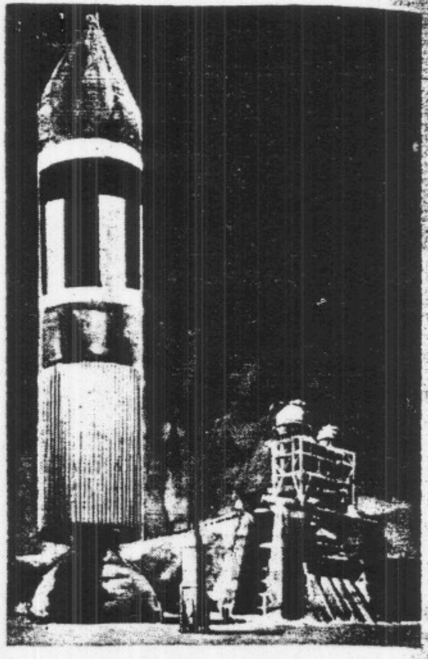


Atlas shows Sea Dragon scale.

Thousand Tons to Orbit

A 20,000-ton recoverable sea-launch rocket may allow the cheap payload-delivery costs required to make extensive manned lunar and planetary programs practical

BY ROBERT C. TRUAX
AEROJET-GENERAL CORP., SACRAMENTO, CALIF.

SEA DRAGON, Aerojet-General's term for its large space-booster concept, has received publicity in recent months primarily because of its operational mode—launching from a floating attitude in the open sea. Although at first glance seeming radical and spectacular, sea launch actually stems logically from fundamental considerations, beginning with the job to be done: Sea Dragon is designed mainly for logistic support of large extraterrestrial bases.

The United States is currently exerting a tremendous effort to be first to land man on the moon, but it is generally recognized that the ultimate objective of our space program is not merely to land a man on the moon long enough to scoop up a few handfuls of moon dust, plant the flag, and depart. The moon has a surface area of some 13,600,000 sq. mi.—greater than the entire North American continent. To profit from our initial investment, this area should be explored and, depending on what we find there, utilized. Furthermore, the planets surely will in time be explored and perhaps colonized.

Such activities, and military activities as well, will require that men, in large numbers, be sent into space and sustained there for extended periods of time, receiving continuous logistic support from the earth; for certainly the epoch of *self-supporting* extraterrestrial civilization is many decades away.

Heavy space-transportation operations are financially impossible now. Even for the minimum space mission, ascent into orbit, the direct vehicle cost is approximately $1000/lb of payload; and the total transportation cost, including amortization of research and development, is much greater than that. At these prices, manned space exploration would quickly consume the total gross national product. Obviously, cheaper means must be found for space transportation.

THE majority of research and development to date has been directed primarily toward increasing the efficiency of the vehicle, that is to say, to improving the payload-to-weight ratio. The Sea Dragon concept assumes that there are three other extremely effective ways of reducing space-transportation costs—making vehicles larger, simplifying them, and making them completely recoverable and reusable.

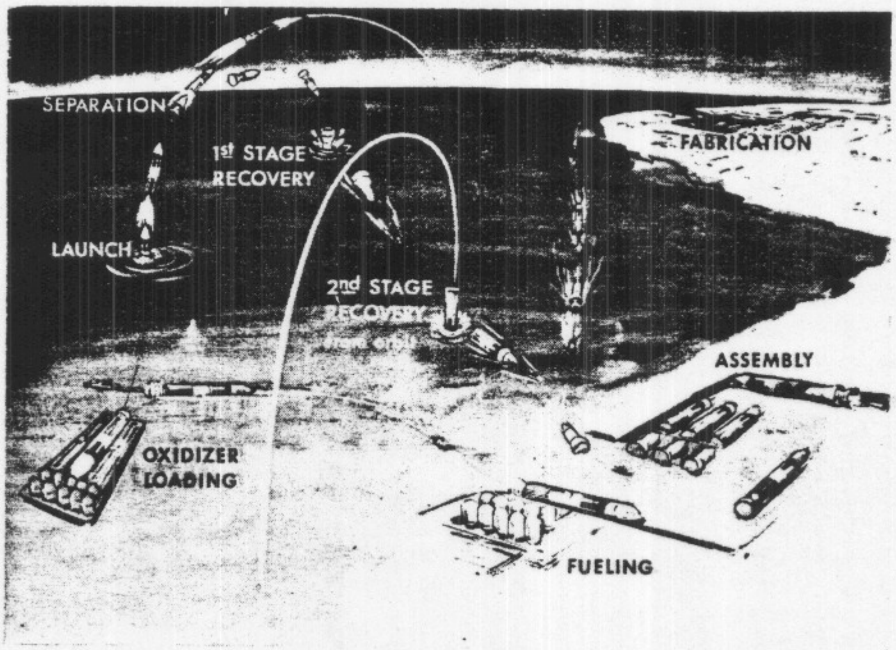
Influence of Size on Cost. Current studies, partly sponsored by NASA, are attempting to determine whether the unique design and operating features of the Sea Dragon concept do indeed bring the over-all costs of space transportation down by a significant amount, as against the Saturn C-5 and other advanced launch-vehicle concepts.

Pending the outcome of those studies, we think that larger vehicles are considerably cheaper in proportion to the payload they carry, on the grounds that many of the elements which enter the total cost picture are independent of size, that many of them increase only slowly with size, that only a few, such as propellant costs, increase in direct proportion to size, and that only a negligible fraction increase more rapidly than a direct proportion to size. Since payload generally increases at least in direct proportion with gross takeoff weight, it seems certain that the cost per pound of payload should diminish as the vehicle grows in size, at least up to some as yet undefined upper limit.

Nonlinear variation of cost with size might be substantiated by an examination of existing vehicles. Unfortunately, there are no directly applicable examples, because all vehicles today which differ considerably in size also differ considerably in design detail. Perhaps the Thor and Agena present the best example of two vehicles that differ greatly in size but have nearly equal numbers of very similar components. Both are single-engine liquid-propellant rockets. Although approximately 10 times as big as Agena, Thor actually costs less, and it even cost less at a comparable point on its learning curve. Such an example does not prove that small vehicles cost proportionately more than large vehicles, but it certainly does indicate that elements other than size can greatly overshadow size effects.

The Influence of Simplicity. When we observe that the difference in payload-to-weight ratio between vehicles using relatively simple propulsion systems and those using very complex ones may be less than a factor of 2, and when we see examples of vehicles and their components which differ by a factor of 10 in size, yet only negligibly in cost, we might well question the degree of sophistication that can be justified on a cost basis. And for man-carrying vehicles, where reliability may well determine the total number of re-uses possible, we might conclude that extreme simplicity must be rigidly adhered to, even at the expense of a considerable loss in payload-to-weight ratio.

OVER-ALL OPERATIONS IN SEA DRAGON CONCEPT



The graph on page 46 gives the approximate exchange ratios. For an ideal velocity increment of 10,000 fps, such as might be representative of a first stage using liquid oxygen and kerosene (RP-1), the size increase required to compensate for a reduction in propellant fraction from 0.95 to 0.85 is only a factor of 1.3, or a 30% increase in takeoff weight. A propellant fraction of 0.85 is probably representative of a fairly good pressure-fed design, and 0.95 would be typical of a well-engineered turbopump system.

A second stage to give 20,000 fps with hydrogen and oxygen would experience a growth factor of 1.4. It should be noted that the spread between pump and pressure-fed propellant fractions is somewhat less in upper stages because of greater "g" penalties on the very thin-walled pump-fed design and the possibility of using lower combustion and tank pressures in pressure-fed stages.

This cursory examination leads one to expect that the simpler vehicle would have to be about 80% larger than the sophisticated one.

The Influence of Recoverability. It takes more than 30 lb of booster to put 1 lb of payload in orbit. Most booster weight, however, is propellant, and liquid propellant can be very cheap. For example, it costs only $2.00 for the propellant (oxygen-hydrocarbon) required to place a pound of payload in orbit, even with a relatively inefficient booster—a small fraction of total booster cost. If each vehicle could be used many times, the hardware cost could perhaps be greatly reduced, particularly if the turnaround costs in the recovery operation were not large compared with the initial cost of the vehicle.

If we assume, for example, that larger size will decrease the empty vehicle cost to $100/lb and we can re-use each vehicle 100 times, then vehicle cost becomes of the same order as propellant cost, and the direct vehicle cost resulting from a combination of these two elements is several hundred fold less than the current cost incurred in the use of ballistic-missile boosters.

Sea Dragon Concept. The design study on Sea Dragon aims to satisfy to the greatest possible extent the cost-saving philosophies just discussed. It envisions a two-stage-to-orbit rocket having a takeoff weight of about 40-million lb and a payload capability between 1- and 1.5-million lb into a 300-mi. orbit. Propellants are liquid oxygen and kerosene in the first stage and liquid oxygen and liquid hydrogen in the second stage. Both stages of the vehicle are pressure-fed and use a single thrust chamber for primary propulsion. A first-stage chamber pressure of 300 psi leads to tank pressures in the order of 450 psi. A second-stage chamber pressure of about 75 psi gives tank pressures in the order of 120 psi.

From a propulsion point of view, the Sea Dragon vehicle is very nearly two scaled-up Aerobees, one stacked on top of the other. It has a first-stage propellant fraction of about 0.89, and a second-stage fraction somewhat in excess of 0.90. The saving from a lower feed-pressure in the second stage is offset by the lower density of its hydrogen and oxygen propellants.

These characteristics give a vehicle of considerable size—a tank diameter of 75 ft and an over-all length of nearly 500 ft. The hugeness of such a vehicle recommends sea-based operations including recovery at sea. It will be seen that the use of a simple pressure-fed vehicle, desirable in itself from a cost and reliability standpoint, greatly reduces the difficulties associated with sea operations.

Operational Sequence. To minimize the operational penalties associated with vehicles of very large size, the Sea Dragon system would have vehicles assembled within a drydock, towed to the launch site, and fueled and launched without ever removing them from the water.

Even though the Sea Dragon vehicle would be much larger than any rocket heretofore constructed—even considerably larger than the conceptual Nova design—it is still a small piece of hardware by shipbuilding standards. Any number of drydocks in the country are large enough to handle its final assembly operations. Shipyard equipment for forming and handling materials is generally adequate in size to meet the Sea Dragon requirements. To be sure, the materials of construction must be different, the design margins made less, and more refined techniques used in many areas. But the basic facilities are already in existence.

To the maximum extent possible, the Sea Dragon vehicle would be handled like a ship. After completion of fabrication, each stage would be towed out of its drydock and transported by means of a tug, without benefit of barge or other protection, to an assembly and checkout lagoon at Cape Canaveral. At dockside there the stages would be mated and most of the checkout performed. Following that, the vehicle would be moved to a nearby dock and serviced with kerosene and hydrogen. It would then be towed several miles off shore to a fueling slip and loaded with liquid oxygen. Upon completion of propellant servicing, the vehicle would be towed to sea an additional 30 mi., erected by flooding a ballast at its stern, and fired directly out of the water.

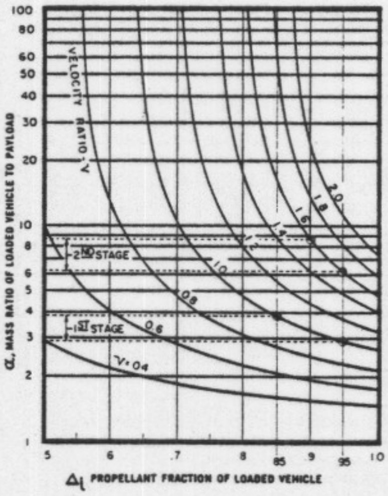
After separation the first stage would re-enter the atmosphere at about 7000 fps, would be decelerated to 600 to 700 fps by aerodynamic forces, and finally brought to a stop by water impact. The first stage would be taken in tow by a tug and returned to the lagoon at Cape Canaveral for reservicing and re-use.

THE second stage would continue into an orbit approximately 300 mi. high, where it would discharge its cargo either by rendezvousing with a space station, by rendezvousing with another vehicle to be serviced, or simply by launching an upper stage which might well constitute its payload. The second stage would then be reoriented and upon reaching a favorable spot, perhaps after several orbits, would receive a retro-impulse out of orbit and subsequently re-enter and be decelerated by the atmosphere and water impact, as with the first stage. By proper selection of the re-entry point, the tow-back operations could be reduced to perhaps as little as a few miles, and certainly kept below a hundred miles. The second stage would then be inspected, remated with the first stage, reserviced, and reflown. The illustration on page 45 depicts the over-all operation.

It is not expected that any of the components of the vehicle would wear out in less than a hundred re-uses. The vehicle life would be terminated not by wearing out, but by loss due to inherent unreliability. A few parts, such as the ablating nose cap for the second stage, would be expendable, but the number of items that would have to be replaced for each flight should be very small. To obtain adequate reliability on the ascent, the vehicle would be piloted or pilot-monitored. There would be a heavy redundancy in the electronics and in other items that in such large vehicles constitute a negligible fraction of the cost and weight. The two stages would be unmanned for re-entry and impact. The astronauts would either continue on a space mission or return in an Apollo-type capsule.

Some Water-Basing Considerations. While water-basing solves a number of particularly pressing problems, it also introduces several not encountered in more conventional operational concepts. Compared with a ground environment, it provides a more uniformly distributed but much less rigid support. It is more corrosive and more dense than air.

SIZE EXCHANGE RATIOS



Note: Velocity ratio, V, equals ratio of ideal burnt velocity to effective exhaust gas velocity.

Consider first the problem of corrosion. Normally we think of a space booster as an extremely complicated and delicate device containing thousands of relays, vacuum tubes, etc., which certainly should not be sloshed around in salt water. A little reflection will show, however, that there are very few components which cannot be suitably protected or completely enclosed within the vehicle structure.

Corrosion is primarily a consideration with respect to the vehicle skin, and perhaps to certain areas of the inside of the thrust chamber from which it may be difficult to exclude salt water in a recoverable device. Candidate materials for the vehicle structure, which is primarily the propellant tankage, appear to be titanium, aluminum alloy, maraging steel, and possibly cryogenically stretched stainless steel of the 300 series. The corrosion resistance of titanium is practically perfect in sea water and salt air; that of stainless steel is probably adequate. Of the aluminum alloys, perhaps only those of the 2000 series are competitive from a strength/density standpoint. Aluminum-alloy tanks and structural members exposed to sea water would require an impervious film to prevent corrosion. Although the corrosion resistance of the maraging steels have not been completely determined, it appears that protection of those alloys would also be required.

NORMALLY, adequate protection of almost any kind of metal from the action of sea water can be obtained through the simple application of a coat of paint. For recoverable boosters, however, there is the possibility that high or moderately high skin temperatures encountered during re-entry would burn away most types of protective organic films. Platings, cladding, or anodic coatings are possible solutions. Since actual water-immersion time after re-entry would be very short, local repainting might suffice.

The thrust chamber and injector very probably would be made of stainless steel.

A second constraint of sea operations is the continuous motion of the vehicle. This motion has implications for guidance and control and in servicing and checkout before launch. A ballast unit at the extreme rear of the rocket would permit it to float horizontally when either wholly loaded or empty. Flooding of a buoyancy chamber in the ballast would erect the rocket to the vertical in the loaded condition. Because of the long length of the vehicle, and its high moment of inertia, it is expected that in, the vertical position, the oscillation of the vehicle, because of wave action, will be less than 1 deg. Its constant angle induced by a steady 50-knot wind will also be considerably less than 1 deg.

Present studies call for a self-erect

ing guidance platform. The erection could be accomplished one of several ways—by torquing the gyro in response to accelerometer signals and thus erecting to an average vertical, by the use of some form of horizon scanner to determine the vertical, or by the use of narrow-beam antennas operating in conjunction with two or more land-based stations.

It will also be necessary to determine the location and velocity of the vehicle before launch, as it would normally be expected to pick up the motion of the current. The present plan calls for launches to be approximately 37 mi. off Cape Canaveral. At such a distance, shoran and radar tracking, or even optical tracking, might be used. Such a distance also makes it possible to use radio guidance for the ascent portion of the trajectory.

Another aspect of vehicle motion is the increased difficulty of performing checkout, propellant loading, and monitoring of various measurements during countdown. To minimize these difficulties, it is expected that most of the checkout would be conducted with the vehicle in the empty condition and tied up to the dock. Here any desired amount of instrumentation could be connected from a dockside facility. The very slight vehicle motion under these conditions should necessitate only slight differences in technique from those used with land-launched vehicles. Fueling with kerosene and hydrogen, also done at dockside, would differ only in detail from conventional practice. It is the large amounts of propellant to be loaded on board, and the consequent explosive hazard which could result in the event of major malfunction, that led to the selection of offshore loading of the liquid oxygen. A tethered floating dock could be used to contain the propellant required for servicing, or the liquid oxygen could be loaded aboard directly from a tanker. Relative motion could be minimized by making the dock in the shape of a ferry slip or artificial lagoon.

The monitoring of various functions during the last portions of the countdown probably constitutes the most troublesome problem in sea launch.

According to one estimate, the Saturn C-5 will have seven umbilicals, each connected to 10,000 lb of checkout equipment. The propulsion simplicity of Sea Dragon will go far toward reducing the number of functions to be monitored; but it will by no means eliminate monitoring. The attack on this problem involves first a careful screen-out of items which, properly checked at dockside, should have small chance of failure between dockside checkout and launch. Secondly, the ability of the crew of the Sea Dragon to monitor the status of the vehicle would be utilized to the fullest. Any items still remaining would probably have to be telemetered to the Cape for monitoring there. A floating communications center might be used to insure the safety of "blockhouse" crews. The "blockhouse" might actually be at the Cape or on a ship somewhat closer to the launch point. (Even if all checkout equipment normally connected with a launch were carried to orbit on Sea Dragon, the effect on payload would be small.) Such functions as auxiliary power and final propellant topoff could be performed from the ballast unit without problems of relative motion. Auxiliary pods on the sides of the vehicle, in the vicinity of the water line, could be detached just before launch.

Besides imparting a continuous motion to the vehicle, sea-basing places certain limitations on accessibility. With vehicle empty, however, the sea denies access to only about 10% of its external skin. If necessary, total access could be obtained by rolling the vehicle around its longitudinal axis. Access to interior spaces could be obtained through hatches. Completely loaded with propellants, the vehicle floats about half submerged. Erected it floats about two-thirds submerged.

Under these circumstances, as indicated on page 48, access to the interstage structure and to the after end of the vehicle would not be possible without a special access trunk, which could be detachable. The rugged structure resulting from the use of pressure-fed propulsion systems makes it possible, however, to erect and de-erect a vehicle in the completely fueled condition. If it were found necessary to have physical access to the after end of the vehicle, ballast could be blown and the vehicle returned to the horizontal attitude.

The sea also introduces the problem of external hydrostatic pressure. This varies directly with the amount of immersion, at the rate of about half a pound per square inch per foot of immersion. Not properly accounted for, it could cause tank collapse. As it turns out, hydrostatic pressure can become serious only when the vehicle has been completely serviced with propellants. Then the internal hydrostatic pressures are so great that tank pressurization must be maintained to avoid inversion of internal bulkheads, as well as to resist external hydrodynamic loads.

Internally pressurized to half the normal rated design pressure or less, rocket vehicles of this general type become extremely strong and stiff. Little or no increase in structural strength would be required to enable the vehicle to be borne completely on a single, centrally located wave or on the crests of bow and stern waves.

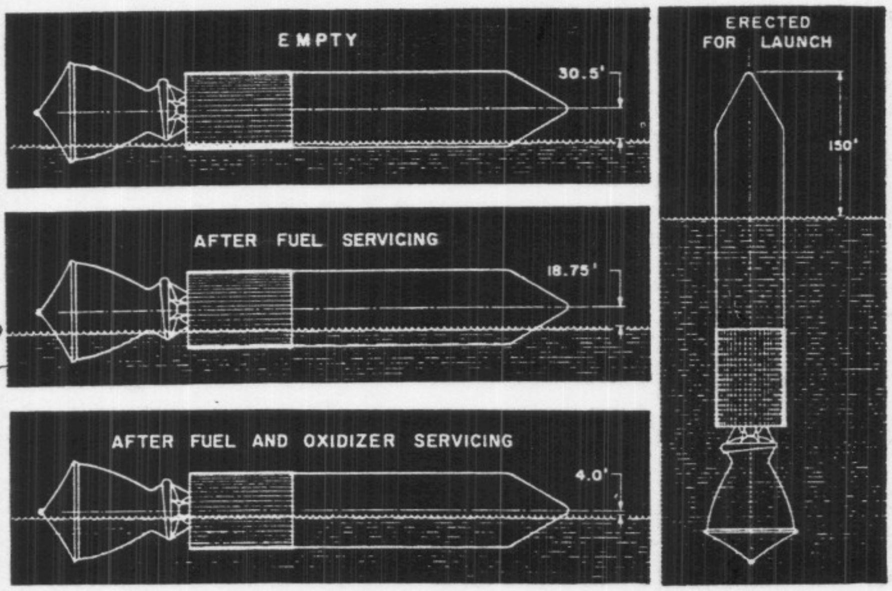
The vehicle skin would vary from 1/2 in. to as great as 6 in. depending on the stage material and design pressure. These thicknesses are as great or greater than the hull plating on ships. Far from being a fragile craft, the Sea Dragon type of rocket will ride out any weather not causing its towing vessels to founder.

Hydrostatic pressure can cause difficulties with a conventional DeLaval nozzle. At the high ambient pressures encountered at light-off, overexpansion and separation will take place in the nozzle, with resulting high loads on the nozzle and possibly erratic thrust alignment. Two solutions appear possible—a compensating (plug or forced deflection) nozzle or insertion of a choke in the diverging portion of a DeLaval nozzle to prevent overexpansion. Such a choke might be an integral part of the ballast.

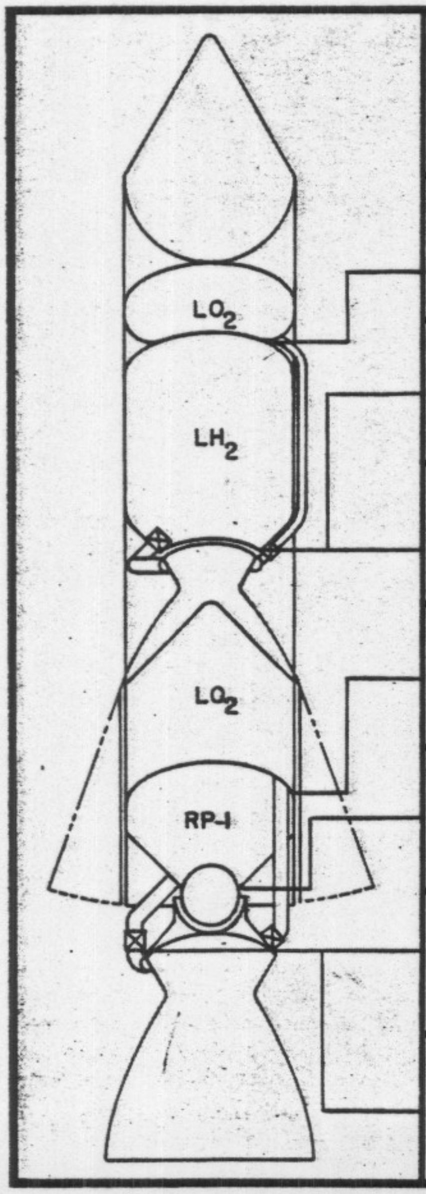
Finally, we have the problem of electrical and thermal conductivity of water as compared with air. Sea water, of course, would quickly short any exposed electrical conductors. So electrical connections not readily canned or potted and located external to the main vehicle shell must be protected by suitable waterproof conduits. The only electrical circuits which appear to be in this category are the servovalve connections for the gimbal actuators, the actuator feedback circuit, and possibly the igniter circuit if pyrotechnic ignition were used.

The higher thermoconductivity of the water would lead to excessive boiloff of the cryogenic propellants and

SEA DRAGON FLOATING CHARACTERISTICS



SYSTEM PRESSURE CHARACTERISTICS



LOCATION POINT	HYDROSTATIC PRESSURES	
	LIFT OFF	STAGE I b.o.
BOTTOM OF LO_2 TANK	34	78
BOTTOM OF LH_2 TANK	6	14
LO_2 AT VALVE	120	276
BOTTOM OF LO_2 TANK	83	0
BOTTOM OF RP-1 TANK	35	0
RP-1 AT INJECTOR	51	42
LO_2 AT INJECTOR	140	131

the formation of external ice if no insulation were provided. It has been determined, however, that 1/2 to 1 in. of ordinary foam-plastic insulation would be adequate to inhibit completely the formation of ice in those areas where relatively free external water convection is maintained. Special precautions would be necessary at the interface between liquid oxygen and water in the line between the propellant tank and the injector. A removable heat barrier must be provided inside the flow passage, and a permanent heat barrier in the duct itself. The first is probably most easily satisfied by a gas pocket; the second by low-conductivity gaskets. In vehicles of this size even several inches of insulation would add only a negligible amount to the total weight.

Potential solutions exist, then, to all of the currently foreseen problems brought about by the use of the sea as an operating medium for very large space boosters. For the rugged vehicle in the Sea Dragon concept, the sea environment contributes no special penalties. On the contrary, using the sea allows convenient, ready transport by standard commercial tugs; eliminates special transporters and erecting equipment, except for the ballast unit; circumvents any need for many square miles of expensive real estate; and provides a variable amount of isolation and ultimately a large amount of freedom in launch location. The sea provides free and automatic fire protection and protection from thrust-chamber explosion.

The sea can also be used for research and development testing, its free expanses solving problems of noise and explosion hazards. The complete safety possible with sea testing would permit tanks in development to approximate flight design, both as to arrangement and safety factors. The result would be a sharp reduction in the problems associated with the marriage of the propulsion system and flight tankage—problems normally encountered after development of a conventional pump-fed engine on a test stand.

For sea testing it is only necessary to equip the tank–engine combination with a thrust-deflector plate which also serves as a thrust neutralizer. The thrust-vector-control system would also have to be installed and activated during development testing. During a test run, the test rig would begin almost completely submerged and would gradually rise out of the water, held erect by thrust-vector control. At exhaustion of propellant, it would be in the neighborhood of 10 to 15% submerged. Perhaps only through the use of the sea as a testing medium can really large single-unit thrust chambers such as proposed for Sea Dragon be developed at a reasonable cost. It is estimated that the cost per sea test of an 80-million-lb-thrust engine would not greatly exceed that of a million-lb-thrust engine tested on land.

Sea-Basing and Recovery. Perhaps its greatest single advantage, sea launch blends perfectly with sea recovery, and sea recovery appears much simpler than recovery on land. Aerojet has demonstrated the parachute recovery without damage of an Aerobee at sea. And the Mercury nose cones and the Discoverer capsules, of course, have also been recovered undamaged at sea by parachute.

An even simpler system is being investigated for application to Sea Dragon—final deceleration by the hydrodynamic and hydrostatic forces of water alone, without the use of parachutes, retrorockets, etc. The Sea Dragon design should survive impact at velocities up to perhaps 700 fps if a pointed conical or ogival nose is used together with stage configurations of rather high drag. It seems nearly certain that its proposed stages would withstand impact velocities of at least 300 fps and that this velocity could be obtained with a parachute only slightly larger than the largest current cargo chute.

Scaling Effects. A number of interesting scaling effects occur with vehicles of the size under discussion. These effects can be favorable or unfavorable, depending on the design of the vehicle and its operating environment. For instance, we find that the size of the thrust chamber increases in proportion to the rest of the rocket for a constant chamber pressure. For geometrically similar chambers this would mean an increase in the chamber weight as well. Fortunately, design economies are possible with large chambers that are not with small. No serious penalty seems to be incurred up to a thrust in the order of 80-million lb.

A beneficial side effect of a big increase in thrust-chamber size is the fact that the nozzle-exit area becomes the largest cross-sectional area of the vehicle. This tends to make large vehicles aerodynamically stable without auxiliary fins or skirts, and so dovetails with a passive recovery system. It also minimizes thrust-vector-control requirements and gives a longer time for the crew to escape in the event of control malfunction.

The boiloff rates are extremely low in vehicles of Sea Dragon size. It has been calculated that, with the insulation (1/2 to 1 in.) required to prevent the formation of ice, the boiloff rate of the liquid oxygen would be less than 1% per day. With reasonable insulation on the liquid-hydrogen tank, its boiloff rate would be less than 5% per day.

Propellant hydrostatic pressures can also be important in very large rockets, particularly with propellants other than hydrogen. For the Sea Dragon, these pressures are approximately as shown on the accompanying page. Consequently, at the low chamber pressures contemplated for the second stage, the normal vapor pressure of the liquid oxygen in conjunction with the hydrostatic head would feed the oxidizer. First-stage hydrostatic propellant pressures significantly reduce the amount of pressure required.

Under the high deceleration of water impact, large and potentially destructive hydrostatic pressures can develop in such items as thrust-chamber tubes. Designs must therefore prevent accumulation of more than a few feet of liquid.

There are at least two interesting scale effects on engine design. The first is a detrimental one, leading to higher wall temperatures in the thrust-chamber coolant tubes. If in scaling up the thrust chamber the tube size is held constant, and only the number and length of the tubes increased, the pressure drops encountered become prohibitively large. If, on the other hand, the tube size is increased, then the tube wall thickness must also be increased. Increased wall thickness leads to increased temperature drop through the tubes and to higher gas-side wall temperatures. With conventional regenerative cooling by fuel, the Sea Dragon first-stage thrust chamber approaches the size at which stainless-steel wall material can no longer be used. Other design possibilities exist, however, including the use of materials having a higher thermal conductivity–strength factor and nonregenerative cooling (coolant discharged overboard or into nozzle section).

If for thermodynamic reasons you take a minimum ratio of chamber-cross-section/nozzle-throat area, and assume that a sphere gives the minimum-weight container for any fixed cross-sectional area, then characteristic chamber length (l^*, chamber volume/nozzle throat area) increases with thrust, and in the Sea Dragon becomes very large, in the order of several hundred. Such an increase in l^* might permit very simple injectors (that is, a small number of large holes) or alternatively give higher combustion efficiency.

Of course, with an increase in size comes an increase in tank skin thickness. This can be highly beneficial from the standpoint of ruggedness against general handling damage and can make the design less susceptible to local imperfections. On the other hand, skin too thick might cause welding difficulty and increased welding costs.

There are scale effects in the external aerodynamics which are generally favorable. At least up to the point where the nozzle-exit diameter equals the tank diameter, the percentage of the total impulse expended in overcoming drag becomes continually less with an increase in size.

In one sense, increased size makes recovery more difficult; impact velocities increase with vehicle size because the weight per unit area increases. The "g" forces, however, decrease in direct proportion to the length of the vehicle.

Conclusion. Very large vehicles can be justified on economic grounds if they exploit a developmental and operational technique that minimizes costs that scale rapidly with vehicle size. Sea testing, launching, and recovery constitute such a technique. Large vehicles, as well as sea launch, put a premium on simplicity to increase reliability and reduce development costs. Single-engine, pressure-fed propulsion systems give this simplicity. All tie in to give a well-integrated concept. Detailed studies must further define sea-launch problem areas and design approaches. Experimental solutions to some of the practical problems have been sought by sea launch and recovery of an Aerobee rocket, and new experiments are currently underway with a larger vehicle.

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