HYDRODYNAMIC ASPECTS OF A DEEP-DIVING OCEANOGRAPHIC SUBMARINE

P. Mandel
Massachusetts Institute of Technology

INTRODUCTION

There is little question that the major problems that arise in the design of very deep diving submarines are in the field of structures and not in the field of hydrodynamics. However, several hydrodynamic problems exist that are peculiar to the very deep diving oceanographic submarines that are of little or no importance in the design of the most advanced military submarines. These problems arise in connection with: (a) the ballast systems needed for operation at great depths, (b) the oscillations that may be excited by vortex shedding during vertical ascent or descent, (c) the effects on depth and trim angle control of the compressibility of the submarine hull and of sea water, (d) the precise control in both the horizontal and vertical planes needed to perform the mission of the boat, and (e) directional stability when under tow on the surface. This paper will concern itself largely with these five questions plus some introductory discussion of how the configuration of a deep-diving submarine compares to military submarines and bodies of revolution of elementary shape.

This paper will draw on experience gained during the design of the oceanographic submarine Aluminaut which is described in Ref. 1. The design of this unique vehicle was based on general concepts initiated by Dr. Edward Wenk, formerly of Southwest Research Institute, San Antonio, Texas. The design was developed to its current state under a project initiated by Mr. J. Louis Reynolds, Vice President, Reynolds Metals Company. Negotiations for construction of the boat are currently nearing completion.

The Aluminaut differs in basic concept from the previous generation of deep-diving vehicles marked by the bathyscaphes FRNS and Trieste which were developed by Auguste Piccard. It will be recalled that it was the Trieste which made the record-breaking dive on January 22, 1960, to a depth of 37,800 feet. These vehicles depend on a buoyant liquid, gasoline, to support about 90 percent of their total weight while their small pressure hulls support only about 5 percent of their total weight. The remainder of their weight is supported by the buoyancy of structure. In contrast the buoyancy of the pressure hull of the Aluminaut supports over 80 percent of its total weight. The marked effect of this change of concept can be seen by study of Table 1. With a total submerged displacement of slightly more than half of the Trieste, the Aluminaut has about 9-1/2 times the useful volume and possesses mobility and endurance that are vastly superior to the Trieste. It is these deficiencies of the Trieste plus the difficulties in handling large quantities of volatile gasoline that prevent full appreciation in oceanographic research work of her superlative depth capability. Even the retrogress of the Aluminaut from the remarkable depth capability of the Trieste is more apparent than real since only about 40 percent of the world's ocean area is greater than 15,000 feet deep. Thus, the Aluminaut has great potentiality as an oceanographic research vehicle.

Table 1
Comparison of Characteristics of the Trieste and the Aluminaut

Category	Items	Trieste	Aluminaut
Dimensions	Length overall, ft	49.5	50.7
	Max. Beam, ft	11.5	10
	Draft, before dive, ft	17.5	11.5
	Inside diameter of pressure hull, ft	6.56	7.0
	Inside length of pressure hull, ft	6.56	39
	Thickness of pressure hull material, inches	3.54	6
Volumes (cu ft)	Total submerged volume at depth	3,940	2,280
	Internal volume of pressure hull	148	1,405
	Buoyant volume of pressure hull	191	1,860
Weights (lb)	Pressure hull structural weight	21,520	89,030
	Other structural weight	33,600	7,500
	Ballast, permanent and jettisonable	24,620	21,200
	Propulsion, batteries, pumps, controls	?	12,400
	Flotation fluid	157,000	12,650
	Scientific payload	~500	~4,000
	Total submerged displacement	252,000	149,000
Materials	Pressure hull material	Steel	Aluminum
	Flotation fluid	Gasoline	Silicone
Performance Characteristics	Operating depth, ft	37,800	15,000
	Test	?	17,000
	Collapse depth, ft	?	21,000
	Max. horizontal speed, knots	1/4	4.7
	Horizontal endurance, miles	4	96
	Endurance, hours	8*	36 normal 72 emergency
	Vertical speed, fps	3	3 normal 11 max
	Power available for instruments, kwh	2-1/2	64
	Crew Number	2	3

*1/2-4 hours at depth depending on time for vertical traverse.

THE ALUMINAUT CONFIGURATION

The configuration of a deep-diving submarine is largely determined on the basis of structural and arrangement requirements. For the Aluminaut a cylindrical pressure hull with hemispherical ends was selected as a good compromise between an optimum structural configuration and a configuration most suitable for housing people and equipment. The forward pressure hull hemisphere and the cylindrical portion of the hull form the basic external hull of the submarine since these are not entirely unsuitable from a hydrodynamic point of view. For hydrodynamic reasons, however, the aft pressure hemisphere is enclosed within a non-pressureproof, almost conical, stern capsule that provides some hydrodynamic fairing and also serves to house the electric propulsion motor and control mechanism. This obviates the need for large mechanical penetrations of the pressure hull. This capsule is filled with a buoyant silicon fluid (specific gravity—0.76) that provides a suitable environment for the motor in addition to providing a modest amount of buoyancy (~13 percent). The stern capsule is pressure equalized to the open sea at all times so that it may be constructed of relatively light structure. Figures 1 and 2 show the general configuration of the submarine.

The configuration, thus determined, has somewhat different proportions than the usual military submarine. The length/diameter, L/D, ratio is lower and the prismatic coefficient, C_p, (ratio of volume of submarine to volume of circumscribing cylinder) is higher than the corresponding proportions of military submarines. These properties of the Aluminaut are conducive to minimizing wetted surface and hence frictional drag at the expense of an increase in separation and form drag. The differences in wetted surface between the Aluminaut and military submarines and the wetted surfaces of elementary body of revolution shapes similar to submarines are shown in Fig. 3. The ordinate of this figure is the wetted surface of solids of unit volume. (For example, a cubic prism of unit volume has a wetted surface of 6.) To compute the wetted surface of geometrically similar volumes, it is only necessary to multiply the value of the ordinates in Fig. 3 by the volume raised to the 2/3 power. It is seen that not only does the Aluminaut have substantially less wetted surface than military submarines because of her low L/D and high C_p, but with those proportions her hemispherical nose and essentially conical stern offer almost as low wetted surface per unit volume as the less hydrodynamically satisfactory combination of conical nose and stern. The comparison is as follows at the Aluminaut L/D and C_p:

Configuration	*Wetted Surface for Unit Volume*
Hemi-nose; conical tail	6.90
Conical nose; conical tail	6.89

The additional useful information shown in Fig. 3, computed on the basis of information given in Appendix A and taken from Fig. 7 of Ref. 2, is in the nature of a postscript to the main purpose of this paper. Primarily, the figure shows the large penalty in wetted surface associated with high length/diameter ratios, which is well known, and the variation of wetted surface with prismatic coefficient and end shape, which is not so well known. Within the range of L/D's suitable for streamlined bodies ($L/D > 3$) and at low values of C_p, the bodies with conically shaped nose as well as tail, have the least wetted surface, the bodies with hemispherical noses and conical tails have the next greatest, while bodies with submarinelike noses and tails have the most wetted surface. This latter fact is consistent with the frequent observation that achieving reasonable form drag usually involves increased wetted surface and frictional drag. At high prismatic coefficients the effect of end shape on wetted surface is not nearly as decisive as at low values of C_p. It might also be observed that to achieve the complete continuity at the intersections of the parallel middle body and the end shapes that is needed to minimize form drag, and that is so obviously missing with pure conical or even hemispherical ends, much higher prismatic coefficients are associated with a fixed percentage of parallel middle body L_x' for the submarinelike bodies than for the simpler shapes. All in all it is evident from Fig. 3 that the L/D ratio is the most important parameter influencing wetted surface and that prismatic coefficients in the practical range from 0.50 to 0.90 are also conducive to minimizing wetted surface for any fixed L/D ratio. For a more thorough discussion of this particular question, the reader is referred to Section 3 of Ref. 2.

Figures 1 and 2 indicate that the Aluminaut is encumbered with many appendages. Most of these are needed to house equipment or ballasting functions (described subsequently) that are advantageously mounted external to the main pressure hull. As shown in Fig. 2, and also subsequently in Fig. 6, some of these appendages are not suitably faired, but this problem is fully appreciated by all concerned and it has been decided that the building plans will incorporate suitable fairings. Even faired, it is estimated that the appendages will more than double the bare hull-drag of the submarine in horizontal motion. Drag estimates will be shown in Fig. 13.

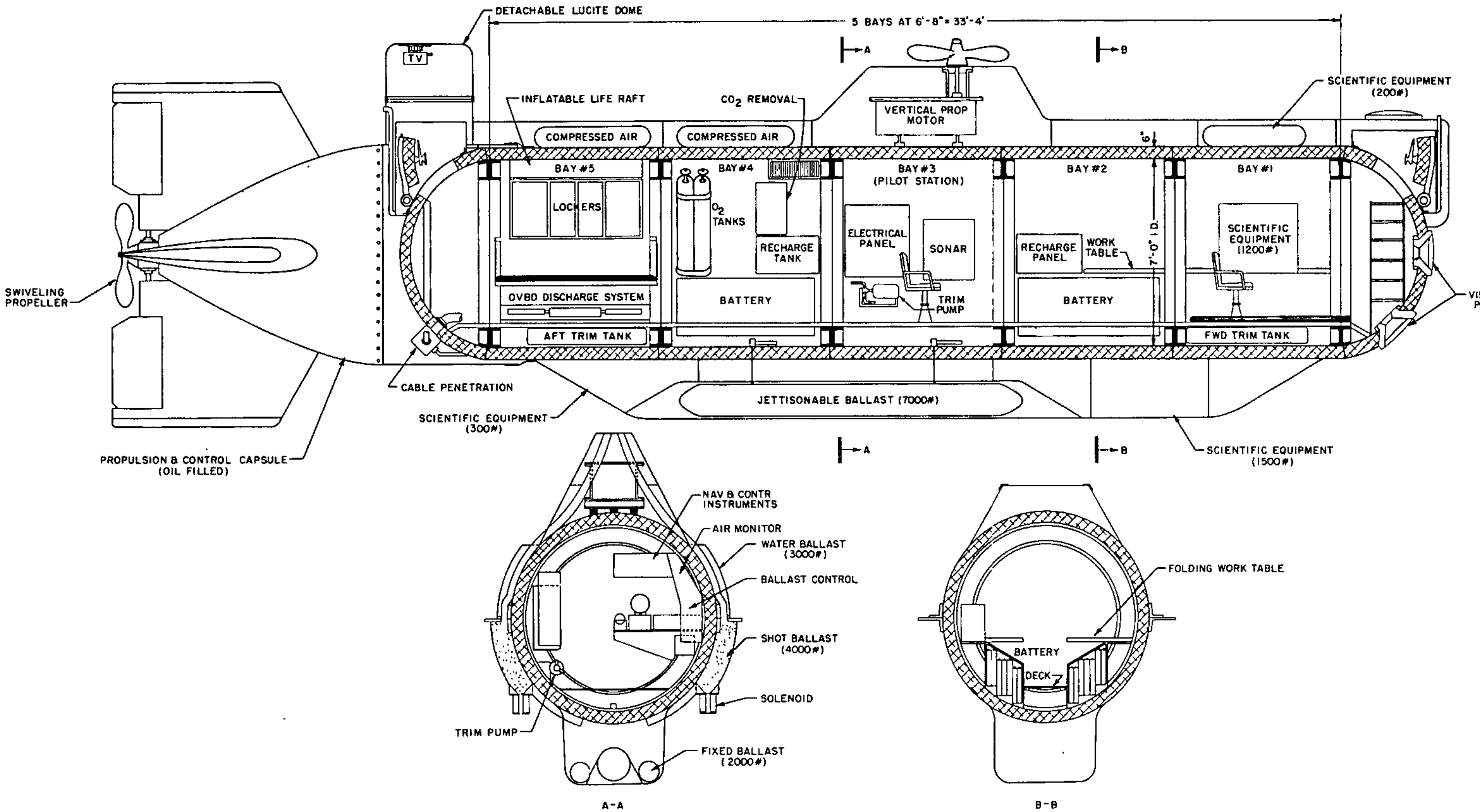

Fig. 1. Aluminaut inboard profile and sections

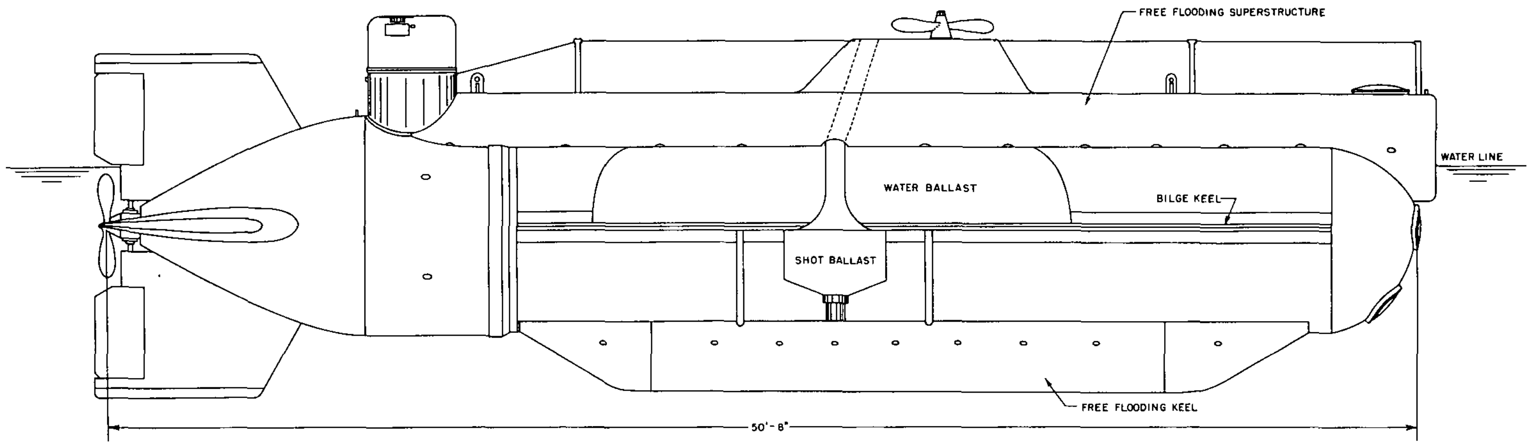

Fig. 2. Aluminaut outboard profile

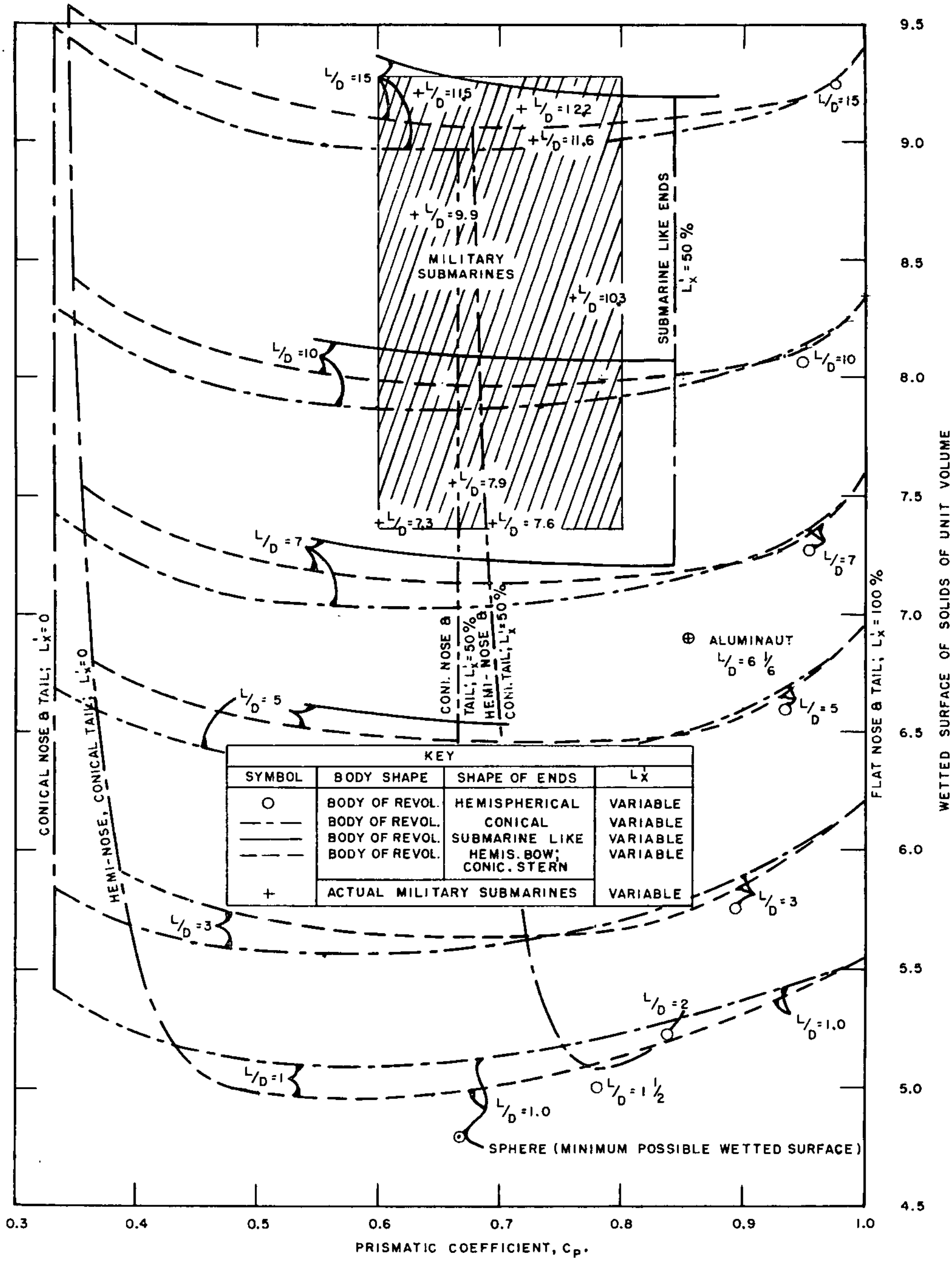

Fig. 3. Wetted surface of bodies of revolution as a function of length/diameter ratio, prismatic coefficient, and end shape

BALLAST SYSTEMS

Although water is ordinarily employed for variable ballast on submarines, the energy and pump weights required to eject water at great depths render almost essential the use of alternate ballast systems at such depths. Actually four ballast systems are employed on the Aluminaut, three of which are variable and one of which is fixed:

1. The ballast intended for routine ascent at great depths is 4,000 pounds of iron shot, contained in two amidship external saddle tanks shown in Figs. 1 and 2. These tanks are loaded through filling tubes in the superstructure when the boat is on the surface and emptied as desired through hollow solonoids at the bottom of both tanks. When energized (they draw only 36 watts each) the solonoids magnetically solidify the shot so as to plug the shot-tank aperture. When current to the solonoids is cut, either deliberately or by accident, gravity will cause the shot to flow out at any depth of operation. Thus, this system which was devised by Piccard for the bathyscaphes is relatively fail safe. To prevent electrolytic action with the iron shot, the aluminum saddle tanks are lined and the filling tubes molded of plastic. Special measures such as the prevention of exposure of wet shot to the air must also be taken to prevent the iron shot from corroding and consolidating. The iron shot described here has been successfully used with the bathyscaphes.

2. To augment the preceding system and also to permit the submergence of the boat from the surface to be under the complete control of the pilot within the boat a conventional water-ballast system is also provided. The tanks of this system which are also external to the pressure hull have a capacity of 3,000 pounds of sea water and are always open to the sea. Like conventional submarines, water is excluded from these tanks by means of a closed air valve; it can be admitted by opening the air valve and can be ejected from these tanks by compressed air stored in flasks located above the pressure hull as shown in Fig. 1. Because these flasks are initially charged for practical reasons to a pressure of only 2,200 psi, the water tanks can only be blown at depths less than about 4,800 feet. It is this fact that necessitates the provision of the iron shot system for use at greater depths.

3. For faster (and more reliable in the event of inadvertent flooding) emergency ascent, provision is made for jettisoning a 7,000-pound chunk of aluminum-wrapped lead stored in the lower keel structure. This ballast can be quickly released by the pilot by a simple mechanism that cuts two 1/4-inch-diameter supporting cables. The penetrations for these cables are the only mechanical penetrations of the pressure hull.

4. The remaining ballast is fixed and is divided between nonwastable ballast needed for stability purposes and wastable ballast margin available for design, construction, or future growth. Two thousand pounds of nonwastable ballast for stability purposes is located very low in the boat in the free-flooding keel in the form of solid aluminum bars. Five thousand pounds of wastable growth margin (on paper until the boat is completed) is allowed for at the location of the center of gravity of the entire boat. Upon completion of the boat, the remnant of this margin would actually have to be installed as ballast in the keel with the nonwastable ballast where it would further improve stability. The distinction between these two kinds of fixed ballast is further clarified in Section 5 of Ref. 2.

The three variable ballast systems permit the submarine to be operated at a great variety of equilibrium and nonequilibrium conditions. The more important of these conditions for the Aluminaut are tabulated in Table 2, which also shows the freeboard to the deck for the surface conditions and the metacentric heights for all conditions. Some of the same information is illustrated in Fig. 4.

Table 2
Weight, Buoyancy, Stability, and Freeboard

Condition No.	Operation	Solid	Shot	Water	Weight (lb.)	Buoyancy (lb.)	Net Buoyancy (lb.)	Free-Board to Deck (ft.)	Meta-centric Height (in.)
1	Surface - light condition	No	No	No	135,140	135,140	0	2.05	2.65
2	Surface - normal condition	Yes	No	No	142,140	142,140	0	1.66	5.44
3	Surface - prepare to dive	Yes	Yes	No	146,140	146,140	0	1.10	5.76
4	Normal descent	Yes	Yes	Yes	149,140	148,640	-500	-	5.22
5	Operation at scheduled depth	Yes	Yes	Yes	149,140	149,140	0	-	5.22
6	Normal ascent - deep	Yes	No	Yes	145,140	148,620	3,480	-	4.99
7	Normal ascent - shallow	Yes	No	No	142,140	148,120	5,980	-	5.53
7A	Normal ascent - shallow (optional)	Yes	Yes	No	146,140	148,640	2,500	-	5.81
8	Panic ascent - deep	No	No	Yes	138,140	147,700	9,560	-	2.56
9	Panic ascent - shallow	No	No	No	135,140	147,200	12,060	-	3.08
10	Surface - special condition	Yes	No	Yes	145,140	145,140	0	1.20	4.92
11	Surface from panic ascent (optional)	No	No	Yes	138,140	138,140	0	1.78	2.11
12	Gradual ascent (optional)	Yes	1/2	Yes	147,140	148,890	1,750	-	5.10

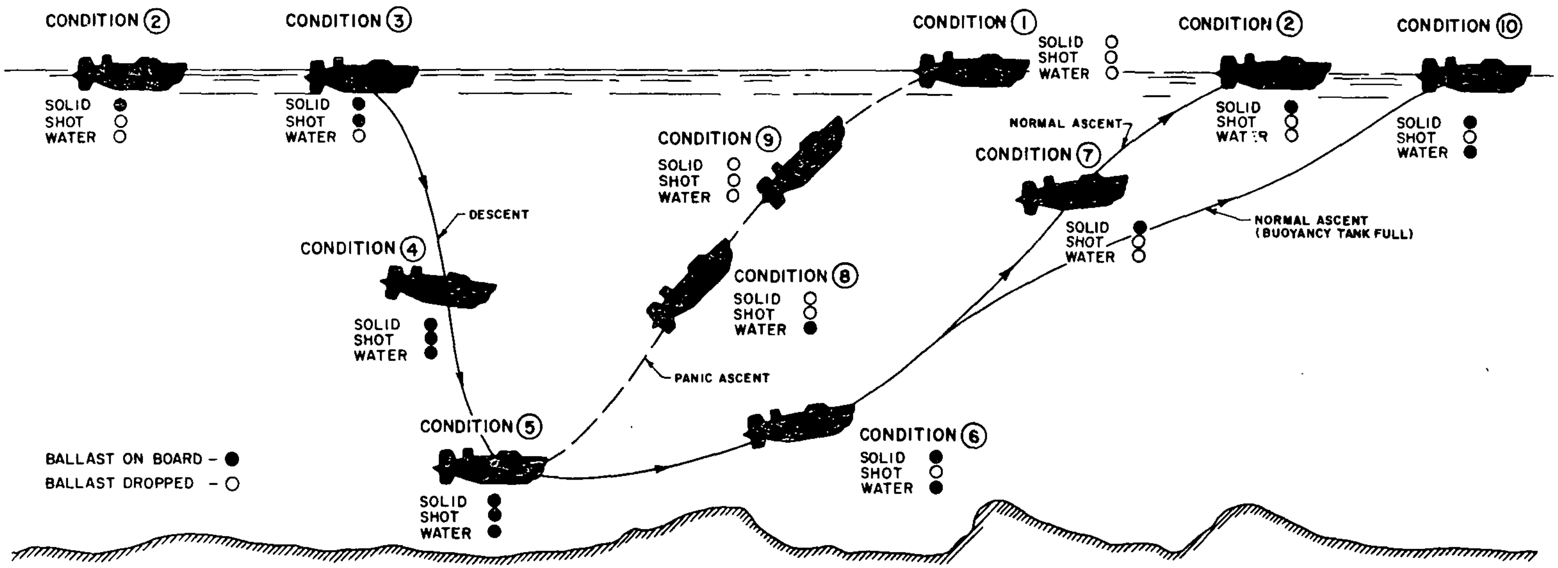

Fig. 4. Aluminaut ballast conditions

Normal diving and ascending procedures will be able to be carried out as follows on the Aluminaut. Condition 2 (see Table 2 and Fig. 4) would obtain when the Aluminaut is alongside an auxiliary vessel preparing for a dive. All solid variable as well as fixed ballast is on board, but it may be considered that the iron shot and water ballast had been jettisoned on a previous dive. When the boat has been made ready for submergence in all other respects, iron shot would be added from the mother ship to produce condition 3. In this condition the water tanks are still empty so that the boat is still afloat with over a foot of freeboard to the deck. The final submergence of the boat is now under the complete control of the pilot and when he is ready, he can flood the ballast tank, bringing the boat to condition 4 with a negative buoyancy of about 500 pounds. In all probability, the pilot would choose at this point to speed his descent by propelling the boat to the desired depth of operation. It would take roughly 50 minutes to reach 15,000 feet with a 30-degree down angle utilizing full power on the main propeller (40 minutes with the vertical propeller working also). Otherwise, it would take about 4-1/2 hours.

With no further change in ballasting the boat would be at neutral equilibrium at 15,000 feet since due to compressibility effects (which will be discussed subsequently) the initial 500 pounds of negative buoyancy would disappear at that depth. This corresponds to condition 5.

Ascent can be achieved by any of the ballast arrangements shown in Table 2 and Fig. 4. The fastest panic condition ascent, which involves jettisoning the solid lead ballast and iron shot at 15,000-foot depth and the ballast water at 4,800 feet, utilizing full power on both the horizontal and vertical propellers, and a 30-degree up angle would take 22 minutes from 15,000 feet with no leakage. With no power available (and no leakage) the panic ascent would consume about 44 minutes. Consideration was given earlier in the design to provision of an overboard discharge pump capable of handling a very modest amount of leakage at 15,000 feet. It was concluded that the weight saved by not installing the pump was greater than the weight of water which the pump could eject during an ascent.

MOTION CHARACTERISTICS DURING VERTICAL ASCENT–PRELIMINARY CONSIDERATIONS

Piccard reported in Ref. 3 that on several occasions the bathyscaphes experienced rather violent oscillations while rising freely under the influence of positive buoyancy. Since it was known that the Aluminaut would possess substantially less metacentric stability than the Trieste, which would tend to permit larger oscillations, it was decided to study this problem thoroughly during the feasibility and design study of the Aluminaut.

Bodies which are streamlined in planes through their longitudinal axis of symmetry, are usually very blunt in planes normal to their axis of symmetry. It is well known that such blunt bodies will shed Karman vortices. For cylindrical bodies moving normal to their axis, which corresponds fairly closely to the case of submarines rising vertically, it can be shown that the dependence of the period of the vortex shedding upon the various characteristics of the flow is expressed by a single curve of the Strouhal number $D/T_e V$ against the Reynolds number VD/ν, where T_e is the period of the vortex shedding (period of excitation), D is the diameter of the cylinder, V is the velocity, and ν is the kinematic viscosity of the fluid. This curve was obtained experimentally in Ref. 4 for Reynolds numbers up to about 10^6 and plotted in such forms in Ref. 5 that extrapolation to slightly higher Reynolds was not too difficult. It is shown in Fig. 5 for Reynolds numbers up to about 4×10^6. Also shown in Fig. 5 is cylinder-drag data as a function of Reynolds number taken from

Ref. 6. It will be noted that the critical Reynolds number reflecting an abrupt change in the flow regime takes place between the model- and full-scale range. These data were used to compute both the vertical velocities of ascent as well as the approximate periods of excitations that could cause oscillations of the Aluminaut during a rapid ascent.

If the excitation periods computed in the preceding correspond to the natural period of oscillation of the submarine during any particular ascent, severe oscillations would

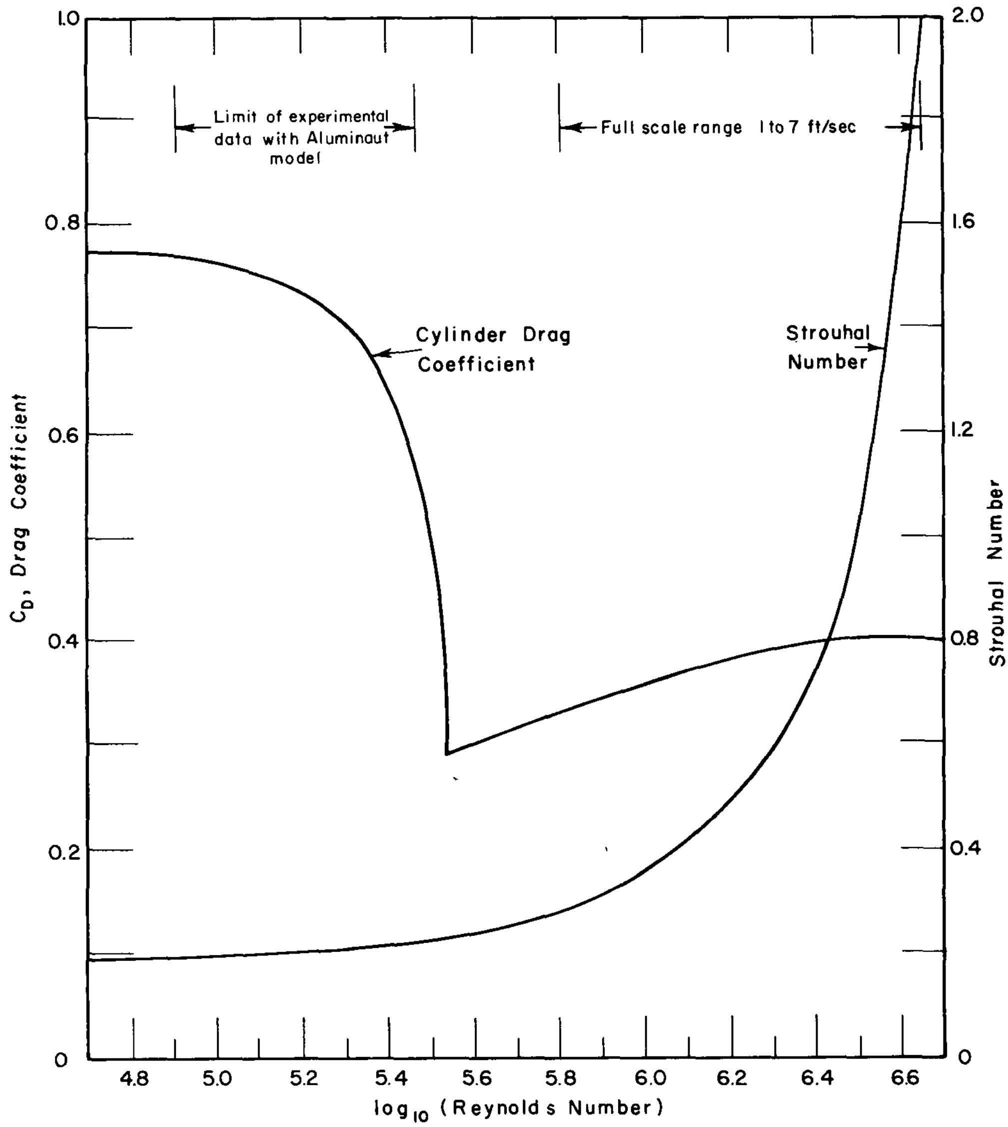

Fig. 5. Effect of the Reynolds number on the vortex shedding frequency and the drag of cylinders

doubtlessly ensue. The natural rolling period of a submerged submarine is conveniently expressed as follows:

$$T_n = 2\pi k_x/\sqrt{gBG}$$

where T_n = the natural roll period
k_x = radius of gyration of weight about the longitudinal axis of symmetry (varies from about 3.3 feet for condition 9 in Table 2 to 3.6 feet for conditions 4 and 5)
g = the acceleration due to gravity
BG = the metacentric height (tabulated in Table 2).

Utilizing all of the preceding information, it would be possible to predict which of the nonequilibrium conditions shown in Table 2 was likely to result in severe oscillations. However, this information would be insufficient to permit an estimate of the amplitude of oscillation. Furthermore, a freely rising submarine could obviously partake of coupled motions that might render the elementary analysis discussed up to this point inadequate. For these reasons the decision was made to conduct an experimental model study of the ascent of the Aluminaut.

MODEL STUDY

The Model and Facility

On the basis of a model-scale study conducted by the author, Southwest Research Institute constructed the 1/12-scale, 49-inch-long hollow aluminum model shown in Figs. 6 and 7. The unfairnesses evident in Fig. 6 were ameliorated by the use of modeling clay, and as

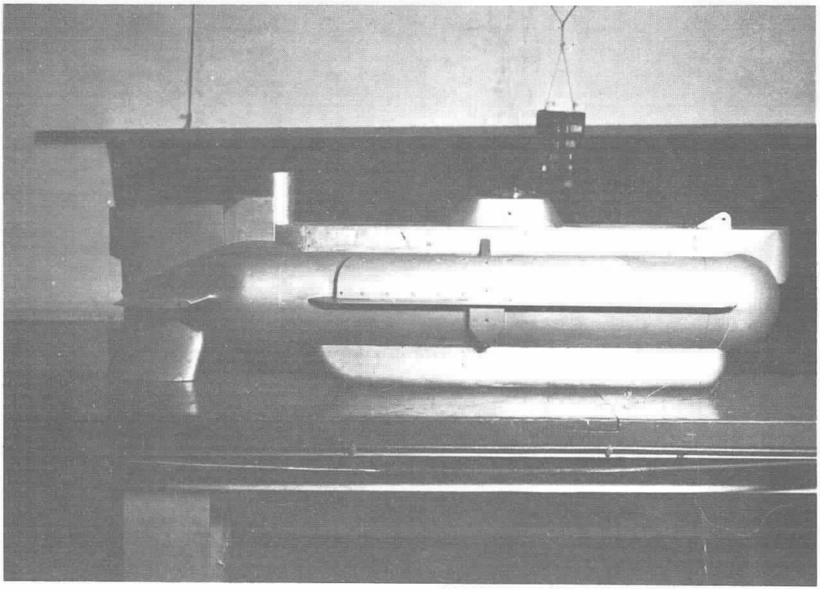

Fig. 6. Assembled aluminaut model

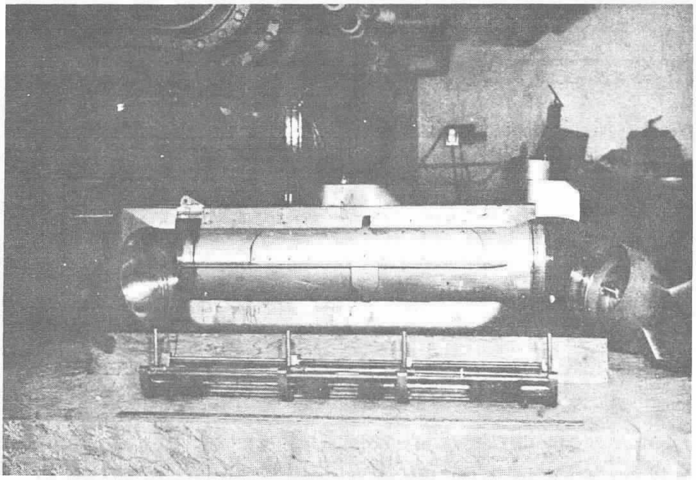

Fig. 7. Internals removed from aluminaut model, showing adjustable weights for vertical ascent tests

indicated earlier these changes will presumably be incorporated into the full-scale. The internal weight arrangement evident in Fig. 7 permitted considerable adjustment not only of the net buoyancy of the model (by means of adding or subtracting weights), but also of its natural period of roll for any fixed net buoyancy (by means of altering the vertical position of the weights as well as the radius of gyration). The amplitude of these adjustments is evident from Table 3 which describes the conditions that apply to each vertical ascent test conducted with the model.

Table 3
Vertical Ascent Tests; Model Variables Tested

Test No.	Date of Test	Weight of Model (lb.)‡	Net Buoyancy (lb.)	Metacentric Height (in.)‡	Roll Gyradius (in.)‡	Free Roll Period (sec.)‡	Bilge Keels§	Stern Fins§
i	6/10-12/59*	64.2	33.2	0.79	4.33	1.57	Narrow	Small
ii	6/10-12/59	64.2	33.2	0.79	4.33	1.57	Narrow	Small
iii	6/10-12/59	82.5	14.9	1.09	4.02	1.23	Narrow	Small
iv	6/10-12/59	86.1	11.3	1.14	3.97	1.20	Narrow	Small
v	6/10-12/59	89.6	7.8	1.19	3.92	1.15	Narrow	Small
vi	6/10-12/59	79.4	18.0	1.05	4.07	1.27	Narrow	Small
vii	6/10-12/59	70.3	27.1	0.90	4.23	1.41	Narrow	Small
viii	6/10-12/59	82.5	14.9	1.09	4.02	1.23	Wide	Small
ix	6/10-12/59	86.1	11.3	1.14	3.97	1.20	Wide	Small
x	6/10-12/59	79.4	18.0	1.05	4.07	1.27	Wide	Small

*Net buoyancies of the 6/10-12/59 tests were computed on the basis of 97.4 pounds total buoyancy.
‡Weights, metacentric heights, and gyradii do not include the effects of inadvertant flooding water.
§See Table 4.

Table 3 (Continued)
Vertical Ascent Tests; Model Variables Tested

Test No.	Date of Test	Weight of Model (lb.)‡	Net Buoyancy (lb.)	Metacentric Height (in.)‡	Roll Gyradius (in.)‡	Free Roll Period (sec.)‡	Bilge Keels§	Stern Fins§
xi	6/10-12/59*	70.3	27.1	0.90	4.23	1.41	Wide	Small
1	7/27-29/59†	97.9	4.1	1.30	3.83	1.08	Narrow	Large
2	7/27-29/59	95.1	6.9	1.26	3.86	1.10	Narrow	Large
3	7/27-29/59	95.1	6.9	0.95	3.75	1.32	Narrow	Large
4	7/27-29/59	95.1	6.9	0.58	3.65	1.54	Narrow	Large
5	7/27-29/59	93.3	8.7	1.24	3.88	1.12	Narrow	Large
7	7/27-29/59	93.3	8.7	0.59	3.67	1.54	Narrow	Large
8	7/27-29/59	91.5	10.5	1.22	3.90	1.15	Narrow	Large
10	7/27-29/59	91.5	10.5	0.59	3.70	1.55	Narrow	Large
11	7/27-29/59	89.7	12.3	1.19	3.93	1.16	Narrow	Large
13	7/27-29/59	89.7	12.3	0.59	3.73	1.55	Narrow	Large
14	7/27-29/59	87.9	14.1	1.17	3.95	1.18	Narrow	Large
16	7/27-29/59	87.9	14.1	0.59	3.77	1.55	Narrow	Large
17	7/27-29/59	82.9	19.1	1.10	4.02	1.23	Narrow	Large
18	7/27-29/59	77.9	24.1	1.03	4.09	1.30	Narrow	Large
18A	7/27-29/59	75.6	26.4	0.99	4.13	1.33	Narrow	Large
19	7/27-29/59	72.6	29.4	0.94	4.19	1.37	Narrow	Large
27-7	7/27-29/59	93.3	8.7	0.59	3.67	1.54	Wide	Large
27-10	7/27-29/59	91.5	10.5	0.59	3.70	1.55	Wide	Large
27-8	7/27-29/59	91.5	10.5	1.22	3.90	1.15	Wide	Large
27-8	7/27-29/59	91.5	10.5	1.22	3.90	1.15	Wide	Large
27-8	7/27-29/59	91.5	10.5	1.22	3.90	1.15	Wide	Large
27-8	7/27-29/59	91.5	10.5	1.22	3.90	1.15	Wide	Large

*Net buoyancies of the 6/10-12/59 tests were computed on the basis of 97.4 pounds total buoyancy.
†Net buoyancies of the 7/27-29/59 tests computed on the basis of 102.0 pounds total buoyancy.
‡Weights, metacentric heights, and gyradii do not include the effects of inadvertent flooding water.
§See Table 4.

Since it was known that the shape and size of external appendages would strongly influence the damping of any oscillations, two different sets of bilge keels and stern fins were made to be fitted to the model. These are described in Table 4 and identified in Table 3.

Table 4

Item	Model Dimensions	Proj. Area (sq ft)	Approx. Drag Coef. (Ref. 7)
Narrow Bilge Keels	29 x 3/4 in. x 2	0.402	2.0
Wide Bilge Keels	29 x 1-1/2 in. x 2	0.805	2.0
Small Stern Planes	2.6 x 3.7 in. x 2	0.133	1.16
Large Stern Planes	5.8 x 3.5 in. x 2	0.282	1.16

The vertical ascent tests were conducted at the Underwater Weapons Tank Facility of the Naval Ordnance Laboratory at White Oak, Maryland. This facility proved to be well suited to the purposes of the tests. Figure 8 shows the facility setup schematically. The fact that the launching platform could be freely raised and lowered permitted great flexibility in conducting the tests. Moving pictures of the vertical ascent tests were obtained by underwater photographers from the staff of the U.S. Naval Underwater Photographic Unit in Washington.

U.S. Naval Underwater Photographic Unit in Washington.

The instrumentation used to measure the results obtained in this facility was, however, quite crude. The speeds of ascent were measured with stop watches while the roll oscillations

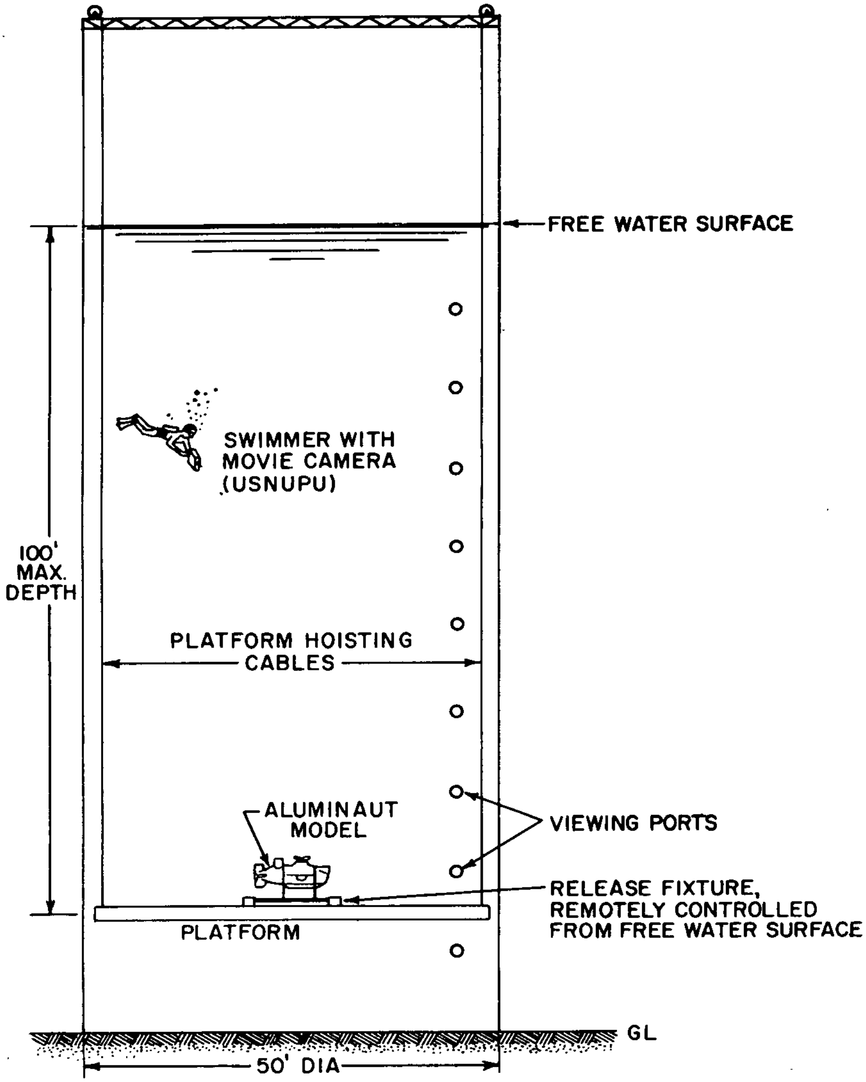

Fig. 8. Vertical ascent test setup at NOL Underwater Weapons Tank Facility

had to be based on visual observations through the viewing ports in the sides of the tank. It might be noted, however, that in spite of the limitations imposed by both the crudity of the measurements and inadvertent leakage of the model, the tests provided important guidance to the design of the Aluminaut.

Model Drag

Results showing the relationship between ascent velocity and the net buoyancy and drag for the model conditions and configurations tabulated in Table 3 are shown in Fig. 9.

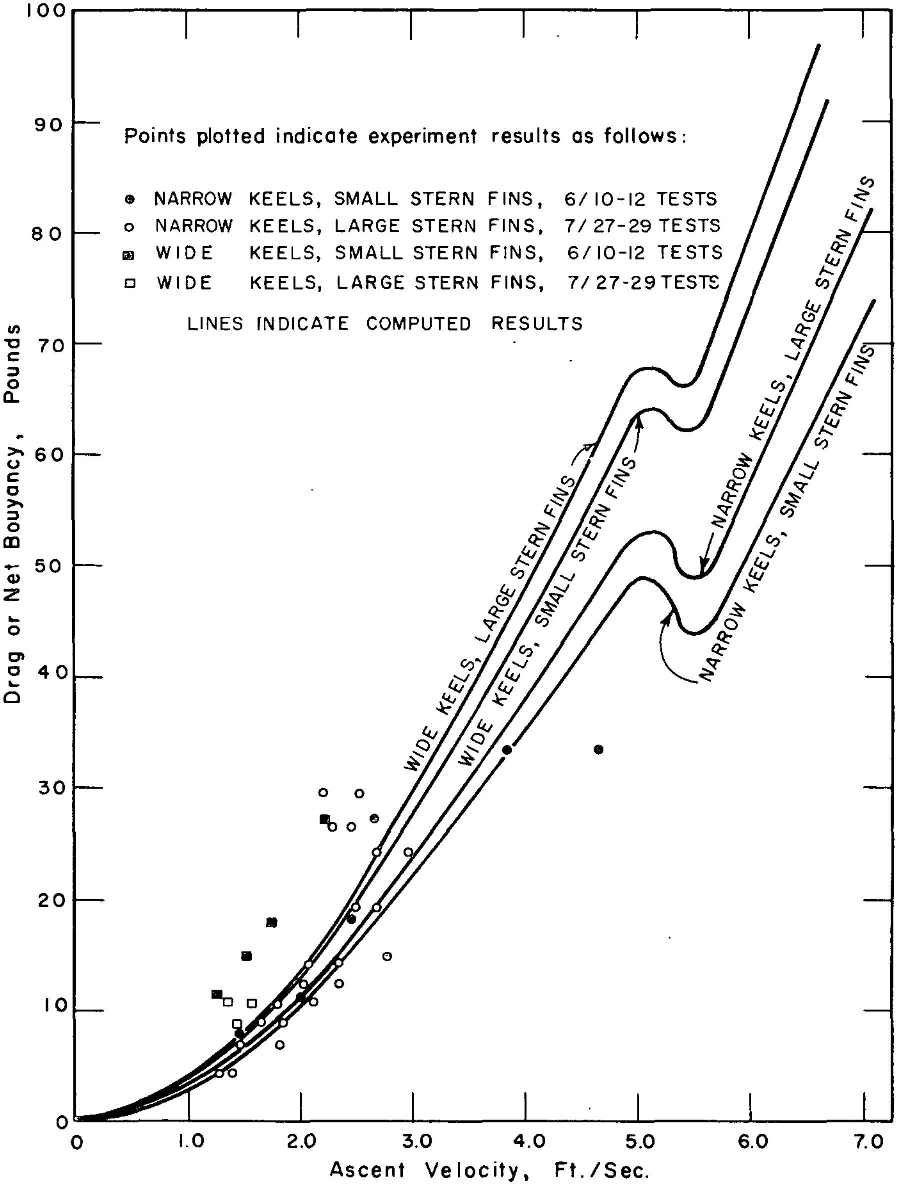

Fig. 9. Model vertical-drag data, experimental and computed

Also shown are computed data for the same configurations utilizing data given in Fig. 5 and Table 4. The scatter of experimental results is large, but considering the uncertainty introduced by the presence of an unaccountable amount of flooding water during some of the tests, the experimental results were considered as roughly confirming the computed data. In particular, the wide keel tests of 6/10-12/59 showed consistent serious deviation from the computed data. It will be noted that in none of the tests did the velocities approach those associated with the sharp discontinuity in the drag curve.

Model Oscillations

Test results of roll oscillation are plotted in Fig. 10 as a function of both ascent velocity, determined experimentally, and natural roll period, as tabulated in Table 3. Maximum double amplitude rolls observed during each test are shown symbolically for each point plotted. Also shown in Fig. 10 are the approximate periods of the roll excitation caused by the periodic vortex shedding computed on the basis of the Strouhal number curve shown in Fig. 5. With the introduction of bilge keels located at the maximum beam of the model, the maximum width to be used in the computation of the excitation period could be either 8 inches, the diameter of the cylinder, or 9-1/2 inches, the maximum tip to tip beam. This accounts for the range of values of excitation period shown in Fig. 10.

In general, as would be expected, the closer the correspondence between the natural roll period and the period of excitation, the larger the roll amplitude that resulted. It might be noted that it is very likely that the actual natural roll periods of the model during some of these tests were longer than the computed periods because of leakage. A moderate increase in the natural roll periods of some of the test spots would have improved the correlation between maximum roll amplitude and resonance.

While the proximity to resonance explains several of the large observed roll amplitudes in Fig. 10, in most instances the test conditions with low metacentric heights (large natural periods) showed larger roll amplitudes than conditions with large metacentric heights (small natural period). Although not directly apparent from Fig. 10, the preceding statement applies at constant tuning factor (ratio of natural period to excitation period). For example, the comparison of results of test 14 to tests 10 and 7 or test 11 to test 4 shows this tendency. The only exception to this pattern are tests 13 and 17. This effect of metacentric height is consistent with vibration theory (e.g., Ref. 8).

Only data for the narrow bilge keel tests of July 27-29 are shown in Fig. 10 since none of the wide keel tests showed strong oscillations and, in fact, most of those tests showed no oscillations at all. Therefore, it may be concluded that a substantial reduction in roll amplitude can be achieved with wider bilge keels. However, this is achieved at the expense of a considerable increase in vertical drag (see Fig. 11), particularly in the range of full-scale Reynolds number where the bare cylinder drag is a much smaller fraction of the total than it is in the model range.

In addition to quantitative data on roll amplitude and vertical velocity, the free ascent tests revealed strong cross-coupling between vertical forces and horizontal motion. As a result, the model usually achieved some ahead velocity while solely under the influence of a vertical force. This cross-coupling is probably enhanced by the strong fore and aft asymmetry introduced by the presence of large stern fins. Usually, only a slight pitch or yaw developed during the tests. However, during test 16 a strong pitch developed. Nevertheless, in no case was there evidence that the coupled motions prevented the predicted occurrence of roll oscillations.

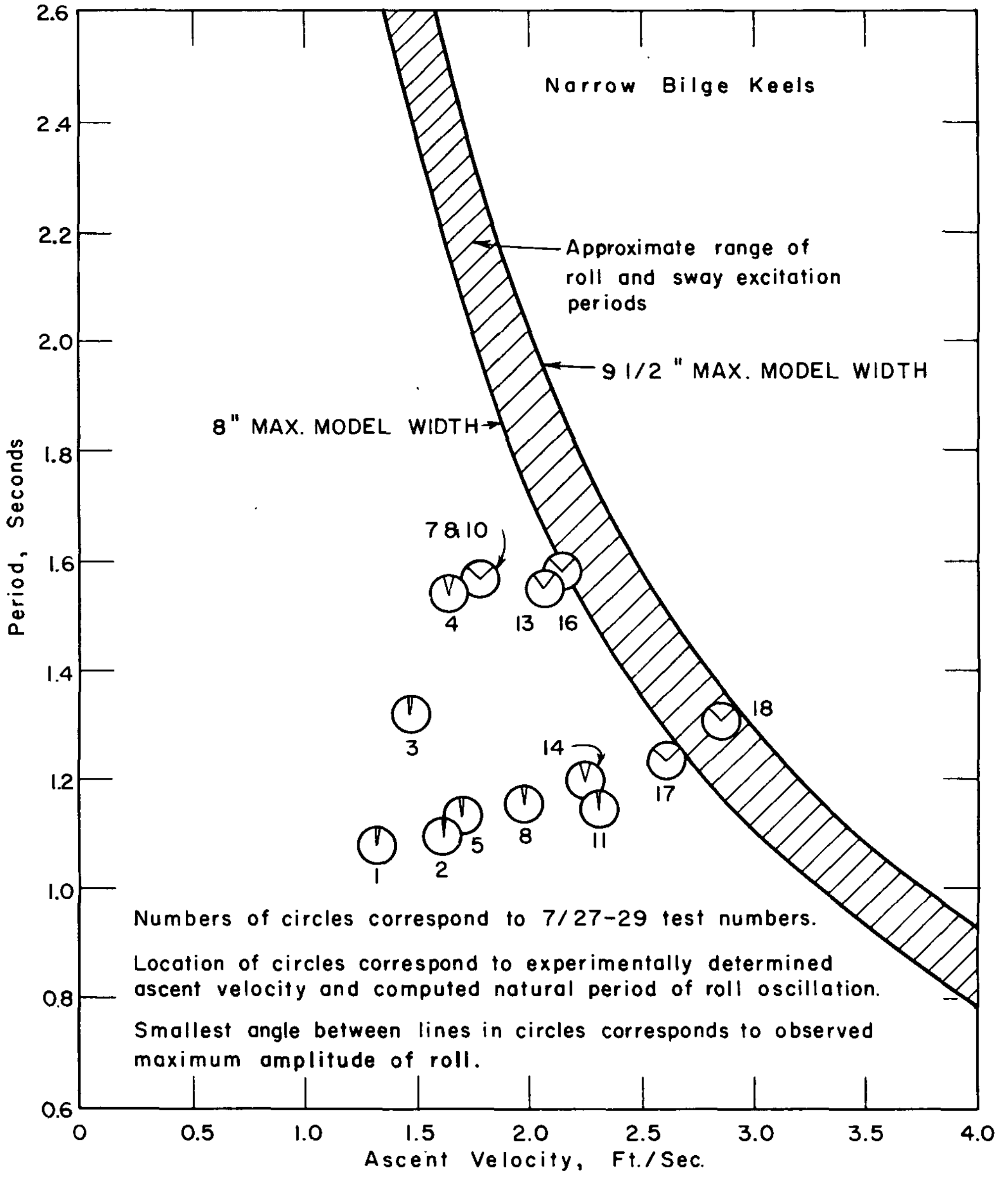

Fig. 10. Model oscillation data, experimental and computed

PREDICTION OF FULL-SCALE DATA

While the model results are of great importance in confirming design philosophy, they cannot be applied directly to predicting full-scale performance. Examination of Fig. 5 shows that both the nondimensional drag and roll excitation period change radically between the model range and the full scale. However, with the assumption that the limited experimental data modestly confirm design calculations within the model range, one can utilize the full-scale data in Fig. 5 with more confidence.

Full-Scale Drag

Full-scale drag vs ascent velocity curves are shown in Fig. 11. The uppermost curve corresponds to the Aluminaut design, as it is contemplated at this time with 12-inch bilge keels and large stern fins. It is seen that this condition results in more than double the bare cylinder drag. Also shown in Fig. 11 are the intercepts corresponding to actual buoyancy conditions of the Aluminaut shown in Table 2. Comments have already been made concerning the speed of descent in condition 4 and the speed of ascent in the panic conditions 8 and 9. In the normal ascent if all of the shot ballast were dropped and water ballast

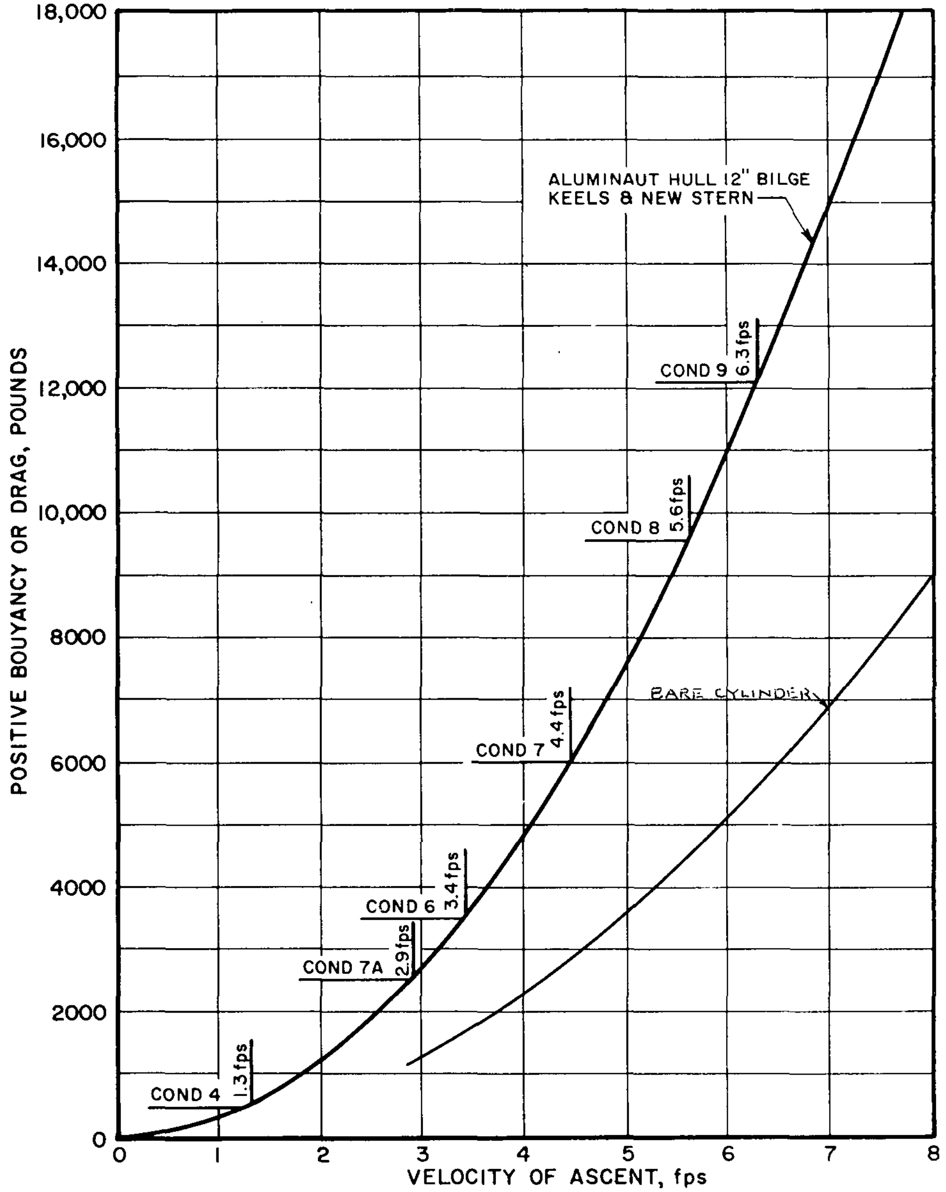

Fig. 11. Full-scale computed vertical-drag data

pumped out at moderately shallow depths (condition 7), it would take approximately 62.5 minutes to reach the surface. In fact, better time would be made if no ballast were dropped, but full power were preserved and utilized for the ascent using a 30-degree up angle. With this assumption it would take only 49 minutes to reach the surface. It appears very likely that this method of ascending will be preferred in the normal situation to dropping and losing expensive shot ballast.

Full-Scale Oscillation

Predicted excitation and oscillation periods for the full-scale Aluminaut are shown in Fig. 12. Bearing in mind the results of the model tests, it might be surmised that normal ascent conditions 6 and 7A might suffer the most severe oscillations of any of the conditions. This conclusion is tempered by the fact that, as noted in the previous section, it is very likely that propulsion would be used to speed the ascent in these conditions. With the boat driven to the surface with, say, a 30-degree up angle, it is not likely that severe oscillations would ensue even if the shot ballast was also dropped.

While it is likely that propulsion will be utilized for normal ascents, in the panic conditions, 8 and 9, propulsion may not be available. Therefore, it is of particular significance that these two conditions are, in fact, very far removed from resonance (tuning factor = 5 and 6 respectively). Therefore, in spite of their low metacentric heights, these conditions should not suffer large roll amplitudes.

Although not noted in Fig. 12, the range of predicted excitation periods on that figure is bounded by two different water temperatures. For the full scale, the influence of the range of possible values of water kinematic viscosity on ascent velocity and frequency of excitation is much more pronounced than the influence of assumed maximum body width. Since water temperatures between 40° and 80°F might be encountered, kinematic viscosities associated with these temperatures were used to form the boundary conditions.

CONCLUSIONS FROM VERTICAL ASCENT TESTS AND COMPUTATIONS

1. Despite large scatter, the experimental drag and oscillation data reasonably conform to analytically predicted results.

2. At resonance a substantial reduction in roll amplitudes can be achieved with wide bilge keels at the expense of a considerable increase in drag.

3. Strong cross-coupling caused the model to attain some ahead velocity. Pitch and yaw also were evident during many of the tests. These did not appear to interfere with the predicted roll oscillations.

4. For the normal ascent, the vertical velocity achievable by dropping ballast is so low that power preserved and utilized for propulsion would provide larger ascent velocities.

5. The only two buoyancy conditions liable to experience large roll oscillations are the normal ascent conditions 6 and 7A. This situation is vitiated by the fact that in actual operation it will probably be preferable to utilize propulsion for the normal ascent rather than drop ballast.

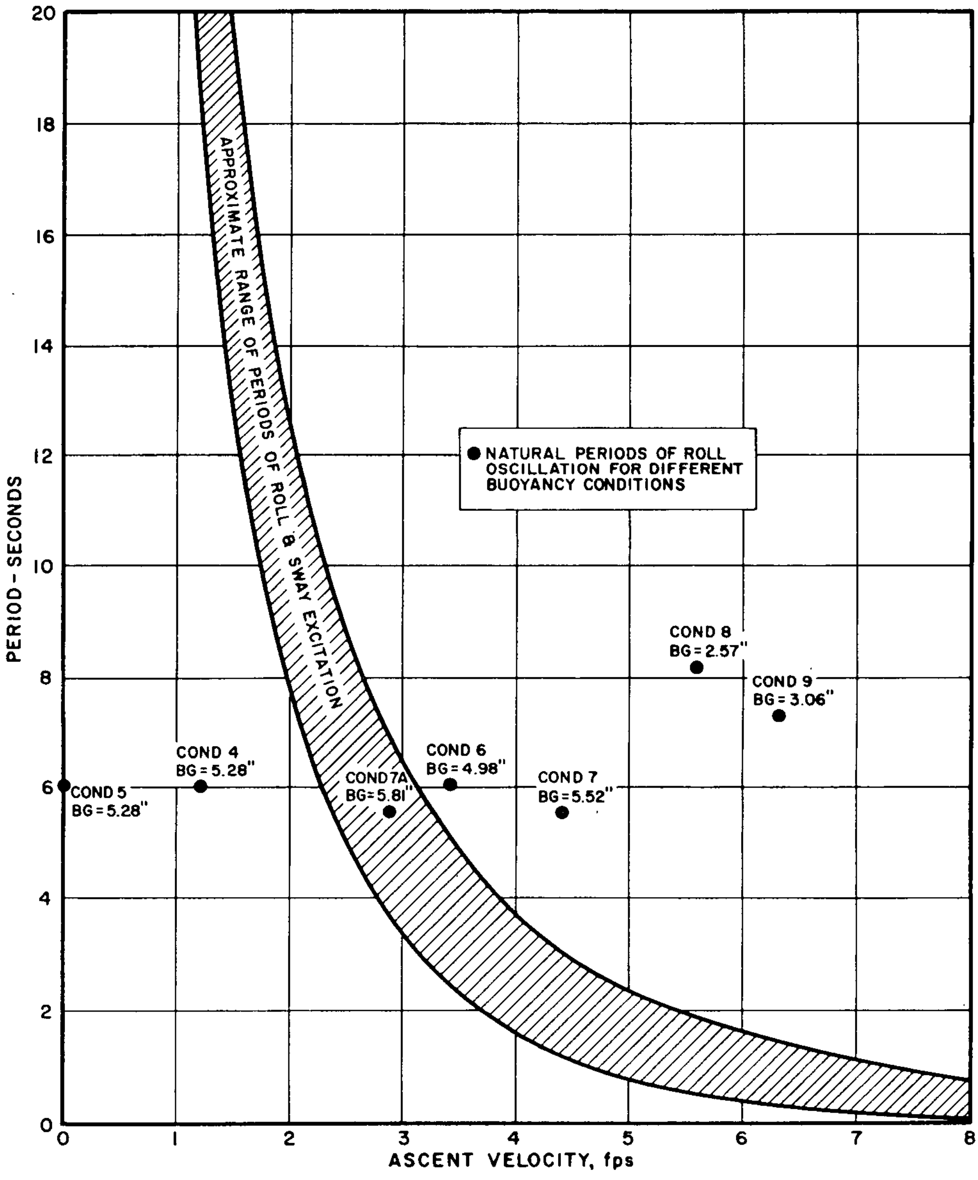

Fig. 12. Full-scale computed excitation and oscillation periods

6. The two panic ascent conditions, 8 and 9, are so far removed from resonance that strong oscillations are extremely unlikely.

EFFECTS OF COMPRESSIBILITY

Pressure hulls of either shallow- or deep-diving submarines deform elastically under the external pressure of submergence. The associated loss in volume is usually small and is to some extent compensated for by the compressibility of water. In relatively-thin-hulled shallow-depth submarines, however, the loss in volume represents a hull compressibility which is greater than the compressibility of the surrounding sea water. As a consequence the hull becomes less buoyant as it dives, which is an inherently unstable condition. Thus, a thin-hulled submarine that is neutrally buoyant near the surface must by some means discharge ballast at deeper depth in order to attain neutral buoyancy again at that depth.

Contrary to this situation, the thick hull of the Aluminaut is less compressible than water. As a result the boat becomes lighter as it sinks. Thus theoretically it should be possible when it is desired to dive the Aluminaut to its operating depth to take in a precise amount of excess ballast so that the Aluminaut has negative buoyancy near the surface. Without further intake or discharge of ballast the boat should then sink slowly to its operating depth where it will be in perfect equilibrium if the proper amount of excess ballast was initially taken aboard.

Particulars are shown in Table 5. The density of water at 15,000-foot submergence is about 2 percent greater than its density near the surface. Thus an incompressible hull would gain about 2 percent of its near surface buoyancy at a depth of 15,000 feet. On the other hand, if a thin-hulled submarine such as are now designed for shallow depths could be designed somehow to accept 15,000-foot submergence, it would lose about 5-1/2 percent of its near surface volume at that submergence and thus lose about 3-1/2 percent of its near surface buoyancy. The Aluminaut pressure hull is closer to the incompressible hull in this respect and loses only about 0.5 percent of its near surface volume at 15,000-foot submergence. Thus, it gains 1-1/2 percent of its near surface buoyancy at 15,000 feet. However, the overall compressibility of the entire Aluminaut configuration is considerably greater than 0.5 percent, primarily because the pressure-equalized silicone fluid in the stern capsule is itself much more compressible than water. It is estimated that the compressibility of the entire Aluminaut configuration is about 1-1/2 percent; thus it gains only about 0.5 percent of its near surface buoyancy at 15,000 feet. However, this calculation is believed to be too sensitive to subtle influence to be entirely depended upon, and must be carefully checked during the initial dive of the boat itself.

Table 5
Effects of Compressibility

Compressibility of Hull	Depth of Submergence, (ft)	Ratio of Water Density at Depth and Water Density at Surface	Ratio of Hull Volume at Depth and Hull Volume at Surface	Gain or loss Buoyancy
Incompressible hull	7,500	1.01	1.00	1% gain
Incompressible hull	15,000	1.02	1.00	2% gain
Hull as compressible as water	7,500	1.01	0.990	0
Hull as compressible as water	15,000	1.02	0.981	0
Thin hull submarine	7,500	1.01	0.975	1.5% loss
Thin hull submarine	15,000	1.02	0.945	3.5% loss
Aluminaut, pressure hull only	15,000	1.02	0.995	1.5% gain
Aluminaut, entire configuration	15,000	1.02	0.985	0.5% gain

The statements that have been made concerning the compressibility of thin-hull submarines apply with equal verity to vehicles like the bathyscaphes that use light-density fluids for flotation. Although the pressure hull of the Trieste may also be less compressible than sea water, the fact that the Trieste derives 90 percent of its buoyancy from light-density gasoline makes its overall compressibility almost as large as that of gasoline. Since gasoline compresses at a rate about twice that of water, the bathyscaphes, like the thin-hulled shallow-depth submarines, are unstable in depth.

There is yet another effect of compressibility with the Aluminaut hull in addition to the effect on net buoyancy at depth. The compressibility of the silicone fluid in the stern capsule of the Aluminaut introduces a significant shift forward in the longitudinal position of the center of buoyancy between near surface operation and operation at depth. This fact in conjunction with personnel movements on board was used to help determine the capacity of the trim tanks that are installed inside the pressure hull.

Because of the contraction of the pressure hull with depth, allowance has had to be made with attachment of all internal and external mountings to make sure that neither they are damaged nor the hull is locally restrained. Calculations indicate that at the test depth of 17,000, the radial displacement of the Aluminaut pressure hull is about 0.172 inch.

MANEUVERING IN BOTH PLANES

Most of the oceanographers who would be the potential users of the Aluminaut emphasized to the designers the necessity for precise control in both the horizontal and vertical planes. Because of the low speed of the Aluminaut, it was apparent that the desired degree of control could not be achieved by control surfaces alone as it is with higher speed submarines. For that reason two techniques are employed that are not usually used with submarines in addition to several other more conventional techniques. One is a propeller to provide thrust in the vertical direction and the other is a swiveling main propulsion propeller to permit directing the thrust in the horizontal plane. These are described in the subsequent sections.

Control in the Vertical Plane

To permit positive control in the vertical plane at all speeds a four-foot-diameter propeller driven by a 5-horsepower motor is mounted on top of a small superstructure about 15 percent of the length forward of amidship as shown in Figs. 1 and 2. This superstructure, which is also oil-filled, houses the motor, which is reversible and has a stepped speed control. With 5 horsepower the propeller can develop about 400 pounds of thrust as shown subsequently in Fig. 13. This thrust can be directed either upward or downward by reversing the motor. Since the magnitude of the thrust is not dependent on the speed of advance of the boat as it would be if it were developed by control surfaces, it should provide positive vertical depth control at any speed of advance.

In addition to the vertical propeller, two additional systems are provided for control in the vertical plane. The most effective of these, particularly in the speed range of the Aluminaut, is a conventional hydrostatic trim system that can be used to control pitch angle. The system as presently designed employs a pump driven by a 1-1/2-horsepower motor that can transfer 1,000 pounds of water between the two trim tanks shown in Fig. 1 in a period of two minutes. The moment produced of 26,500 foot-pounds is sufficient to trim the submerged Aluminaut about 20 degrees against her metacentric stability. As mentioned earlier, the trim system is currently sized primarily to accommodate the trim unbalance imposed by the loss of buoyancy in the stern capsule at depth and the movement of personnel within the boat. However this system could be readily enlarged after completion of the boat if it is evident that additional capacity is needed to augment pitch angle control.

Stern control surfaces are also employed partially to improve directional stability in the vertical plane, but also to serve as trim tabs to assist in maintaining horizontal flight without constant use of the vertical propeller. It is possible that they may not be able to fulfill even the latter limited mission in the event that the critical speed (see Section 7 of Ref. 2) falls within the operating speeds of the Aluminaut. At this speed no combination of hull pitch angle and stern plane angle can simultaneously balance out both the hydrodynamic forces and the combination of hydrodynamic and hydrostatic moments that act on any submarine. However, at speeds just slightly removed from the critical value the stern planes will be effective as trim tabs even though they may have to be used in a sense opposite to that which intuition would dictate.

Even with the preceding systems for controlling pitch angle and depth, difficulty may be encountered in maneuvering along an irregular bottom. For this purpose use of a trail rope such as is used by balloonists for maintaining constant distance above an irregular land terrain may be helpful. However, there has been little or no experience with this device with submarines and the forces involved may be too small to be effective. In the event that difficulties are experienced after the boat is in operation, the alternatives remain of refining the controls of the vertical propeller or increasing the capacity and refining the controls of the hydrostatic trim system.

Main Propulsion and Control in the Horizontal Plane

A 15-horsepower dc motor located in the stern capsule and connected via bevel gears to a four-foot-diameter propeller is used for main propulsion. This motor (as well as the topside motor for the vertical propeller) has hydrodynamic problems of its own since it must operate in an environment of very high pressure oil. To improve motor efficiency, both the rotating as well as the fixed elements must be especially streamlined to minimize hydrodynamic drag. Even with these measures a motor efficiency of only about 50 percent is assumed. It is expected, however, that the motor can be substantially overloaded because of the excellent heat dissipation into the surrounding medium. As shown in Fig. 13, a maximum horizontal speed of about 4.7 knots is expected with 15 horsepower.

Stability and control in the horizontal plane is effected by large fixed fins, balanced rudders (each 6 square feet in area) and provision to swivel the main propulsion propeller through a total arc of 120 degrees. Both the rudders and propeller pivot on a common vertical shaft as indicated in Figs. 1 and 2. The swiveling propeller by itself should assure excellent control at any speed in the horizontal plane.

DIRECTIONAL STABILITY IN TOW TESTS

Full-scale operations with the Aluminaut doubtlessly, will at some time require that she be towed on the surface to the scene of diving operations. Experience in the past with vessels of similar shape to the Aluminaut has revealed that in some conditions, the behavior

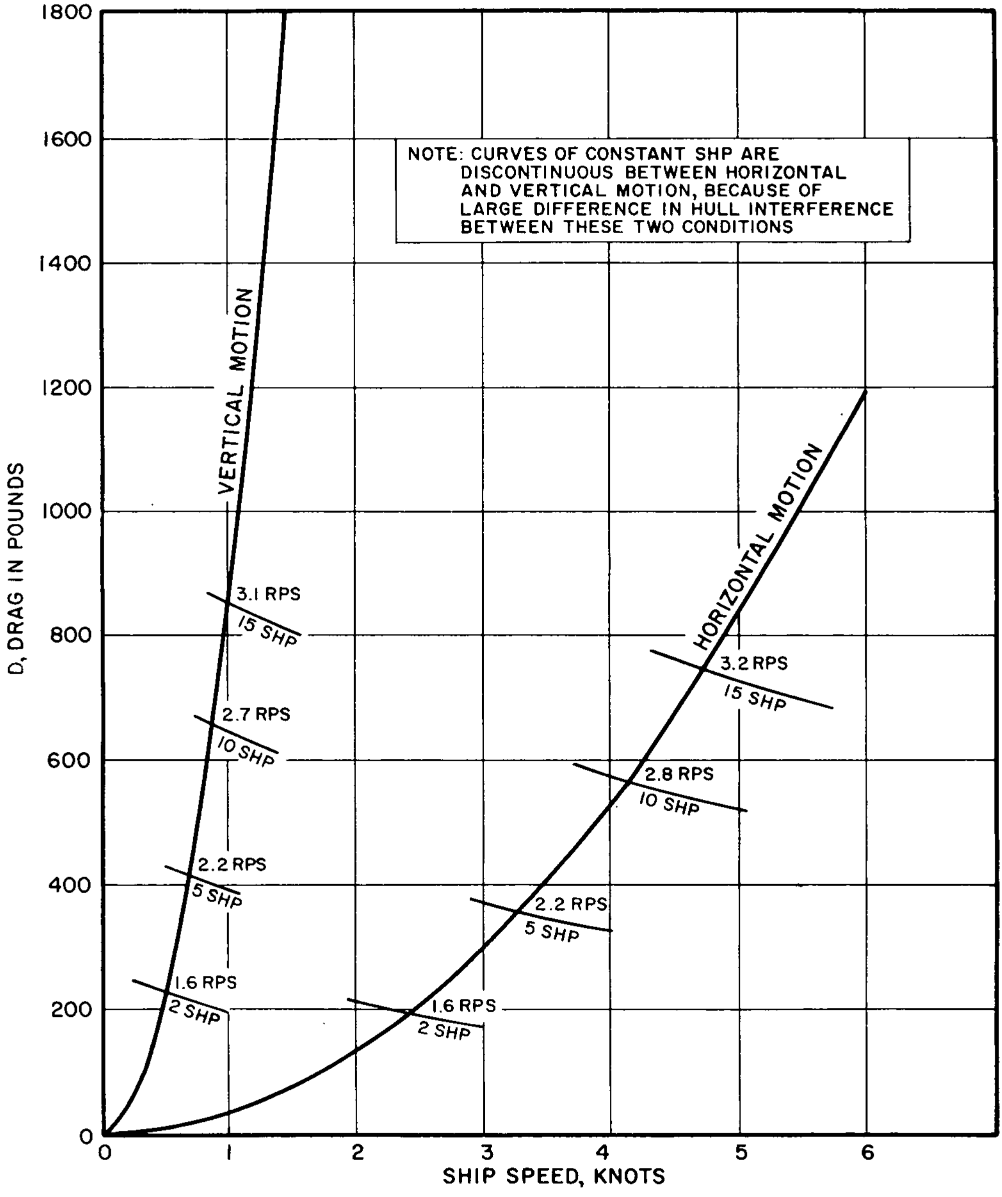

Fig. 13. Resistance and power, ship and shaft

of the towed vessel is so erratic that towing becomes difficult and hazardous. It was for these reasons that tests were carried out with the 1/12-scale Aluminaut model in order to observe its behavior while being towed on the surface.

Test Arrangements

The Aluminaut model was towed about two model lengths behind a model of an Oceanographic Research ship at the M.I.T. Ship Model Towing Tank. The research ship model was in turn towed by the ordinary gravity towing arrangement employed at the M.I.T. tank. Thus, the towing vessel was restrained to straight-ahead motion while the towed vessel was unrestrained except for the tension on the towing line.

Several towing arrangements were employed:

(a) Ahead tow - single tow line attached to a bracket on the centerline of the forward deck of the Aluminaut.

(b) Ahead tow - bridle tow lines attached to the extremeties of a one-foot-wide spanner fixed to the forward deck of the Aluminaut.

(c) Ahead tow - bridle tow line attached to the leading edges of the Aluminaut bilge keels.

(d) Astern tow - single tow line attached to upper rudder of the Aluminaut.

Tests were conducted with both the small and the large stern planes and rudder described in Table 4. During all tests the model was equipped with the wide bilge keels. Limited tests were also conducted with the stern fins removed.

Test Results

Distinct differences in the behavior of the towed Aluminaut model were observed with the different towing arrangements. The Aluminaut model was initially set directly behind and in line with the towing model. Upon release and movement of the towing model, the following situations could be observed:

Description of Behavior	Characterization of Behavior
1. The Aluminaut model would veer off course and collide with nearest tank wall.	Unsatisfactory
2. The model would initially veer off course, but return and cross its initial position and collide with the opposite tank wall.	Unsatisfactory
3. The model would initially veer off slightly to one side, but within the length and width of the tank, it would tend to return to a stable equilibrium position.	Satisfactory

Description of Behavior	Characterization of Behavior
4. The model would remain in a stable equilibrium position throughout the run.	Satisfactory

Tests with the small stern fins yielded the following results:

Towing Arrangement	Characterization of Behavior	Comments
(a)	Unsatisfactory	
(b)	Satisfactory	Equilibrium position slightly to port of initial position
(c)	Satisfactory	Equilibrium position slightly to port of initial position
(d)	Satisfactory	

Similar results were obtained with the large stern fin tests except that with towing arrangements (b) and (c) the model veered more to port and the equilibrium position was further to port. In order to help ascertain the cause of this distinct bias, configurations (b) and (c) were tried with the model set initially heading to starboard. The model still turned to port and established a stable equilibrium position on the port side of its initial position. Subsequently, the model was also tested with the stern fins removed entirely. In this condition, towing arrangements (b) and (c) became unstable, although no bias either to port or starboard was evident. It was concluded from these tests that both the original and enlarged rudders were not set exactly parallel to the center line of the model, and that the bias to port which was even more evident with the enlarged rudders was due to the inaccurate initial setting of the rudders.

Application to Full-Scale Towing

The model results indicate that towing arrangements (b) and (c), or (d), would be satisfactory for the full scale. From a practical point of view, (c) or (d) appear preferable to (b) which involves the fitting of a large spanner subjected to very heavy cantilevered loads. The bias that the model possessed for the port side is considered of little consequence since the zero position of the full-scale rudders can be easily adjusted. It was concluded from the tests that satisfactory towing of the Aluminaut on the surface could be accomplished with at least two simple towing arrangements.

SUMMARY OF PAPER

The contrasts between the Aluminaut and both the previous generations of deep-diving vehicles and conventional military submarines are emphasized in this paper. In the field of hydrodynamics, special problems arise with deep-diving submarines that require different ballasting systems as well as different devices for effecting superior control at low speeds.

646551 O—62——23

In addition, the oscillations arising from rapid vertical ascent or descent and the effects of compressibility become nonnegligible for deep-diving submarines. It is believed that the compromises made in the design of the Aluminaut effect reasonable solutions to each of these problems.

In particular, the use of iron shot as ballast appears to be a satisfactory substitute for water ballast and pumps at very deep depths. The possibility still exists, nevertheless, that the iron shot may prove to be redundant for normal ascents and it may prove feasible to abandon its use. In that event its equivalent weight would be incorporated in solid ballast for use in emergency ascents.

Model tests have reasonably confirmed theoretical predictions of the measures needed to avoid large oscillations in vertical ascents. In particular, the tried and true measures of avoiding resonance and incorporating damping devices such as bilge keels promise to yield satisfactory solutions. It has been demonstrated that in the panic ascents where it would be particularly desirable to avoid large amplitudes of roll the tuning factors are in fact far removed from resonance.

The fact that the overall configuration of the Aluminaut is somewhat less compressible than sea water yields the desirable characteristic of stability in depth. This is in contrast to thin-hull submarines and earlier bathyscaphes that must drop ballast to achieve neutral buoyancy at any depth below the surface.

The use of a vertical propeller augmented by a hydrostatic trimming system as well as stern planes is expected to provide satisfactory depth and pitch angle control at all speeds. The possibility of using a trail rope for navigating over the bottom remains to be explored. Excellent control in the horizontal plane should be achieved by the ability of the main propulsion propeller in conjunction with the rudders to swivel through an arc of 120 degrees.

Model tests indicated that satisfactory towing of the Aluminaut on the surface could probably be accomplished either by towing it stern first or by towing it bow first with a bridle arrangement attached to the leading edges of the bilge keels.

Taken as a whole, the Aluminaut promises to open a new era in ocean exploration and ocean utilization. While the primary problems associated with its development lie in the field of structures, this paper shows that careful consideration has also been given to its potential hydrodynamic problems.

ACKNOWLEDGMENTS

The author is indebted to the Reynolds Metals Company of Richmond, Virginia, and the Southwest Research Institute of San Antonio, Texas, for sponsoring his work in connection with the Aluminaut and for giving him permission to use the results contained in this paper. In addition, the majority of the figures contained in this paper were prepared at Southwest Research Institute.

In particular, the efforts of Mr. Ernest Brunauer of Southwest Research Institute are acknowledged. It was largely he who shouldered the burden of carrying out the vertical ascent tests at the Naval Ordnance Laboratory. In this connection the efforts of the staffs of the Underwater Weapons Tank Facility, the Office of Naval Research, and the U.S. Naval Underwater Photographic Unit are acknowledged. Mr. Ernst Frankel, Research Assistant at M.I.T., conducted the towed directional stability tests.

But, it is to Dr. Edward Wenk, Jr., formerly of Southwest Research Institute, that the author is principally indebted. Dr. Wenk enlisted his work on this project and it is largely his enthusiasm, initiative, and drive that have carried the project through the difficult formative stages.

REFERENCES

[1] Wenk, Dehart, Kissinger, and Mandel, "An Oceanographic Research Submarine of Aluminum for Operation to 15,000 feet," Royal Institute of Naval Architects, Mar. 23, 1960

[2] Arentzen, E.S., and Mandel, P., "Naval Architectural Aspects of Submarine Design," Trans. Soc. Naval Architects Marine Engrs., Vol. 68, 1960

[3] Piccard, A., "Earth, Sky, and Sea," New York: Oxford University Press, 1956

[4] Relf, E.F., and Simmons, L.F.G., "The Frequency of Eddies Generated by the Motion of Circular Cylinders through a Fluid," British Advisory Committee for Aeronautics, R. and M. 917, 1924

[5] Landweber, L., "Flow About a Pair of Adjacent Parallel Cylinders Normal to a Stream," David Taylor Model Basin Report 485, July 1942

[6] Marks, L.S., "Mechanical Engineers Handbook," 6th edition, New York: McGraw-Hill, 1958, pp. 11-84, Fig. 21

[7] Hoerner, S.F., "Aerodynamic Drag," Midland Park, N.J., 1951, pp. 21-25 (The 2nd edition, published in 1958, is titled "Fluid-dynamic Drag")

[8] McGoldrick, R.T., "A Vibration Manual for Engineers," 2nd edition, David Taylor Model Basin Report 189, Dec. 1957 (obtainable from Office of Technical Services, Dept of Commerce, PB131785)

APPENDIX

The data plotted in Fig. 3 for the elementary body of revolution shapes are based upon the expressions for the dimensional and nondimensional volume and wetted surface of simple cylinders, cones, and hemispheres as follows:

	Cylinder	Hemisphere	Cone
Dimensional Volume, ∇	$\frac{\pi}{4}D^2L_x$	$\frac{\pi}{12}D^3$	$\frac{\pi}{12}D^2L_t$
Nondimensional Volume, C_p	1.0	2/3	1/3
Dimensional Wetted Surface*, S	πDL	$\frac{\pi}{2}D^2$	$\frac{\pi}{4}DL_t\sqrt{\frac{D^2}{L_t^2}+4}$
Nondimensional Wetted Surface, C_s	1.0	1.0	$\frac{1}{4}\sqrt{\frac{D^2}{L_t^2}+4}$

*Excluding area of flat ends in these cases.

Where:

L = length
L_x = length of cylinder (parallel middle body)
L_t = length of single conical end
D = diameter of cylinder, hemisphere, or base of cone
∇ = volume
C_p = prismatic coefficient $= \dfrac{\nabla}{\frac{\pi}{4} D^2 L}$
S = wetted surface
C_s = wetted surface coefficient $= \dfrac{S}{\pi D L}$.

When these basic shapes are combined together with either the cones or the hemispheres forming the ends, the sums of the wetted areas as expressed above form the total wetted surface including that of the ends. The total Length L is then the sum of L_x plus the length of both ends. It then becomes convenient to introduce the nondimensional expressions $L_x' = L_x/L$ and $L_t' = L_t/L$. With these definitions the following relationships apply:

Hemispherical Ends:

$$L_x = L - D;\ L_x' = 1 - \frac{D}{L}$$

$$C_p = \frac{\frac{\pi}{4} D^2 L_x + \frac{\pi}{6} D^3}{\frac{\pi}{4} D^2 L} = 1 - \frac{1}{3}\frac{D}{L}$$

$$C_s = \frac{\pi D L_x + \pi D^2}{\pi D L} = 1.0$$

Conical Ends:

$$L_x = L - 2L_t;\ L_x' = 1 - 2L_t'$$

$$C_p = \frac{\frac{\pi}{4} D^2 L_x + \frac{\pi}{6} D^2 L_t}{\frac{\pi}{4} D^2 L} = 1 - \frac{4}{3} L_t'$$

$$C_s = \frac{\pi D L_x + \frac{\pi}{2} D L_t \sqrt{\frac{D^2}{L_t^2} + 4}}{\pi D L} = 1 - 2L_t' + \frac{1}{2}\sqrt{\frac{D^2}{L^2} + 4L_t'^2}$$

Hemispherical nose, Conical Tail:

$$L_x = L - L_t - \frac{D}{2};\ L_x' = 1 - L_t' - \frac{1}{2}\frac{D}{L}$$

$$C_p = \frac{\frac{\pi}{4} D^2 L_x + \frac{\pi}{12} D^3 + \frac{\pi}{12} D^2 L_t'}{\frac{\pi}{4} D^2 L} = 1 - 2/3 L_t' - \frac{1}{6}\frac{D}{L}$$

$$C_s = \frac{\pi D L_x + \frac{\pi}{2} D^2 + \frac{\pi}{4} D L_t \sqrt{\frac{D^2}{L_t^2} + 4}}{\pi D L} = 1 - L_t' + \sqrt{\frac{D^2}{L^2} + 4L_t'^2}$$

Flat Ends: $L_x = L;\ L_x' = 1.0;\ C_p = 1.0$

$$C_s = \frac{\pi D L_x + \frac{\pi}{2} D^2}{\pi D L} = 1 + \frac{1}{2}\frac{D}{L}\ .$$

For all configurations the wetted surface can be expressed in terms of the volume ∇, C_p, C_s, L/D as follows:

$$S = C_s \left(16\pi \frac{L}{D}\right)^{1/3} \left(\frac{\nabla}{C_p}\right)^{2/3}\ .$$

Cursory inspection of all of the preceding relationships will indicate the wisdom of leaving them in the parametric form in which they are expressed. Since both C_p and C_s are expressed in terms of L_t', it could be eliminated as a parameter and the wetted surface could then be expressed directly as a function of C_p and L/D for any given volume. The resulting expressions would, however, be extremely ponderous.

DISCUSSION

E. C. Tupper (Admiralty Experiment Works)

My remarks are not so much a question directed to the author, but rather a request to him that he might study certain problems associated with the control of this submarine when it is in operation. I think it is desirable to go a little into the background of the problem to bring out the points I wish to make. There are two points of great interest in the control of an underwater body in the vertical plane. So as not to become involved in any problems of nomenclature, I will call these points A and B.

Point A is a fixed point in the submarine which would typically be about a third or a quarter of the length from the bow. Ignoring transient effects, a vertical force applied at point A would cause the submarine to rise or dive while still maintaining level trim. Point B moves with changing speed; at very high speed it is almost coincident with point A, but, with decreasing speed, it moves aft until, at zero speed, it is infinitely aft of the submarine. Again, ignoring transient effects, a force applied at point B will cause a submarine to change trim but not to change depth. The author did mention that the action of these after hydroplanes might be reversed at low speed. This will occur at the speed at which point B coincides with the position of the after hydroplanes. At that speed, the after hydroplanes can only change the trim and not depth. A downward force applied ahead of point B would cause an increase in depth and a downward force applied after point B would cause a decrease in depth so that, in passing through the speed at which point B coincides with these after hydroplanes, there will be a reversal in the effect on depth of using the planes.

I would like to suggest to the author that it would be interesting to study, when he has the submarine in operation, whether the vertical propeller, which would seem to be almost at point A, does in fact control depth without significant effect upon trim, and also to study the actual speed, which may well be about 2-1/2 knots, at which the reversal of the after hydroplanes' influence on depth occurs.

Serge G. Bindel (Bassin d'Essais des Carenes, Paris)

I was very interested in the results given by Prof. Mandel, and particularly in those concerning the rolling oscillation during vertical ascent; they confirm the results obtained in the Paris Model Tank when studying the bathyscaph of the French Navy.

I should like, however, to make one remark regarding the dynamic stability of such a ship during vertical motion. There is a problem for ascent, but there is generally no problem when diving. This fact may be due to the presence of the bridge fairwater, which plays a nonsymmetrical role in the two directions of the motion, even if, as in the present case, its height is not too large. The effect of the fairwater is, in some manner, like this of a longitudinal fin on the stability on straight course for a surface ship; when diving, the fairwater is aft and its effect is favorable; in the contrary, when ascending, the fairwater is fore and its effect is unfavorable. The problem is, of course, more complicated than for a surface ship, because of the existence of a static positive stability. Therefore, if Karman's vortices are responsible for the excitation, my opinion is that it is necessary to take into account the dynamic stability of the motion and, when designing such a submarine, to avoid, if possible, a too developed bridge fairwater.

Owen H. Oakley (U.S. Bureau of Ships)

I couldn't resist commenting on Mr. Mandel's excellent paper because he and I were involved together in the business of submarine design for a number of years. I would like to make only one comment and that with respect to the comparison of the Aluminaut with the Trieste. Mr. Mandel noted a ratio of one to ten in the internal volumes of the two craft in favor of the Aluminaut, but that is really not quite fair. One thing should have been emphasized more, and that is that the Aluminaut is good for about 15,000 feet of submergence, where the Trieste is good for some 37,000 feet. The problem of density of structure required for the deeper submergence comes into the matter very strongly, as does the basic difference in the means of providing buoyancy. Mr. Tupper covered a point very nicely that I wanted to touch upon, namely, what is the critical speed, and I would like to inquire whether an attempt was made to estimate this.

P. Mandel

Mr. Oakley has pointed out an oversight in the oral presentation of the paper. The fact that the Trieste is capable of diving to more than twice the depth of the Aluminaut places some very severe constraints on her design that are not nearly as limiting for the Aluminaut. I have more amply covered this point in the written text of the paper.

I have not attempted to predict the critical speed for the Aluminaut. The critical speed is extremely sensitive to the magnitude of the hydrodynamic vertical force and moment due to asymmetry, designated Z^* and M^* in Ref. 2. There is no known method of analytically predicting this force and moment and attempts to rationalize experimental values have been unsuccessful. In any event there is little necessity for accurately predicting the critical speed in the case of the Aluminaut since it is intended to place primary reliance on the vertical propeller and on the hydrostatic trim system for control in the vertical plane.

With respect to the oscillations in dive as well as in ascent, the Aluminaut can only descend by means of overweight at a very modest speed. As shown in Table 2, the

Aluminaut can only be ballasted to be some 500 pounds overweight and with that overweight its descent to 15,000 feet would take some four and one-half hours. Therefore, the vertical descent shown in Fig. 12 corresponds to a very modest speed where oscillations do not occur, and where the conditions are well removed from resonance. This is why we were primarily concerned with the ascent condition in the investigation.

* * *