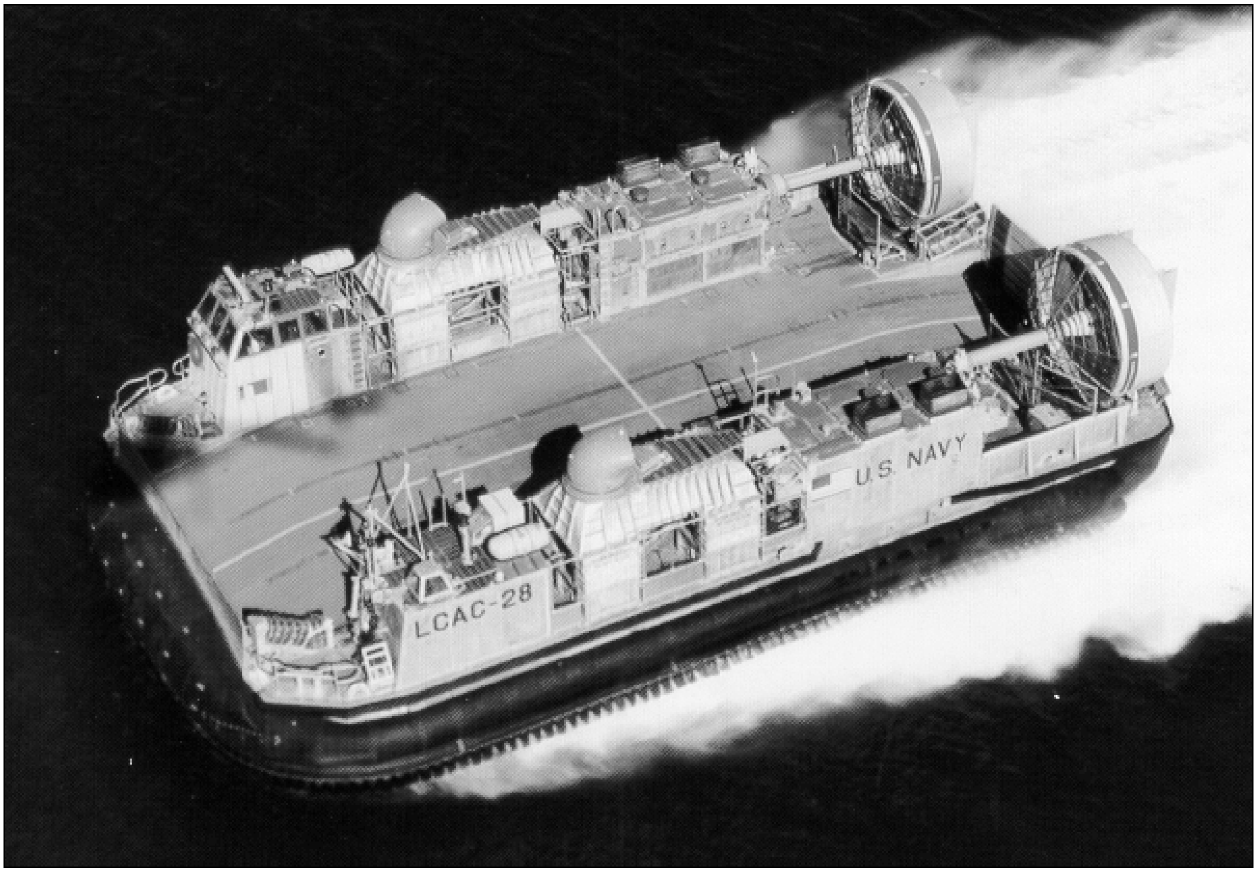

Figure 8. U.S. Navy's Landing Craft, Air Cushion LCAC (designed and built by TM&LS), by Courtesy of the U.S. Navy

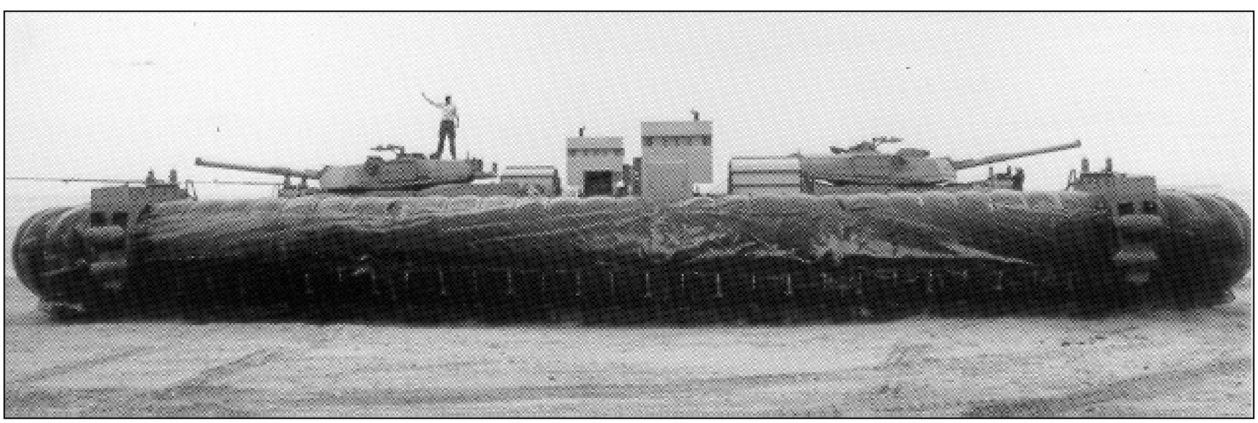

Figure 9. U.S. Army's PACK During Overland Operations With M1A1 Tanks, by Courtesy of the U.S. Army

In 1968, Mitsui of Japan produced their first large ACV, the MV-PP5 MKI which, carries 52 passengers and is used primarily for fast-ferry services on Japanese coastal and inland waters. The MV-PP5 MKII is a stretched version of the MKI and is capable of carrying 76 passengers. The Mitsui MV-PP15 is the largest high-speed Japanese ACV.

The Mitsui MV-PP05A ACVs are prototypes of a utility craft that have undergone evaluation in the Antarctic.

Military ACV development in the rest of the world has been primarily confined to the United Kingdom and Russia. The first British ACV to be built specifically for military application was the 36-ton SR.N3, launched in 1963. Its mission was to determine the operational potential of hovercraft in a variety of military roles.

The 6-ton SR.N5, launched in 1964 was the predecessor of the 16-ton SR.N6 launched in 1965. The SR.N5 and SR.N6 variants have been utilized for military operations for over 30 years. Variants of the SR.N6 have been in service with a number of the world's military and para-military forces for coastal defense and logistics support. Forces include the Egyptian Navy (3), Iraqi Navy (6), Saudi Arabian Frontier Force (16), Canadian Coast Guard (2) and Iran (8).

The 55-ton BH.7, launched in 1969, was also developed specifically for military operations but only one was the subject of trials by the British Royal Navy, primarily in a mine countermeasures role. Six were purchased by Iran.

The Vosper Thornycroft 105-ton VT-2, converted to an amphibious ACV in 1975 from the marine-screw propelled VT-1, was a prototype which was also extensively evaluated by the Royal Navy but was subsequently scrapped. One of the four commercial 200-ton SR.N4 MK2's car ferries was also temporarily converted and tested by the Royal Navy for an MCM application. The West German Navy also explored MCM applications for the SR.N4 MK2s.

The former Soviet Union has, since 1965, produced more military ACVs than any other country. Table 1 lists 13 of their most prominent craft, most of which have been put into quantity production. Their largest craft is the 380-ton Pomornik which was launched in 1985 and is shown in Figure 10.

The Spanish VCA-36 was launched in 1986 to improve the rapid-lift capability of the Spanish armed forces. This ACV will carry a 14-ton payload 189 nm at a cruise speed of 50 knots. Bow and stern ramps on the VCA-36 provide access to the vehicle deck, which can also be reached from the side cabins. Maneuvering control is assisted with the unique application of vectored engine exhaust at the stern (Figure 11).

South Korea has developed several small amphibious-assault ACVs of about 50 tons.

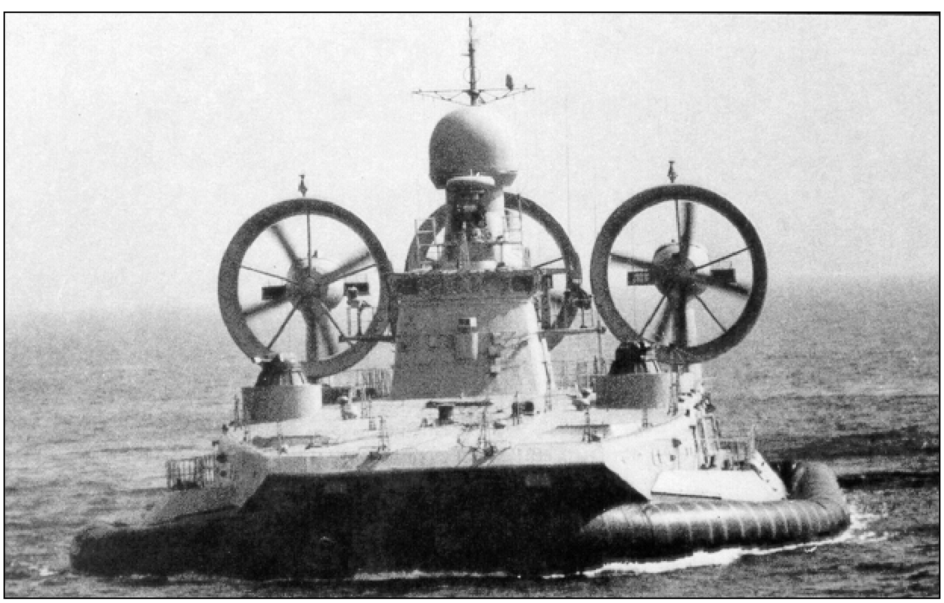

Figure 10. The Former USSR Pomornik Military ACV

Figure 11. Spanish VCA 36

A military variant of the commercial BHC AP.1-88 was also built and delivered to the Canadian Coast Guard in 1987 (Figure 12). Two were used as trainers for LCAC crews.

The enlarged version of the AP.1-88 was, as mentioned earlier, recently delivered to the Canadian Coast Guard as the DASH 400 (Figure 4).

Another fairly recent development is the ABS M-10 by ABS Hovercraft Ltd of the UK. The prototype of this FRP craft was launched in 1994 and has been on numerous demonstrations for primarily military applications (Figure 13).

Figure 12. Canadian Coast Guard AP.1-88

2.2.3 Commercial SES

The modern development of commercial SES stems from the pioneering work of the British [17, 18].

Figure 13. The ABS M-10, Courtesy of ABS Hovercraft Ltd, UK

Progress in the 60's and 70's was dominated by Hovermarine, later known as Hovermarine Transport, then, Vosper Hovermarine, then Hovermarine International, and more recently, as International Hovercraft. Hovermarine built more than 100 SES which have been operated in over 28 different countries. It is interesting to note that, during the 1970's, this company was a wholly owned subsidiary of U.S. Corporations. The Hovermarine craft are designated the HM-200 and 500 series.

The HM-221 is a stretch of the 200 series to a 70-ft long 35-ton craft. Two HM-221s have been in use by the Port of Tacoma, Washington, as harbor patrol/fire boats since 1982-1983 and operational experience has been highly favorable. Two more were built by TM&LS (under license) for delivery to the Port of New York in 1992, Figure 14. Initial designs of the Hovermarine "700" series were also developed in the early 1980's. The concept, described as the "Deep Cushion" craft, provides a cushion depth of 20-ft or more on a 200-ft SES, an approach demonstrated by a manned model to provide reduced motions in high sea states.

Hovermarine International also marketed the 82-ft HM 424 design, a 165 to 200 seat passenger-ferry design in GRP capable of predicted speeds up to 50 knots, depending upon engines selected.

A more recent SES builder is Korea Tacoma Marine Industries (KTMI). KTMI specializes in metal-hull patrol boats and offshore-supply vessels. In 1979 the company began building and marketing a line of SES ferries for commercial use with capacities between 60 and 160 passengers.

The Norwegian company Brodrene Aa Batbygerri A/S launched the Norcat from their Hye Yard in Nordfjord in June of 1984. The craft, designed by Cirrus, was diesel powered and of GRP-sandwich construction. This craft was launched with marine-screw propulsion and was subsequently converted to waterjets. The Cirrus/Brodrene Aa team

Figure 14. HM2 Fire Rescue Craft for Port of New York, Courtesy of TM&LS, USA

subsequently produced a second “Norcat” (CIRR 115P), the Ekwata and the experimental, hybrid propeller driven, Harpoon (CIRR 60P), followed by series production of eleven CIRR 120P class ferries, operated in many parts of the world. Of GRP cored construction, they are powered by MWM diesels with KaMeWa waterjets, providing a service speed in the mid-to-high 40s.

Early in 1990 Cirrus acquired a 50% interest in a shipyard in Rosendal and, on 1 June, the partnership with Brodrene Aa was dissolved. Cirrus had developed designs for two large SES car ferries and a 220-ton SES attack craft. They also participated in the design of the Norwegian Navy’s Mine-Countermeasures SES.

Brodrene Aa subsequently joined the Ulstein Group and built the luxury 37-meter SES passenger ferries designated UT904. The first was delivered to a customer in South Korea in 1991 with another to a customer in Greece in 1992, (Figure 15).

Figure 15. Ulstein Group UT904 Luxury SES Passenger Ferry

The Norwegian company, Westamarin, in partnership with Karlskronavarvet (KkrV) in Sweden, produced two aluminum SES-4000 class ferries, the Super Swede and the Super Dane. Also, two SES Jet-Rider 3400 ferries previously designed by KkrV in conjunction with Textron Marine Systems and constructed by KkrV in cored GRP, were fitted out at the Westamarin yard.

A five-year project, “Techno-Superline ’93,” was initiated in Japan at the beginning of 1989. Funding of the study was provided by the Ministry of Transport and by seven shipyards and heavy industries, The objective of the study was the definition of a feasible concept, by the end of 1993, for a vessel carrying 1000 tonnes at 50 knots for 500 miles. Such a high speed carrier would allow transit from Japan to China, Taiwan or Korea in one day (Figure 16). A unique feature of the 0.55-scale, 1500-ton TSL A70 (HISHO) demonstration vessel that was launched in 1994, is the combined use of T-foils and cushion venting for ride control. Following its technical demonstration period, HISHO renamed “KIBO” entered into operational service in 1997.

Royal Schelde in the Netherlands produced the Seaswift 23 and developed designs for a 34-meter Seaswift 34 and the 60-meter Seaswift 60.

Commercial-SES developed in Russia concentrated on moderately high-speed, shallow-draft passenger ferries for operation in Russia’s vast network of shallow rivers and tributaries. Craft built and operated to date have been relatively small (50 to 80 seats) and have operated predominantly on short routes in protected waters.

SES research and development has been underway in China since the early 1970’s. Given China’s vast geographical area, extensive river and lake systems, and a populace dependent on public transportation, it seems reasonable to expect a significant growth in Chinese SES activity.

Commercial SES development in the U.S. has been minimal, with only, Bell Halter, Inc. and Avondale, having constructed SES for commercial operations. The Bell Halter Dashboat is one commercial variant of the BH-110, two of which were engaged in commercial operations.

The Rodolf is a hydrographic survey variant of a Bell Halter utility SES. It is owned by the U.S. Army Corps of Engineers.

Military SES

The development of military SES started in the U.S. following the pioneering work of Allen Ford with the XR-1 which was designed and built in 1960 to 1963 at the Naval Air Experimental Center (NAEC). The XR-1 was the first in a series of manned SES testcraft used by the U.S. Navy. It has been a workhorse in successfully demonstrating a large number of advances in SES technology through a succession of modifications. The XR-1 was still in use in 1983; its last series of tests (as the XR1-E) were in connection with a second-generation ride-control system.

Figure 16. TSL A70 "KIBO"

The XR-3 was built at the David Taylor Naval Research and Development Center (DTNSRDC) from 1965 to 1966. The craft was evaluated in a test program on the Severn River, Maryland, and then used for training at the USN Post Graduate School in Monterey.

Early in 1969, the Navy awarded separate contracts to Aerojet General and Bell Aerospace Textron for the design and construction of two 110-ton SES test craft, the SES-100A and SES-100B. Both the SES-100A and SES-100B test craft were operational from 1972 to 1982 and regularly achieved speeds in excess of 80 knots. The SES-100B (which reached 94 knots) was the first Navy ship to fire a vertically-launched SM-1 medium-range guided missile. This was achieved with the SES traveling at a speed of 65 knots.

In 1973, the U.S. Navy launched the XR-5 for research into the advantages of very high length-to-beam ratios.

In 1976, the SES Project Office was instructed to design and built a 3000-ton SES having an L/B of 2.6 and speed greater than 80 knots. In December 1979, after completion of contract design, the Navy canceled this program. Since that time, the U.S. Navy has directed SES designs to feature higher L/B ratios (3.5 and higher), moderate speeds (40 to 60 knots), buoyant sidehulls and CODOG propulsion.

In 1978, Bell launched the commercial low-L/B BH-110 [18]. Six were built, of which three were used by the USCG. Known as the Seabird Class, the Cutters Seahawk (WSES-2) and Shearwater (WSES-3) were delivered in 1982 and the Petrel (WSES-4) was delivered in 1983. These three craft, based at Key West, successfully performed search-and-rescue duties and maritime law-enforcement duties, including interdiction of narcotics and aliens in the Gulf of Mexico and Caribbean Sea.

To further validate the technology associated with high length-to-beam SES, NAVSEA procured in 1982, a 110-ft commercial SES, the BH-110 Mark I, and increased its length-to-beam ratio from 2.65 to 4.65 by installing a 50-ft hull extension amidships. This vessel is the SES-200.

For the same installed horsepower, the displacement of the SES-200 was 65 tons (45%) greater than that of the BH-110, and it had nearly three times the fuel capacity. Less than 20% of the volume in the 50-ft hull extension was utilized to increase the fuel tankage. The remaining space was left vacant for future Navy or Coast Guard additions.

For ocean-capable vessels, research has shown that a ratio of length-to-beam greater than 4 offers efficient operation at task-force speeds without unduly compromising the SES advantage of being able to operate at higher speeds. Following acceptance trials, the SES-200 was underway for a total of 713 hours in sea conditions up to sea-state 5 and served to validate the advantages of high length-to-beam ratio for SES [19, 20].

Following the retrofit of two additional lift engines and two additional lift fans, the SES-200 underwent extensive tests and evaluations by various NATO nations during a 1985 to 1986 European and Canadian Tour [21].

In 1990, the SES 200 underwent a conversion to waterjet propulsion with new higher powered diesel engines. She was evaluated at the DTRC Special Trials Unit at the Patuxent Naval Air Station, Maryland (Figure 17).

Figure 17. U.S. Navy's SES 200, Photo by Courtesy of NSWCCD

During the late 1970's, serious interest in the military potential of SES was beginning to appear in Mainland Europe and, by 1981, the French Navy's Direction Des Constructions Navales (DCN) were testing a small experimental craft called Molenes.

DCN recognized the potential of SES as a helicopter platform and embarked upon an extensive research and development program aimed at developing a 1250-ton ASW corvette, the Eoles. Their next step beyond the Molenes was the AGNES 200 which was launched at CMN in Cherbourg during 1990 (Figure 18).

The Swedish Defence Materiel Administration (FMV) and KkrV have engaged in the development of SES concepts and technology since 1983. Studies and tests were conducted by KkrV from 1985 to 1986 and, in 1987, FMV initiated a comprehensive SES R&D program involving a number of Swedish firms and government agencies. These activities led to a 1989 building contract with KkrV for the stealth test craft "Testrigg SMYGE," Figure 19.

Figure 18. French Navy's AGNES 200 SES, Photo Courtesy of the French Navy

The Royal Norwegian Navy (RNN), in November of 1989, signed a $352M contract with Kvaerner Mandal a.s. to build nine 350-ton cored-GRP SES, Mine Countermeasures Vessels (MCMVs); four hunters and five sweepers, with a sixth optional sweeper, Figure 20. They will replace Norway's nine Sauda-Class sweepers built in the 1950s. A new production facility for cored GRP construction, to 100 meters in length, was erected in Mandal

The selection of the cored GRP SES configuration over the more conventional monohull and catamaran options was based upon extensive analysis and shock testing.

Kvaerner have also built a very high-speed SES patrol craft for the Royal Norwegian Navy which is due out this year.

The firm of Blohm und Voss in Hamburg, Germany, began their studies of SES in 1982. These studies culminated in the launching, in 1989, of the 36-meter Corsair. This demonstrator, for both military and commercial applications, embodies several significant technology advances and achieves speeds over 50 knots. The hull is cored GRP utilizing a high-strength core material. MTU diesels, suspended in modules from an overhead foundation for shock and vibration isolation, drive Escher-Wyss seven-bladed semi-submerged CP propellers with flow-control flaps mounted forward of the propellers. The design is based on the Blohm und Voss modular MEKO principles, allowing use of various demonstrator modules.

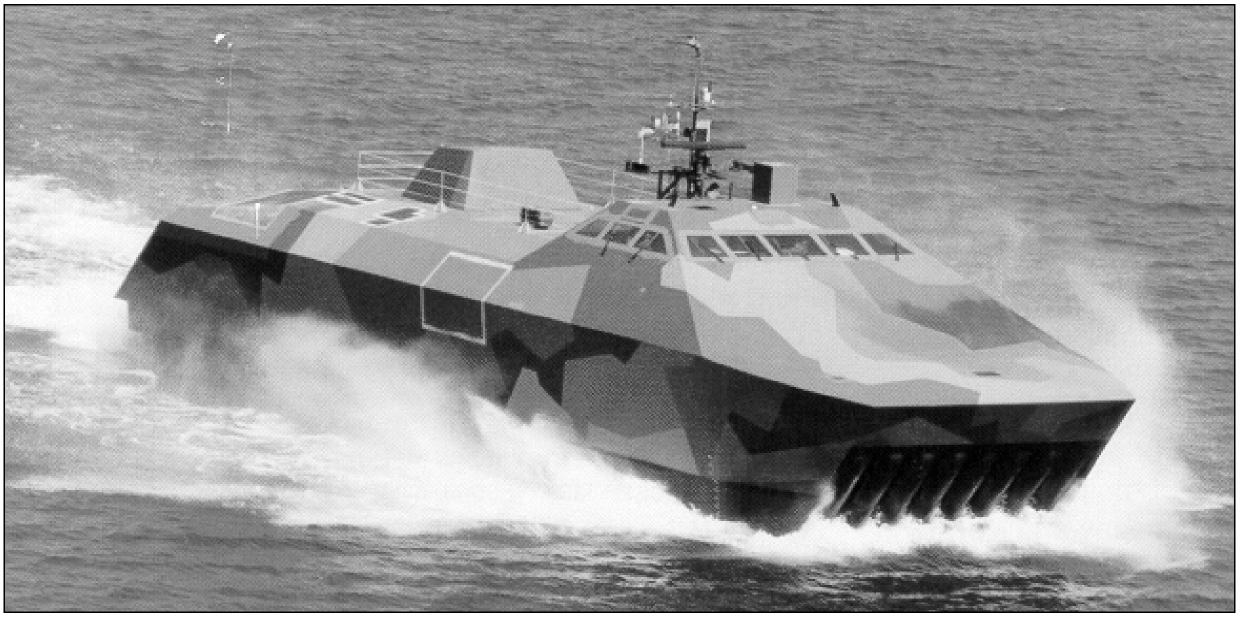

Figure 19. SMYGE by Courtesy of the Royal Swedish Navy

Figure 20. Royal Norwegian Navy's Oksoy MCM Vessel, Courtesy of Kvaerner Mandal a.s.

For eight years, the German MoD, supported by MTG in Hamburg, developed, in cooperation with the U.S. Navy, the design of a 700-ton SES. A 10-meter 1 to 6.3-scale test craft, the Moses, designed by MTG and built by Lurssen Werft in Bremen, was evaluated at the MoD Navy Ship Test Center at Eckernforde, near Kiel.

In South Korea, the SEMO Company has built three ACVs and four SES [6]. Their latest, "Democracy 5," is a 40-m, 50-knot, FRP SES passenger ferry shown in Figure 21. Samsung Heavy Industries have also built an SES ferry the "Dong Yang Gold". This SES is also of FRP with a length of 37-m and maximum speed also of 50 knots [6].

Figure 21. SEMO SES "Democracy 5", Courtesy of the SEMO Company Ltd, South Korea

In the Spring of 1990, the world's then largest SES was commissioned by the Soviet Navy after a year of sea trials. The 1000-ton, 45-knot, Dergach was built at the Kamysh-Burun Shipyard in Kerch on the Black Sea.

Propulsion and lift power for the 650-ton Dergach is provided by three gas turbines. Armament consists of two SS-N-22 quad launchers, twin SA-N-4 Gecko missile launchers, a 76.2-mm gun and two 30-mm Gatling guns (Figure 22).

Figure 22. Russian 650-Ton Dergach Combatant SES (Canadian Forces Photo Courtesy of Guide to the Soviet Navy)

Summary of Development

Since 1961, there have been over 60 ACV and over 50 SES designs which have been built as test craft or as prototypes which have led to quantity production. Figures 23 and 24 show, respectively, the number of the most prominent ACV and SES of a new design launched each year. The numbers include only the first in any series production and craft having major modifications.

Figure 23. ACV Prototypes

The annual breakdowns by regional group are shown in Figures 25 and 26. The three groups are (1) the United States and Canada, (2) Far East and the former Russia, and (3) Europe. This shows that the majority of the recent growth in activity for new designs of ACVs is in the Far East and the former USSR. For SES, the largest recent growth has been in Europe. In the U.S., only six new designs (ACVs or SES) of a significant size have been built since 1980.

Figure 24. SES Prototypes

Figure 25. ACV Prototypes by Region

The growth in the world's market for fast ferries is illustrated in Figure 27. This growth has been met by hydrofoil craft, catamarans, monohulls, SES and ACVs.

The competition is fierce and ACVs and SES can only be justified on routes where high speeds, generally over 40 knots, are of interest.

Figure 26. SES Prototypes by Region

Figure 27. The Fast-Ferry Market (1996)

3.0 TECHNOLOGY DEVELOPMENT

In the last 25 years, significant advances have been made toward developing a well-established discipline of hovercraft design practice, approaching that which is available for conventional ships. This has come about as a result of the wealth of experience gained by comparing and validating design procedures and design criteria against the very large database of full-scale and model-scale information which has accumulated over a period of more than 30 years.

Foremost in this experience in the U.S. has been that provided by the U.S. Navy/Marine Corps Amphibious Assault Landing Craft Program, which produced the AALC JEFF(A) and JEFF(B) prototypes, and by the Amphibious Warfare and Strategic Sealift Program which produced the Landing

Craft Air Cushion (LCAC), which has been in quantity production since 1984 [22].

Close to this in significance was the U.S. Navy's 3KSES program which during the period of 1969 to 1980 expended over $400M on SES development.

This section of the paper provides an overview of the experience as it relates to some of the more important technology developments which have influenced craft design.

Unlike the hull of a conventional ship, the hard structure of an ACV or the wet-deck of an SES, under normal operating conditions, is seldom in contact with the water. The study of craft resistance, stability and seakeeping normally associated with the hullform design of a conventional ship is, therefore, for an ACV or SES, associated strongly with the study of ACV skirts or SES seal systems.

3.1 Performance

ACVs and SES can be designed for very high speeds. In calm conditions, the speed of an ACV or SES can generally be much higher than for other forms of marine transport having the same installed power. Usually, the thrust and installed propulsion power are determined by one or more of the following requirements:

- To climb an overland slope of a specific gradient (ACV only),
- To traverse the hump in the overwater drag curve with a specified forward acceleration (ACV and SES), and
- To cruise at a particular speed, above hump speed, in a specified sea state (ACV and SES).

The characteristic shape of the resistance versus craft speed curve for an ACV or SES operating overwater is similar to curves for other high-speed marine vehicles, but unlike the curve for a conventional displacement craft. Figure 28 shows predicted and experimentally determined drag for a typical ACV, the JEFF(B) experimental landing craft. Total drag for an air-propelled ACV such as JEFF(B) is typically considered to be comprised of four components: external aerodynamic drag, momentum drag of the lift-system air, cushion wavemaking crag, and skirt or seal-system contact drag.

Figure 28. JEFF(B) Drag Overwater

It has been customary in the past to assume that rough-water skirt drag would vary with changes in cushion geometry, craft displacement, forward speed and wave height. Studies conducted in 1990 using an extensive series of full-scale tests of the LCAC have shown that the craft heading and modal period of the encountered seaway has a much stronger influence on rough-water drag than had been previously thought. Figure 29, for example, shows how the coefficient of rough-water drag varies with the modal frequency of wave encounter. It was found that the wave-height energy spectrum of the seaway during full-scale testing varied significantly from day-to-day and from location-to-location, particularly when comparing results from testing on the East and West Coast of the USA. Ignoring such an effect was found to have a profound influence on the ability to accurately predict either craft speed performance or fuel consumption. A similar treatment was developed for SES as reported in Reference [23].

Figure 29. Rough-Water Skirt Drag Coefficient

However, the manner in which ACV or SES total resistance varies with changes in planform shape and size is only one factor among several which govern the selection of geometry. Figure 29 shows, in carpet-plot form, the trade-off involved in total displacement and power for ACV designs required to carry nearly three times the payload the JEFF(B). The performance required was to cruise at 40 knots in sea-state 2. The selection of length and beam which results in minimum total power is well defined. The extent to which length and beam can be changed without appreciably changing this power is shown by the shaded area on the upper plot of Figure 30 [21, 24, 25, 26, 27].

Figure 30. Variation of Full-Load Displacement and Power With Hull Length & Beam for an ACV

3.2 Structural Design Loads

Considerable emphasis has been placed on the development of rational design loads during the design and testing of the U.S. Navy's AALC, LCAC, SES-100A, SES-100B and XR-1D and during the very extensive design work carried out for the 3KSES. One important development in the structural loads work for the 3KSES was the use of scale models to measure bending moments experimentally. Both rigid and structural-dynamic grillage models were developed and tested [28, 29]. It was by using these models that it was discovered that the loads experienced while operating SES at low speeds in the hullborne condition were usually higher than the loads measured at high speed on-cushion.

Structural loads for new ACV and SES designs are developed from a number of sources:

- The growing database of loads used for earlier, successful designs.
- Loads measured experimentally during model tests and during full-scale trials. These loads are extrapolated by probabilistic methods to define maximum life-time loads [28].
- Loads specified by classification societies for high-speed craft such as those formulated by Det Norske Veritas, the British Civil Aeronautics Authority, and the American Bureau of Shipping [30, 31, 32].
- Procedures developed by U.S. Navy activities such as the Combatant Craft Detachment of NSWCCD in Norfolk, Virginia.

All of these sources provide information that can be used directly.

The loads of concern are the maximum expected lifetime values of, and fatigue-stress cycles related to the following quantities:

- Hog and sag longitudinal bending moments
- Transverse bending moments
- Vertical shear force
- Torsion about the longitudinal axis
- Hydrodynamic and hydrostatic pressures on all external surfaces
- Inertia loads on all components, subsystems and cargo due to wave-induced accelerations
- Machinery-induced vibration.

While design loads will vary depending upon operational requirements, a sanity check can be made by comparing the derived loads with the design loads used for prior designs and successful operational craft. An example of a chart that can be used for the midship longitudinal bending moment of SES is shown in Figure 31.

Figure 31. SES Midship Structure Longitudinal Bending Moment

3.3 Hull Structure

ACV and SES hulls are being built from a variety of materials including welded marine-grade aluminum alloy, single skin or foam-cored Fiber-Reinforced Plastic (FRP), and high-strength steel for some SES. Each has its advantages and disadvantages and each yard tends to select that which they know best. Major considerations include material and construction cost, weight, strength, maintainability and fire resistance.

3.3.1 Aluminum Alloy

Aluminum alloy has usually been the preferred choice in the U.S. It is readily available, its properties are well known, it can be easily formed and joined without expensive tooling, with careful design it can be reliably inspected and, more importantly, design standards and criteria are well established.

All the early amphibious ACVs used lightweight skin and stringer design in aircraft-type alloys. However, the Saunders Roe SR.N2 and SR.N3 ACVs employed a certain amount of Redux bonding, particularly in the buoyancy tank construction.

For the next generation of hovercraft (SR.N4/BH7), high grade alloys were retained, but extensive use was made of sandwich panels for buoyancy tank and deck construction. Although thin-skinned, these honeycomb-cored panels have given excellent service.

Edge-grain balsa was used as the core for deck panels and some vertical bulkheads on the BH7, and this proved unsatisfactory, particularly, in hot climates where the slightest damage to an outer skin allows salt water to enter, leading to extensive corrosion.

Late in 1979, British Hovercraft decided to replace the SR.N6 with a new family of passenger/utility craft, the AP.1-88. To reduce labor costs of the craft, the number of components, and, therefore, the amount of welding, was minimized by the extensive use of large, light alloy extrusions. In order to reduce heat distortions, machine MIG (metal arc inert gas shielded) welding was used extensively. Where this was not possible, either manual MIG or TIG (tungsten are inert gas shielded) was used on thicknesses down to 2 mm. The result of using this type of construction was that the structure weight per unit cushion area was approximately twice that of an SR.N6.

The major structural consideration in minimizing fabrication cost of the LCAC was also the use of all-welded construction. Welded construction involved significantly fewer manhours than mechanically-fastened construction. In addition, welded construction lent itself more readily to automated fabrication. For this reason, the LCAC structure was designed with emphasis on longitudinally-stiffened flat panels, which are compatible with automated welding with a vacuum table, automated stiffener loading equipment, and automated stiffener tracking welding heads. Following this approach has resulted in 70% of the welds being made mechanically and only 30% manually.

For the LCAC the separation of the superstructure into modules also produced structural benefits. For instance, the modules are isolated from hull girder bending. Although this might seem to be undesirable, because it produces a hull that is only a relatively shallow box, this proved not to be so. By using only the hull as the primary hull girder, the massive cargo-deck structure, which is designed to carry heavy cargo, is also made to contribute to hull stiffness. If the superstructure were a part of the hull girder, the cargo deck would be near the girder neutral axis and relatively ineffective for resisting overall bending loads. In addition, when the superstructure is part of the hull girder, the superstructure becomes the main shear-carrying member of the hull because of its depth. This creates larger bending moments in the transverse hull frames, with appropriate weight penalties, and requires heavy reinforcement of the many openings in the superstructure that are necessary for access, air intakes, exhaust openings, etc.

Note that because of the relatively low fatigue strength of welded aluminum, high-cycle fatigue of local structure is usually the greatest concern, avoidable preferably in the design stage by the avoidance of, or appropriate location of, stress concentrations, and by ensuring that the natural frequencies of structural components are not excited by predictable machinery vibrations.

3.3.2 Fiber-Reinforced Plastic (FRP)

The first SES ferry (the Denny D-2, 1962) was constructed of single-skin glass fiber-reinforced plastic (FRP) as were the extensive production series of Hovermarine (HM) craft in the UK. Fiber-Reinforced-Plastic (FRP) construction offers lightweight, durability, repairability, corrosion resistance, ease of construction (particularly of complex shapes) and reasonably low cost. The HM craft used woven and unidirectional glass rovings with polyester resin. The structure of this craft could be built in less than four months while the cost of the molds and tooling amounted to about 15% of the total cost of the prototype. The molds were designed to be sufficiently durable to produce over 100 craft.

Cored GRP was introduced by the U.S. Navy in 1955. Over the seven years up until 1962, 32 Navy GRP boats from 33 to 50 ft in length were constructed by the “core mold” method, a technique similar to that employed today in Norway and Sweden. Since the early 1960’s, the Royal Netherlands Navy has had many PVC-cored GRP craft constructed in lengths up to 77 ft. The 77-ft Pilot Boats, in particular, have seen nearly 30 years of extremely rough service. After many years operating off the Hook of Holland, they were sold to India where they are still in operation [1].

Currently, the very successful series of craft designed by Cirrus and constructed by Brodrene Aa in Norway, the MCM SES and fast SES patrol craft built by Kvaerner Mandal, the SES by Karlskronavarvet (KkrV) in Sweden, and the Blohm und Voss Corsair from Germany are examples of successful efforts to significantly reduce structural cost and weight using foam-cored structures.

Traditionally, glass-reinforced polyester is used for the skin, to sandwich a laid-up core of expanded cellular PVC. With the trend toward larger SES, the introduction of higher-modulus fibers (aramids or carbon) may be attractive to improve laminate stiffness.

Cored FRP structure also offers advantages in thermal and acoustic insulation. The Norwegian Oksoy MCMs and the Swedish stealth SMYGE have emphasized the noise and vibration damping advantages along with IR reduction. In the case of the passenger ferries it is clear that cost savings played as much a role in selection of cored GRP as did weight savings. The most advanced FRP structures are now those used on the ABS M-10, the Oksoy and SMYGE.

3.3.3 Steel

China was the first to use steel for SES structures. High-tensile steel results in a heavier, more rugged structure, but is less expensive than aluminum alloy or FRP. It is also more fire resistance and has a higher fatigue strength than welded aluminum alloy.

As SES become larger, steel becomes more attractive since the use of minimum gauges for welding no longer presents a serious weight penalty. Also, the technology required for the design and construction/producibility of large steel structure is less of a technical risk. The 20,000 ton SES fast-sealift ship designed by Ingalls has a structure of high-strength steel.

3.4 <u>Propulsion</u>

One measure of the overall performance of an ACV or SES is the total hp/ton-knot at cruise speed. Figure 32 summarizes values of this parameter for a range of craft, plotted versus calendar year. As can be seen, there has been a dramatic improvement from approximately 5 hp/ton-knot for the SR.N1 to less than 1 hp/ton-knot for current generation ACVs and SES. This measure of craft efficiency depends on the resistance to forward motion and on the efficiencies of the lift and propulsion systems. The historical improvement evident in Figure 32 is due primarily to the following factors:

1. The reduction in lift power possible with current flexible skirt systems.

2. The reduced drag of fingered skirts compared with early jetted-bag configurations.

3. The development of fans and propellers tailored more closely to operational requirements.

Figure 32. Improvements in ACV/SES Efficiency

Improvements in all of these areas can reasonably be expected to further reduce hp/ton-knot to perhaps 0.4 to 0.6 over the next 20 years. It is important to realize, however, that other design constraints may prevent the achievement of best efficiency for specific designs. This is particularly the case for the LCAC, where dimensional limits result in high cushion density and high disc loading for the propulsion system. However, some very significant improvements have recently been gained for the LCAC as reported in [52]. It is also worth noting that performance is not always the controlling parameter. Cost effectiveness, as measured by cost per payload ton-mile, is often a more meaningful parameter, and this is influenced not only by cruise performance, but by items such as structural efficiency, engine specific fuel consumption, maintenance costs, and acquisition cost.

3.4.1 Airscrew Propulsion

ACV propellers can lose efficiency and may suffer vibration problems when used in an installation where the airflow entering the propeller disk is severely non-uniform. Manufacturers of aircraft propellers have paid relatively little attention to this problem compared with the marine propeller industry where wake effects have always been a major consideration. Nearly all propeller-driven aircraft use tractor installations in which the propeller is designed to operate in an essentially uniform airflow. Even the few pusher-prop aircraft have a relatively undisturbed propeller inflow compared with that of most marine propellers. Accordingly, the air propeller performance technology is not geared to dealing with severe wake problems.

When the AALC JEFF(B) was being designed, for example, Hamilton Standard, the propeller manufacturer, was given simplified inflow velocity profiles based on model tests in a wind tunnel. In this installation, the propellers were mounted behind a bluff superstructure. It was thought that the propeller ducts, acting as a strong sink, would essentially straighten the flow before it reached the blades. Accordingly, performance predictions were little affected by the stipulated velocity profiles. Later, tests on other models and on full-scale craft, in which propeller thrust was measured independently of aerodynamic drag, indicated that superstructure ahead of the propeller has a marked effect on net thrust and on propeller-vibration levels. Static tether tests on JEFF(A) and JEFF(B) revealed, in each case, a significant difference between predicted and measured thrust values. However, satisfactory craft performance at speed indicated that the problem was less severe when underway.

Undoubtedly, propeller-installation effects remain as a technical issue requiring further attention when considerations are made of craft performance, and perhaps more importantly, when considerations are made of aerodynamically induced propeller vibration, stress, and noise. In addition to the effects of propeller blockage, JEFF(B) propellers are subject to interference from the bow-thruster jet efflux and to a lesser extent, by ingestion of the turbine-engine exhaust gases. Both of these phenomena, particularly the former, have a direct affect on propeller thrust. The affect of bow-thruster interference can be seen in Figure 33.

To minimize bow-thruster interference with the propellers, the nozzles are aimed upwards and outwards for normal ahead operation. The loss of forward thrust due to the cosine of the angles of deflection is quite small and is significantly smaller than the loss of propeller thrust which would result from direct impingement of the bow-thruster jet on the propellers.

Figure 33. Effect of Propeller-Blade Angle and Bow-Thruster Interference on JEFF(B) Total Static Thrust [50]

3.4.2 Marine Screws

Marine propellers have been used on many SES, including the UK HM-series of craft, the U.S. Coast Guard WSES patrol craft, the original SES-200 and the world's fastest ship, the SES-100B. Propellers may be of conventional high-speed subcavitating design, e.g., Gawn-Burrill types, or of partially submerged, fully ventilated supercavitating design, as on the SES-100B and Corsair. A detailed account of propeller theory and the matching of propellers to SES requirements can be found in Reference [49].

For moderate speeds, waterjets have been preferred to propellers for recent SES because they allow operation in shallower water, have minimum appendage drag and are more easily matched to diesel engines. However, for very high speeds (>60 knots), partially submerged propellers continue to be attractive. Generally, a propeller installation will be lighter and the effective disc area allows for a high potential propulsive coefficient. Careful detail design of the propeller installation may allow a high overall propulsive efficiency to be released.

3.4.3 Waterjets

Defining the performance of waterjets, is relatively complicated. To reproduce performance maps generated by a manufacturer usually requires the selection of high value for component efficiencies such as inlet recovery, pump efficiency and nozzle efficiency, etc., unless account is taken of other factors such as hull influences. These influences include the nature and thickness of the boundary layer on the hull ahead of the inlet, changes to the hull pressure distribution due to the presence of the flowing inlet, changes to the hull flow field far ahead of the inlet, and factors associated with outflow from the air cushion and features of the sidehull shaping in the vicinity of the inlet.

KaMeWa, for example, has shown, by painstaking inlet model testing over many years, that relatively small shaping changes to the inlet, particularly, the inlet lip configuration, can exert a profound influence on the inlet performance. KaMeWa provides the inlet duct drawings to the shipyard for each application.

KaMeWa is not alone in discovering anomalous waterjet inlet effects. During the waterjet-inlet model test program for the 2K/3KSES much attention focused on inlet drag. It was found that, over a certain range of flow conditions, the inlet drag coefficient appeared to be negative. Originally, this effect was thought to be due to either an instrumentation error or an accounting error. It is now believed that it may have been due, in part at least, to the hull effects postulated and investigated by KaMeWa.

An important aspect of waterjet propulsion for SES concerns the phenomenon of air ingestion by the waterjet inlets.

Inevitably, the water approaching a waterjet inlet contains air bubbles. The mixture of water and air bubbles may arise from air entrainment at the forefoot, which is swept back to the inlets in the wake (boundary layer). Normally, the pump is very tolerant of this type of air/water mixture and there is minimal effect on thrust performance. However, entrainment of air exiting from the cushion under the sidehulls of an SES can affect pump performance. When this occurs, the usual symptoms are surging of the engine speed due to sudden loss of resisting torque when air is gulped by the inlet. In severe cases, this over-speed can cause the engine governor to shut-down the engine. Obviously, the effect is likely to be more severe in waves than in calm seas.

Steps which can be taken to minimize inlet broaching (gulping of air) and other forms of air ingestion include careful design of the sidehull ahead of the inlet, choice of inlet (sidehull) submergence and deadrise, and sometimes the provision of inboard fences to exclude cushion air, and outboard fences to minimize air ingestion directly from the atmosphere [1].

Waterjet propulsors designed for high speed cannot normally operate at full power at low ship speed due to cavitation in the impeller. KaMeWa, for example, provides guidance on the operation of its pumps in the form of limit lines on the pump map (thrust versus ship speed for various power levels). These limit lines, which divide the map into Zones I, II and III, are similar to, but not coincident with, lines of constant suction specific speed, and are based on operating experience. Operation in Zone I is unlimited with regard to ship speed and pump power (rpm). Operation in Zone II is for rough-water operation. Sustained operation is permitted and will not noticeably affect pump performance, or life, but will not be cavitation-free. Operation in Zone III is for emergency use only and will be marked by reduced torque, severe cavitation, cavitation damage resulting in reduced pump life and vibration.

Part of the pump selection process is to superimpose the ship-resistance curves for various sea states on the pump map to see under what conditions operation in Zones II and III may occur. A speed-sea state envelope can be generated for each ship displacement of interest, limiting operation to Zone I, and to Zones I and II, for instance. Of particular interest, is hump transition in rough seas. If the hump is pronounced (depending on the length-to-beam ratio of the ship) hump transition with adequate thrust margin may necessitate intrusion into Zone II. Since the condition is transitory, this is of no consequence. Use of Zone III for this purpose might be questionable, however.

Some variation of the pump thrust curves is possible before or after pump installation, by choosing a nozzle diameter within the normal range of nozzle ratios provided by the pump manufacturer. A larger nozzle will provide higher low-speed thrust with a steeper fall-off with speed and possibly a lower ship maximum calm-water speed. The final choice of nozzle size is a refinement reserved for the detailed-design phase [51].

3.5 <u>Wake Generation</u>

Ship's wake has been a topic receiving more attention in recent years in connection with craft operation in coastal waters and rivers where shore erosion is of concern.

ACV and SES have interesting features in this regard. At high speeds, the elevation of the surface waves and, hence, the wave drag generated by the cushion of an ACV or SES becomes quite small, as illustrated in Figure 34. This is the main reason why, in comparison to conventional monohulls, the powering requirements and energy dissipated at high speeds become significantly less for ACVs and SES. Figure 35 illustrates this for SES. Thus, the wake generated by high-speed operation of ACVs and SES can be relatively small.

Figure 34. Cushion Wave-Drag Parameter Versus Froude Number

Figure 35. Installed Power/Full-Load Displacement Versus Froude Number

At low speeds, the wave drag and wake generated by an ACV or SES can become very large, particularly if operation is maintained at speeds corresponding to the primary or secondary hump in the wave-making drag curve as illustrated in Figure 34. However, since at speeds between the primary and secondary humps, the wave drag is seen to reduce significantly, operation at such speeds also produces a relatively small wake. Here, the bow and stern waves tend to interfere to cancel each other, since they are close to being equal in magnitude but opposite in phase [46].

From Lamb's two-dimensional theory, ACVs or SES having uniform cushion pressure distributions make no waves for speeds corresponding to:

$$F_N = (gL_c)^{1/2} = (2\pi\eta)^{-1/2} \text{ for } \eta = 1, 2, 3, \text{etc.}$$

Thus, F_1 (= 0.4) corresponds to the trough between the secondary and primary hump speeds predicted by the three-dimensional theory [45] that was used to produce Figure 34. Thus, at speeds below the secondary hump speed, additional "troughs" in the drag curve occur at $F_2 = 0.28$ and $F_3 = 0.23$, etc. All of these are practical operating speeds [46].

The magnitude and nature of the surface elevations produced can be readily predicted by numerically integrating the equations of References [47] and [48]. The results are illustrated in Figure 36, and have been validated by full-scale measurements. Thus, the magnitude of the wake and the selection of the speed to minimize the wake of an ACV or SES can be readily determined.

Figure 36. Computed Wave Pattern Developed by an ACV at $F_N = 0.4$ (Vertical Scale Exaggerated)

3.6 Lift Air Supply

The cushion air supply system of an ACV or SES consists of air intakes, fans and air-distribution ducting. The fans usually have centrifugal impellers housed within rectangular spiral volutes. The performance of such a fan is usually characterized as illustrated in Figure 37 in which fan static discharge pressure and power absorbed is shown as a function of air flow rate and the rotational speed of the impeller. Figure 38 shows the development of the theoretical prediction of the non-dimensional pressure and flow for this fan. Figure 39 shows the correlation between the theoretical prediction and model test data as derived from the BLA test facility. The impeller of the model fan had a tip diameter of 12 inches compared to 3.67 ft for the full-scale impeller. Both were configured as a double-width/double-inlet fan, which has become usual practice in order to conserve space. By parametrically varying impeller and volute geometry, the shape (Figure 38) of the pressure flow curve can be optimized for a given set of requirements. As can be seen, this fan can be designed to have a very flat pressure-flow characteristic which gives a design operating point favorable to good seakeeping behavior. The fan has a high capacity for its size, resulting in a compact installation, and also has a high static efficiency of 81% (86.4% total efficiency), resulting in economic lift-engine operation and fuel saving. The impeller is of welded aluminum and is very rugged, allowing it to withstand the harsh marine environment.

Figure 37. SES Fan Curves

Fans of similar geometry were recently designed by BLA and fabricated in advanced composites by DuPont for the Norwegian OKSOY MCM SES.

Fan rotational speeds are limited by noise, by structural considerations and by blade erosion problems. The noise limitation usually limits the tip speeds of axial fans to about 750 ft/sec. For centrifugal fans, the working limit for high-quality, lightweight aluminum fans is about 500 ft/sec. For steel, industrial fans, the limit is usually taken to be 330 ft/sec. The riveted and bonded JEFF(B) fans run at tip speeds up to about 460 ft/sec.

Figure 38. Theoretical Development of Non-Dimensional Pressure and Flow

Figure 39. Correlation Between Prediction and Test Data

The limits to both the diameter and the speed at which a fan can be turned are set by the material properties and geometry of the fan blades. Figure 40 shows the relationship between radial acceleration, fan diameter, and fan speed [33]. This figure also compares the range of maximum tip speeds for some existing fans and propellers.

3.7 <u>Skirt and Seal Design</u>

By far the most successful and widely used skirt or seal configuration has been the finger or bag/finger system, which was first developed by HDL in the United Kingdom. The arrangement was used for the HD-1, SR.N5, SR.N6, BH7, SR.N4, HM2, JEFF(B), LCAC, LACV-30 and most modern SES.

Figure 40. Lift-Fan Impeller Speed Limitations

Figures 41 and 42 compare the bag/finger seal used on the AALC JEFF(B) with the loop-pericell skirt used on the AALC JEFF(A). For both skirt designs, the highly compliant fingers or cells provide a responsive, low-drag cushion seal, while the bag acts as an air-distribution duct and provides increased restoring moments at large pitch or roll attitudes. Additionally, these skirts provide a high level of redundancy in that the failure of individual fingers or cells is largely compensated for by expansion of the adjacent units.

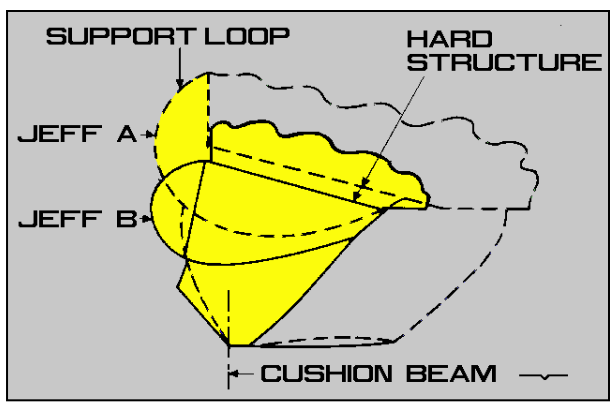

Figure 41. Comparison of JEFF Craft Side-Skirt Sections

For bag/finger skirt systems, the cushion plenum is normally subdivided by stability seals to increase roll or pitch stiffness and damping. Most commonly, this is achieved with a longitudinal "keel" on the centerline, and a lateral seal close to amidship. This arrangement results in three or four, approximately rectangular, cushion compartments. Sometimes, the forward section of the longitudinal keel is omitted to save cost & weight, at the expense of some roll stiffness. For the loop-pericell skirt, longitudinal stability keels have been found to be unnecessary and are omitted, since they are difficult to inspect and maintain.

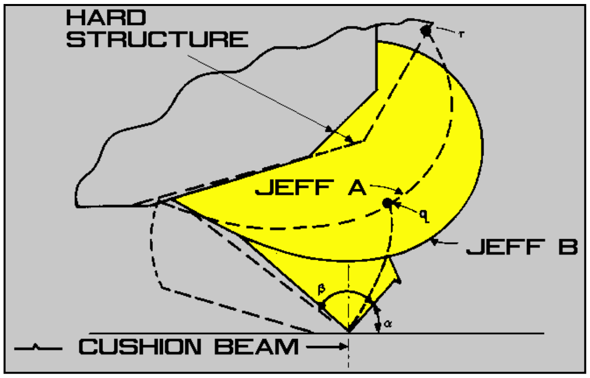

Figure 42. Comparison of JEFF Craft Bow-Skirt Sections

Alternative skirt configurations have found limited application to date. Some of these are described in more detail in Reference [5]. The important issues to be considered in the selection of the geometry of bag-and-finger skirts are discussed at length in References [1, 24 and 53].

3.8 Maneuvering

For ACVs, maneuvering control can be achieved by rudders in the propeller slipstream, by airjets issuing either from side ports (i.e., puff ports) or from swiveling nozzles fed from the lift-air supply fans, or by differential propeller thrust. ACV air propellers are sometimes pylon-mounted with freedom to rotate in azimuth and often have controllable- and reversible-pitch blades for additional control. Craft trim can be controlled by the transfer of fuel, by aircraft-type elevators placed in the propeller slipstream, or by a skirt shift, or lift, mechanism which controls the location of the skirt hemline relative to the hull. Often a combination of these maneuvering and trim-control methods is used.

For SES, maneuvering control is achieved using vectored waterjet thrust, rudders, differential thrust and sometimes airjets to assist low-speed control.

One simple method of conveniently expressing the maneuvering performance of surface ships was developed by the author in 1976 [35] and is illustrated in Figure 43. This shows tactical diameter, normalized with respect to ship overall length, (L) plotted as a function of Froude Number squared. The Froude Number $\left(V/\sqrt{gL}\right)$ is expressed in terms of ship's forward speed (V) during the steady-state portion of the maneuver.

Figure 43. Comparative Maneuvering Performance of Advanced Craft

The curves shown on Figure 43 represent maximum turning performance (e.g., hard-over rudder) for each ship class. In all cases, the curves may be taken as representative of calm (or low sea state), deep-water, still-air conditions. For SES, ACVs and Hydrofoil craft, the curves are presented for on-cushion or on-foil operation only and represent the boundaries of current day maneuvering performance for each class of ship, respectively.

In addition to the boundary curves shown in Figure 43, diagonal lines have been drawn to indicate the approximate non-dimensional turning rates achieved and lateral accelerations experienced during a steady turning maneuver. This has been achieved by assuming that the Tactical Diameter (D) is equal to twice the steady-state radius of turn (R). This assumption implies that the transient maneuver (and speed loss) necessary to initiate a steady turn is of relatively small duration and that a constant forward speed is subsequently maintained throughout the turn. The equation for lateral acceleration, ϕ, (in units of g) during the turn is then simply expressed as:

$$\phi = 2V^2/gD \qquad (1)$$

$$D/L = (2/\phi)\ (V^2/gL) = (2/\phi)\ F_N^2 \qquad (2)$$

where D is assumed equivalent to the Tactical Diameter (D = 2R)

F_N is the Froude Number $\left(V / \sqrt{gL}\right)$

and g is the acceleration due to gravity.

Similarly, the rate of turn (r) can be expressed as:

$$r = V/R \text{ (radians/second)} \qquad (3)$$

and the non-dimensional rate of turn can be expressed as:

$$r\sqrt{L/g} = 2F_N\,(D/L)^{-1} \qquad (4)$$

For any additional data in which only the steady rate of turn (r) is available, for a steady speed (V) during a turning maneuver, the normalized Tactical Diameter may be determined as:

$$D/L = (2F_N)/r\sqrt{L/g} \qquad (5)$$

and included on Figure 43 with the aid of the diagonal lines for constant non-dimensional turn rate.

Predictions of maneuvering performance are usually made using a time-domain simulation of craft motion in, at least, the yaw, sway and surge degrees of freedom.

The computer program used for the following example was developed by BLA, Inc. to perform a turning maneuver using the procedures outline in an ACV's operating manual. That is, a turn is initiated using bow thrusters and the craft sideslip angle is controlled using the craft rudders. An initial problem with the predicted transition phase of the turn was that the craft sideslip would increase at a very high rate. In order to solve this problem, a rather complex rudder logic was developed which attempted to mimic a man-in-the-loop. This logic reacts to sideslip angle in conjunction with transverse and rotary accelerations in much the same manner as a car driver would when making a turn on snow-covered roads. The various decision points inherent in this type of logic were derived from full-scale test results. Following this program modification, good correlation with full-scale test results was obtained as shown in Figures 44 and 45. The corresponding track of the craft is shown in Figure 46.

Figure 44. Craft Speed, Rudder Angle and Sideslip Angle for a 40-Knot Port Turn Over Water

Figure 45. Comparison of Predicted & Measured Craft Track Angle During a 40-Knot Port Turn Over Water

Figure 46. Predicted Craft Track During a 40-Knot Port Turn Over Water

3.9 Pitch and Roll Stability

The question of what constitutes adequate stability for the more common types of displacement ships has been essentially answered over the years through a process of trial and error. Criteria have been developed by the classification societies, or naval authorities, which the naval architect must use as guidelines to establish and define the capabilities of each new design and determine the survivability of the ship when subjected to both environmental and operational effects. These criteria (for displacement ships) govern the requirements for pitch and roll, intact and damaged stability, and are usually based on the assessment of both initial metacentric height (GM) and area under the righting-arm curves for large angular excursions in pitch and roll. Often, however, a compromise must be considered, since the high level of stability required to ensure a small amplitude of rolling directly opposes the low stiffness (or small GM) necessary to produce the desirable low angular accelerations which lead to habitable operation. Similarly, the high level of directional stability necessary to ensure satisfactory course keeping will detract from the ability to maneuver.

For high-performance craft, however, no generally recognized stability criteria exist and, in the early stages of development, designers must rely heavily upon model testing and theoretical static and dynamic analysis [35, 36, 37, 38]. Eventually, such new ship types are built and put into operational service. There are now many SES and ACVs operating, both commercially and with the worlds' navies, thereby providing considerable operating experience. To date, very few of these vehicles have capsized due (presumably) to the provision of adequate stability and prudent operation. Since their introduction in the early 1960's, only four capsizing events have occurred with SES and ACV types [34].

What is now considered the conventional approach to assessing the stability of high-performance ships (SES, ACV, Hydrofoil craft, etc.) is a process of extensive model (or prototype) testing combined with mathematical simulation and the use of standard "rules-of-thumb" guidelines. Presumably, if a dynamic simulation of a ship in all six degrees of freedom can be adequately verified with model and prototype data (and, if scale effects are well understood), then such a representation can be subjected to all possible environmental and control disturbances (and even ship subsystem malfunctions) and the behavior of the ship can be observed for signs of instability. The success to which such simulations have been developed for the various types of high-performance ship has, however, varied considerably, and in some cases, considerably more development work will be necessary before they become sufficiently reliable.

Normally, for ACVs, the avoidance of instability in pitch is controlled by the placement of the craft's longitudinal center-of-gravity. Pitch instability manifests itself in terms of a greater tendency for the leading portions of the skirt to tuck under as speed is increased or as the center-of-gravity is moved forward, which, in the extreme, can lead to plow-in. Although plow-in is not normally particularly dangerous, it should be avoided. Figure 47 illustrates how operational limitations can be defined to avoid skirt tuck under or plow-in and how the limits of plow-in are influenced by decreasing the pressure in the bow bag of a bag-and-finger skirt.

Figure 47. Typical ACV Skirt Tuck Under and Plow-In Boundaries

Although the time-tested approach of assessing the stability of ACVs and SES from simple rules-of-thumb, model testing and dynamic simulation, has proven to be adequate, an approach (as suggested in [1]) is needed, at least for early-stage design, to permit the quick and inexpensive exploration of preferred geometries which might otherwise be considered unsafe.

3.10 <u>Heave Stability</u>

It is not possible to accurately predict full-scale cushion behavior based upon model test results. This is due to the problems presented in trying to scale cushion dynamics [39, 40]. Because the compressibility of the cushion is governed by the gas laws, which depend upon absolute pressure rather than gauge pressure, it has been shown [39] that heave motion of an SES (or ACV) is more lightly damped than its corresponding model. This explains the tendency for ACVs and

SES to "cobblestone" at full-scale in relatively smooth seas where the predominant wave encounter frequency can excite the cushion natural frequency in heave. In rough seas the predominant encounter frequency is usually too low to excite heave at its resonant frequency unless the SES, or ACV is large [40]. For large ACVs or SES (greater than say 2000-ton) heave instability can occur unless the craft is equipped with a lift system having the appropriate fan (P-Q) characteristic (as discussed earlier), a simple means of venting the air cushion or uses a ride-control system.

3.11 Seakeeping

It is extremely important that considerations of seakeeping by included in the earliest stages of design. Too often, designs have been developed (even recently) without this consideration, only to be faced with serious problems later that development in the towing tank or use of a ride-control system cannot necessarily solve.

It is important to start with a good knowledge of the area in which the ACV or SES is expected to operate. This knowledge must include a description of the energy-frequency spectrum of the waves, and frequency of occurrence and their direction relative to the intended route.

First of all, it is important to select a vehicle that is large enough and that has an appropriate length-to-beam ratio. The size and geometry of the craft may be dictated by the size and geometry of the payload, but can also be dictated by seakeeping, particularly, when avoiding pitch or roll resonance in high sea states for the operational area of interest.

Figure 48 [21], is an example in which seakeeping requirements have determined the minimum acceptable size of an SES.

Figure 48 was produced with the use of a whole-ship design synthesis computer model [25] from which a plot has been produced showing relative cost versus platform dimensions. Plots like Figure 48 can be used to determine the minimum cost solution for any set of requirements. This design synthesis model for SES has been under development at BLA, Inc. for over 20 years. BLA, Inc. has also developed similar math models for ACVs, catamarans, semi-SWATH, trimarans, planing monohulls, and displacement monohulls. Figure 43 presents a busy chart, but shows how cost varies with changing length and beam for a family of SES designed to meet just one set of speed, payload and range requirements.

Figure 48. Typical Plot of Cost Versus Length and Beam for an SES

Overlaid on Figure 48, as broken lines, are two sets of curves of varying rms vertical acceleration. There is one set for CG acceleration and another set for bow acceleration, all for operation at 35 knots while heading into a sea-state 3.

Craft which exceed the bow vertical acceleration limit (of 0.275 g rms) are below the lowest shaded area of the plot. None of the craft, however, exceed the CG vertical acceleration limit (of 0.15 g rms). A single value, in each case, for an acceptable rms vertical acceleration at the bow and CG in head seas was selected here for convenience in early-stage design. These limiting values of rms accelerations can change, depending upon operator's requirements.

Also shown are the freeboard limits for acceptable deck wetness, which restrict the choice of platforms to those which are to the left of the shaded areas on the right-hand side of Figure 48. The freeboard limits used are based on the curves derived from results developed by Savitsky and Koelbel for small monohulls and show the ratio of freeboard (at the forward perpendicular) to the length on the waterline, plotted as a function of waterline length. The curve suitable for open ocean was adopted for this example and was applied to govern the minimum acceptable freeboard for SES operating hullborne.

The least-cost solution which satisfies these specific requirements is a craft having cushion dimensions of 98 ft by 39 ft, as shown in Figure 48.

The results shown in Figure 48 were for operation in sea-state 3. Thus, all craft were designed with power to achieve 35 knots while heading into a sea-state 3 with acceptable ride quality.

However, for operators interested in a higher sea-state capability, the effect on seakeeping of operating these same craft in sea-state 4, at a lower speed of 25 knots, is shown in Figure 49. This is a speed that all the craft could achieve without an increase in total power.

In this case, as shown in Figure 49, much larger craft are required to meet the requirements. Here, the vertical acceleration at the bow is the controlling factor and we cannot select craft dimensions from within the shaded area of this figure.

Figure 49. SES Design Selection of the Basis of Seakeeping

The least-cost craft for sea-state 4 that meets the stated requirements listed at the top of this figure is, therefore, a craft with cushion dimensions of 164 ft by 59 ft, as compared to 98 ft by 39 ft for sea-state 3. The corresponding cost had, in fact, doubled as a result of designing for sea-state 4 as compared to sea-state 3.

The prediction of SES vertical accelerations shown in Figures 48 and 49 used a seakeeping model developed at BLA, Inc. which has seen extensive verification by comparing simulated results with a wide range of data from model and full-scale tests. For ACVs, a pitch, heave, roll, non-linear time domain program is available at BLA as described in Reference [52].

3.12 Commercial Regulation and Classification

Fulfilling all regulatory, statutory and classification requirements for the safe design and operation of fast passenger craft is a challenge and must be considered early in the design process. The various statutes and regulations to be satisfied are numerous, subject to interpretation, often not conducive to the use of lightweight systems and dependent upon the country in which (or to and from which) the craft will operate. In the United States the Coast Guard has jurisdiction over the certification of commercial craft via the general rules established by the applicable Code of Federal Regulations (CFR Title 46, for example). This code applies rules which vary, depending upon the size (i.e., gross tonnage) and length of the craft and the number of passengers to be carried. Often design standards, such as those defined by the American Bureau of Shipping (ABS), are referenced directly by the CFR. Until recently, neither the CFR nor the ABS rules recognized the unique features of and construction methods for lightweight craft, but in 1991, ABS published their first set of applicable rules [47].

Classification societies in other countries have also been very active in updating their rules for classification of high-speed commercial craft, spurred on by the rapid worldwide expansion of the fast-craft market. Most notable are the revised rules published by Det Norske Veritas (DNV) in Norway and by Lloyd's Register (LR) in the UK, although UK craft are governed (at least until recently) by the rules set, in the 1960's (and periodically updated since), by the British Hovercraft Safety Requirements published by the British Civil Aviation Authority (CAA) [31]. Both the ABS and DNV rules follow the basic philosophy adopted initially by the British CAA and subsequently by the International Maritime Organization's (IMO's) Code of Safety, Reference [41]. This philosophy recognizes that high-speed ferries will be restricted to operate in well defined (coastal) areas where rescue services would be readily available and restricts craft to operate within set limits such as speed and sea state.

This flurry of activity by the classification societies is testimony to the recent and projected rapid expansion of the fast-ferry market. Readers interested in how these various rules are applied can refer to the respective codes or the summary given in Reference [53].

4.0 SUMMARY AND CONCLUSIONS

This paper has reviewed the history of major developments of ACV and SES design, and the options available to, and the constraints imposed on, the designer. With a few exceptions, ACV and SES design technologies are mature and we are now taking advantage of this as we enter an era of renewed hovercraft activity in North America, Europe and the Far East. The fleet of over 90 Navy assault landing craft, LCACs, are now in operation; the Norwegian Navy has most of their MCM SES in operation; the Swedish Navy is considering stealth SES like the ABS M10; the 1500-ton SES "KIBO" is being evaluated in Japan; South Korea is now building SES; and the Canadian Coast Guard has recently taken delivery of the new ACV DASH 400. With the expected rapid growth in experience gained from such programs of construction and operation, we anticipate a continued improvement in the technology base which will ensure the future growth in the use of these craft.

ACVs and SES are competing with planing craft, fast catamarans, wave piercers and hydrofoils (with fully-submerged or surface-piercing foil systems), as well as the slower conventional ferries. There appears to be considerable semantic confusion in the minds of potential operators and builders, regarding distinctions between the various catamarans, SWATH, semi-SWATH, and SES designs [1].

The essential parameters of a successful operation are cost, comfort and speed. "Convenience" may also be considered as a factor in the sense that amphibious ACVs may more effectively access shore connections and the increased draft of hydrofoils and SWATH may restrict their operations in shallow waters. Generally, increased speed and/or comfort will increase the cost per passenger mile. In most applications, comfort tends to be more important than speed. The majority of current ferry routes are two hours or less in duration and are associated with traffic and queuing delays on either end, which diminish the importance of small time savings. Given a choice, few passengers will return, however, after a bout of seasickness or the discomfort of a noise cramped passage with an ability to move about the cabin. There are a number of quantitative measures (rms acceleration, roll period, etc.) which are applied to define acceptable motions, but true measures of passenger satisfaction are elusive and, in the final analysis, only ridership and profit balance will determine the success of an operation.

Speed, which could exceed 60 knots but more practically would be in the 40 to 55 knot range, is the most obvious near-term military advantage of the ACV or SES [1]. With careful design and installation of state-of-the-art ride-control systems, SES (or ACVs) offer significant seakeeping improvements over equivalent monohulls. There are other advantages, depending on the mission. For MCM, shock attenuation is most important. In the case of the U.S. Coast Guard SES, which had operational speeds only a little over 30 knots, platform stability during long hours of loiter on drug-interdiction patrols made these craft the most popular cutters in the fleet from a habitability standpoint. The twin-hull configuration and shallow draft introduced survivability/vulnerability benefits. SES deck area is particularly generous, as is enclosed volume, since designs are generally volume and not weight-driven. Excess volume is desirable where modular concepts are considered.

It is clear that the key to the success of the ACV will continue to be the exploitation of its speed and the many advantages of its amphibious capability. The success of the ACV can be attributed to developments in technology which have provided improved efficiency, improved controllability and reduced operating costs. Advances in skirt design, lift fan and propeller design, the development of bow thrusters, all-welded marine aluminum hulls, and lightweight composites have all contributed significantly to this success.

In the past, ACVs have been expensive largely due to machinery costs. Gas turbine engines, controllable pitch propellers, and high-speed lightweight transmissions are all expensive. The BHC AP.1-88 and ABS M10, which utilize air-cooled diesel engines, fixed-pitch propellers, and a toothed-belt drive, are examples of an approach to a much less expensive ACV. Trends such as these, plus continued improvements in basic technology, will ensure the future growth in the use of these versatile craft.

The performance of an SES or ACV, and other high-performance craft, is more sensitive to weight than the performance of conventional low-speed craft. Thus, there is always a motivation to find acceptably reliable subsystems of minimum possible weight, albeit at a higher price. This has been construed, in some circles, as a major disadvantage for ACVs or SES. However, we prefer to view the ACV or SES as craft that can take cost-effective advantage of using lightweight systems, unlike most other marine craft (and, particularly, unlike Monohulls). What seemingly little motivation there has been in the marine industry to develop lightweight systems (for power plants, transmission systems, structures, outfitting, auxiliary systems, etc.) has resulted, however, in very significant progress over the years, and at a rate which is continuing. For example, without high power-to-weight diesel engines and the use of aluminum alloy or foam-core FRP for hull structure, all of the total power-to-weight advantage of SES (and ACVs), shown in Figure 32 would not have been possible. As further progress is made to develop even lighter systems, the advantage for the SES and ACV will increase.

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