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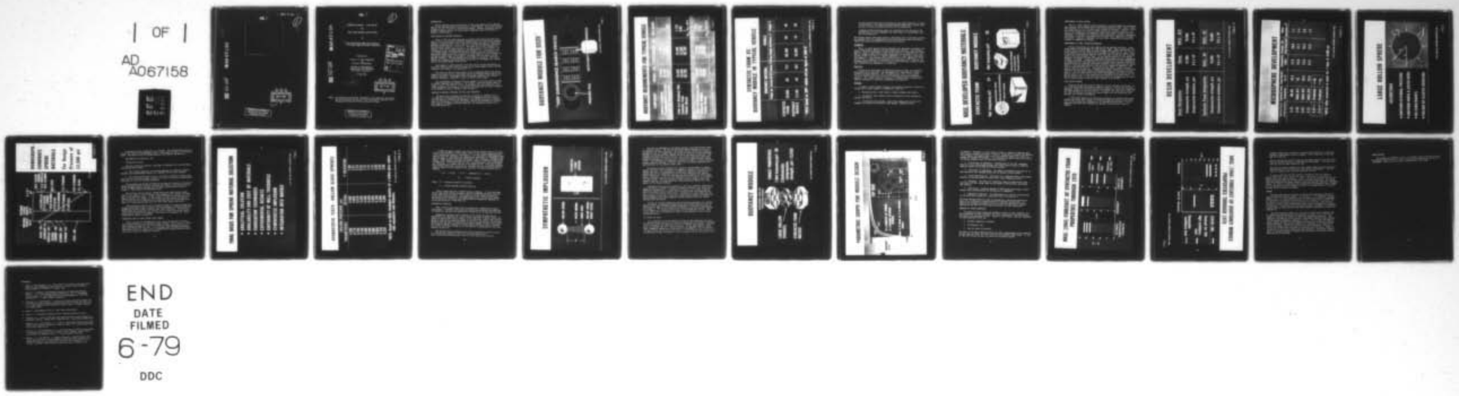

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COMPOSITE MODULES: A NEW DESIGN FOR DEEP OCEAN BUOYANCY APPLICATIONS

by

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NOTE: The opinions or assertions contained in this paper are the private one of the authors and are not to be construed as official or reflecting the views of the Naval Service at large.

INTRODUCTION

Future exploration and exploitation of the ocean depends on the development of new vehicles capable of operating at great depths. One of the critical systems in such a vehicle is the buoyancy system. Without an adequate and dependable buoyancy system, the vehicle once submerged would not be able to return to the surface.

APPLICATIONS OF BUOYANCY MATERIALS

Since it does not seem reasonable to predict that within the next five years it will be practical to develop pressure hulls with sufficient positive buoyancy to operate safely with a pay load at depths as great as 20,000 feet, buoyancy systems must be devised that will both provide buoyancy and assure the structural integrity of the hull. The materials in such a system will probably constitute a large portion of the gross weight of the vehicle. As illustrated by the following examples from reference (1), the buoyant structure weight needed to provide net positive buoyancy for such vehicles with negatively buoyant hulls may be expected to vary between 15 and 50 percent of the vehicle gross weight, see Figure 1, depending upon the density of the buoyant structure. For the example shown in Table 1, syntactic foam with a density of 0.65 would constitute about 45 percent of the weight in a typical vehicle with gross weight of 66,700 lbs.

Development of lighter buoyant structures would provide substantial reduction in vehicle gross weight as shown in the above example using a buoyant structure with $(W/D)_B = 0.45$ instead of 0.65.

The saving in vehicle gross weight in this comparison equals the entire weight of the pressure hull and almost equals the assumed total weight of the external equipment. Development effort on buoyant materials thus appears to offer an attractive trade-off in terms of vehicle gross weight.

The relationship of buoyant structure volume to the total vehicle volume is another important consideration. For example, using the vehicle shown in Figure 1 with a W/D ratio of 1.2 for the pressure hull and 20,000 lbs of external equipment, the volume of the buoyant structure may vary from 19 percent to 30 percent of vehicle volume as seen in Table 2.

FUNCTION OF BUOYANT STRUCTURE FOR FAIL-SAFE OPERATION

The function of a buoyant structure, as discussed in reference (1), is "In addition to furnishing buoyancy or lift to compensate for the weight of the high density structures and equipment, the buoyant structure is a major factor in the design of a fail-safe search vehicle for operation at 20,000 ft. With respect to buoyant structure selection, two essential criteria for a fail-safe design are:

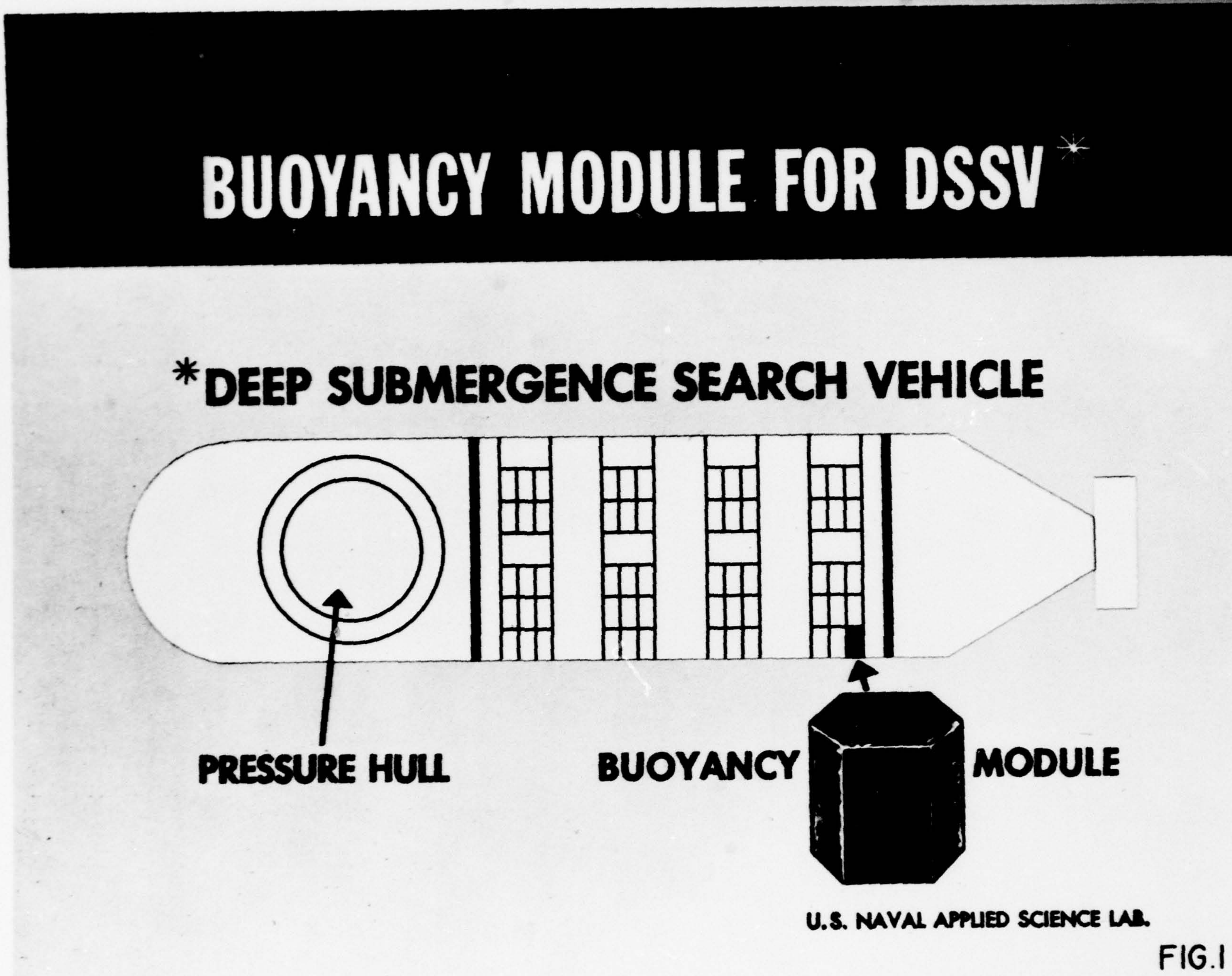
BUOYANCY MODULE FOR DSSV*
*DEEP SUBMERGENCE SEARCH VEHICLE
PRESSURE HULL
BUOYANCY
MODULE
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FIG.1

BUOYANCY REQUIREMENTS FOR TYPICAL VEHICLE

COMPONENT	WEIGHT, LBS.	DISPLACEMENT, LBS.	W/D RATIO
External Equipment	20,000	[illegible]	3.
Pressure Hull (7 1/2 ft. dia)	16,900	[illegible]	1.2
Total w/o Buoyancy Mat.	36,900		1.775
Total w/o Buoyancy Mat.	36,900	20,800	1.775
Syntactic Foam	29,800	45,900	0.65
Vehicle (Gross)	66,700	66,700	1
			$W_{SF}/W_G = 45\%$
Total w/o Buoyancy Mat.	36,900	20,800	1.775
Buoyancy Module	13,100	29,200	0.45
Vehicle (Gross)	50,000	50,000	1
			$W_{BM}/W_G = 26\%$

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TABLE I

SYNTACTIC FOAM VS BUOYANCY MODULE IN TYPICAL VEHICLE

	BUOYANCY MATERIAL			VEHICLE		
	Weight, lbs	Density (W/D)	Volume, ft^3	Gross Weight, lbs	Volume, %*	Weight, %
SYNTACTIC FOAM	29,800	.65	717	66,700	30	45
BUOYANCY MODULE	13,100	.45	457	50,000	19	26

*NOTE Based on 100% vehicle volume figure of 2400 ft^3

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TABLE 2

The vehicle must have positive buoyancy, at any depth, sufficient to effect a safe return to the surface from any operating mode when all power, propulsion or ballast systems have failed or are inoperative.

A buoyant structure failure shall not contribute to the failure of the pressure hull or other equipment that would result in catastrophic failure of the vehicle."

The buoyancy module containing syntactic foam meets both of the above criteria. See reference (2) for a comparison of syntactic foam with other low density liquids and solids considered for buoyancy applications.

BACKGROUND

The U. S. Naval Applied Science Laboratory has developed a candidate syntactic foam buoyancy material for deep submersible vehicles. This buoyancy material, which is identified as NASL ML-B3, consists of approximately 65 percent by volume of small hollow glass microspheres on the order of 10 to 100 microns (0.0004 to 0.004 in.) diameter embedded in a rigid epoxy resin matrix (see Figure 2). This material has a density of 0.6 to 0.7 gms/cm^3 (37 to 44 lbs/ft^3) and is capable of withstanding a uniform pressure of 10,000 psi for prolonged periods of time, as well as cyclic conditions over a range of hydrostatic pressure from atmospheric to 10,000 psi.

OBJECTIVE

Following the development of NASL ML-B3 syntactic foam, the Laboratory established a new objective - the development of a lower density, higher strength system of materials with a target density of 0.3 to 0.4 gm/cm^3 (19 to 25 lbs/ft^3) which will be able to withstand 13,500 psi hydrostatic pressure. This target system will consist of a module made of large hollow spheres contained in a syntactic foam matrix (see Figure 2).

APPROACH

In order to obtain higher strength, lower density materials, several approaches may be taken together or separately; these are:

a. Develop and use a lower density, higher strength resin matrix.

b. Incorporate lower density hollow microspheres in the existing or improved new matrix.

c. Incorporate high strength, large hollow spheres, one to four inch diameter, in a syntactic foam matrix thus making a composite module.


NASL DEVELOPED BUOYANCY MATERIALS
SYNTACTIC FOAM
BUOYANCY MODULE
Net buoyancy, pcf - 24
MAGNIFIED VIEW
GLASS MICROSPHERES
EPOXY RESIN
Net buoyancy, pcf - 36
HOLLOW SPHERES
IN SYNTACTIC
FOAM MATRIX
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FIG.2

IMPROVEMENTS IN RESIN SYSTEM

The U. S. Naval Applied Science Laboratory has investigated and formulated high strength resin systems used in fabricating syntactic foam. Table 3 shows the properties of two of the many resin systems investigated. Originally ML-B3 was chosen because of its high strength properties, as seen in Table 3. Recently, both commercial and laboratory resins with higher strength have been developed. For example, the Applied Science Laboratory's new resin formulation, identified as NASL-GL-9 illustrates the increased resin compressive strength and modulus. Syntactic foam made with this resin system shows an almost 20% increase in compressive strength.

IMPROVEMENTS OF SMALL HOLLOW MICROSPHERES

Hollow microspheres of lower density are now becoming available. These should permit the development of lower density foams. These microspheres have a lower specific gravity than the high strength microspheres that are used in ML-B3 foam and will thus permit the development of lower density foams. Table 4 shows four foam materials made with the same resin system but with different types of hollow microsphere filler. As the specific gravity of the spheres decrease, the density of each corresponding foam decreases and the compressive strength is reduced. Formulation NASL-B13 was made with the same microspheres as formulation NASL-B12 except that the microspheres were pressure screened by subjecting them to 2,000 psi hydrostatic pressure, thus eliminating the weakest spheres. The unbroken floaters, which were the stronger microspheres, were used in formulation NASL-B13. The resulting foam shows a slight increase in density over the NASL-B12 but a compressive strength comparable to the NASL-B11 foam made with the higher density microspheres having a 0.4 nominal specific gravity. Two new lower density type hollow microspheres with nominal specific gravity from 0.3 to 0.25 are expected to be available in the near future. It may be expected that, if these microspheres follow the pattern shown in Table 4, the resultant syntactic foam will have a density of 34 lbs/ft^3.

LARGE HOLLOW SPHERES

Based on the existing state-of-the-art of glass and resin technology, the third approach offers the greatest immediate promise. Spheres have the best geometric shapes for resisting hydrostatic compression, and hollow shapes have the added property of very low density. Therefore, the large hollow spheres will make it possible to reduce the overall density of the system and still maintain the strength requirements.

A theoretical analysis of significant variables was conducted with glass, ceramic and hollow metal spheres to determine promising materials and sphere size for the module (see reference (3) for mathematical analysis). The assumptions upon which this mathematical analysis are based are listed in Figure 3.

RESIN DEVELOPMENT

Resin Designation	Epoxy	NASL-GL9
Compressive strength, psi	21,000	30,000
Compressive modulus, psi	5.5×10^5	7.6×10^5
Syntactic Foam Designation	**NASL-B4**	**NASL-B7**
Compressive strength, psi	16,800	20,000
Compressive modulus, psi	5.6×10^5	6.5×10^5

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TABLE 3

MICROSPHERE DEVELOPMENT

Nominal Sp Gr. of Microspheres	Syntactic Foam Designation	Foam Density lb/ft^3	Compressive Strength, KSI		Water Absorption, %*
			Initial	After Immersion*	
0.45	ML-B3	44.2	17.5	16.8	1.1
0.40	NASL-B11	42.	14.5	12.7	1.4
0.35	NASL-B12	38.5	12.4	10.5	3.0
0.35	NASL-B13	39.4	14.2	12.5	1.3
0.30 ←	Predicted	→ 36.			
0.25 ←	Predicted	→ 34.			

*NOTE: After immersion in water for 7 days at 10,000 psi

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TABLE 4

LARGE HOLLOW SPHERE

ASSUMPTIONS

- UNIFORM EXTERNAL PRESSURE
- UNIFORM INNER & OUTER RADII
- NO CONSTRAINTS
- FAILURE BY ELASTIC BUCKLING

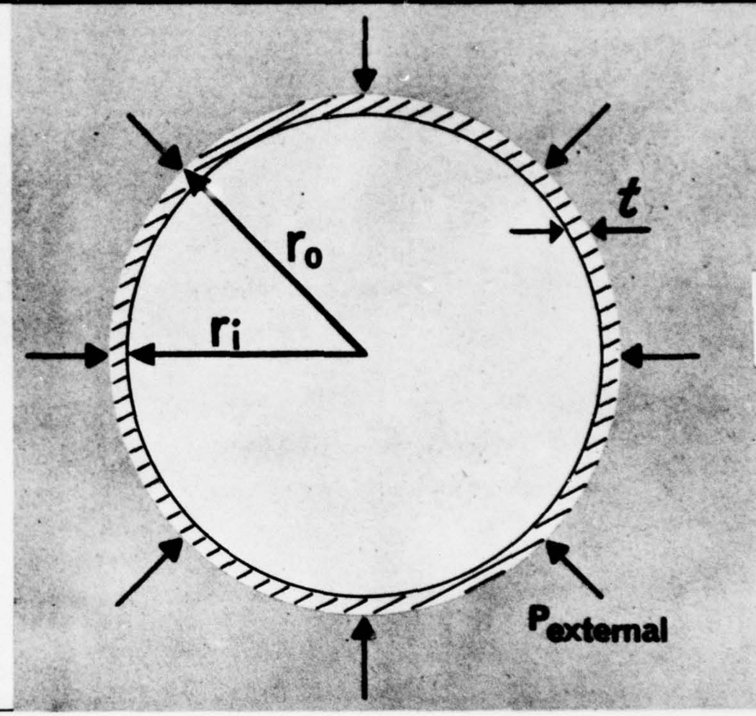

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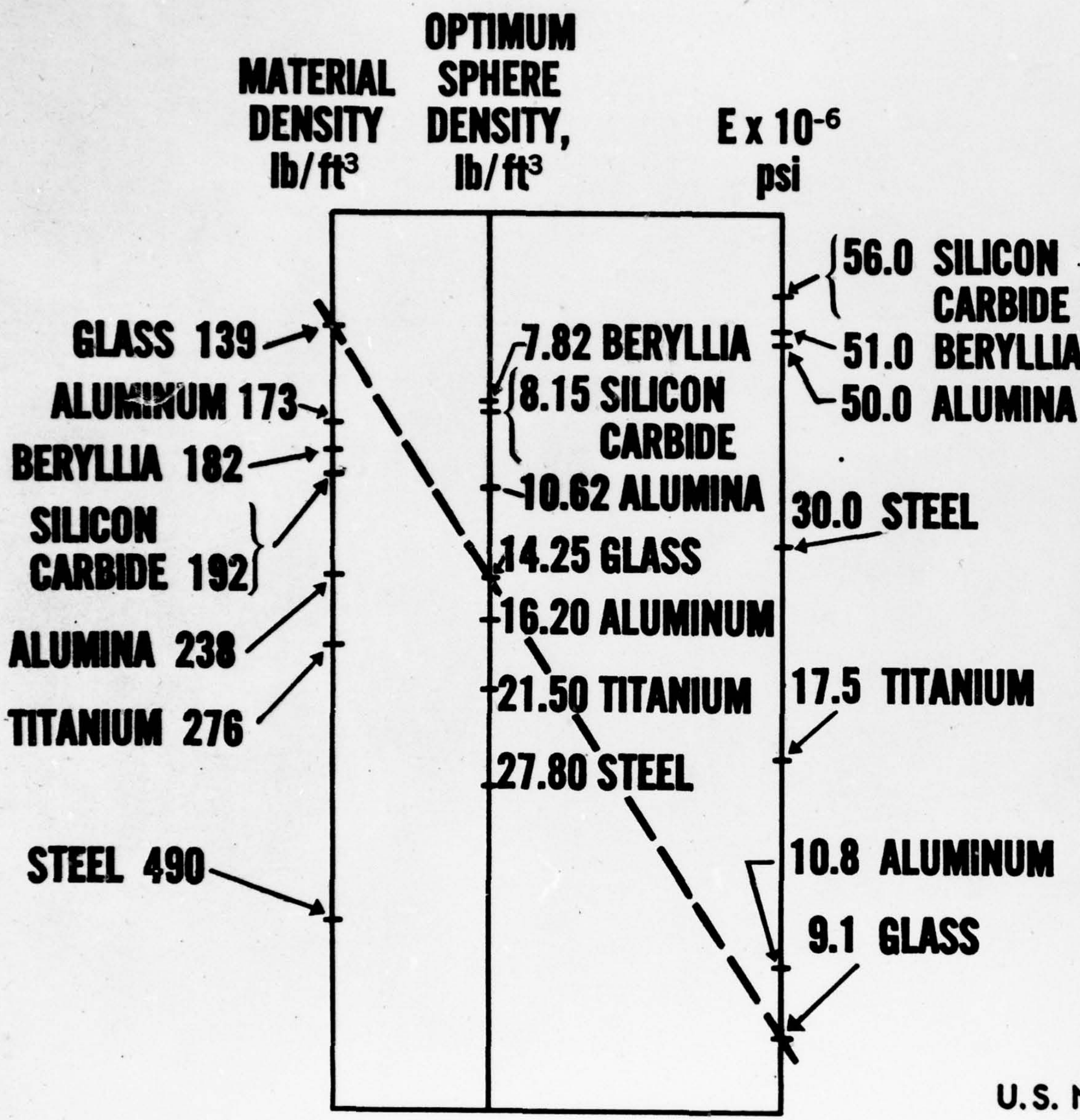
FIG.3



NOMOGRAPH- CANDIDATE SPHERE MATERIALS

For Design Pressure of 13,500 psi

TABLE 5

An extensive group of materials was reviewed. The candidate materials selected are listed in the Nomograph, Table 5 under material density in ascending order. The selection of the optimum material was based on the need for:

High Modulus of Elasticity, and

Low Material Density.

From the theoretical analysis, described in reference (3), the following conclusions can be drawn:

a. For a hollow sphere of a particular material at 13,500 psi external pressure the optimum sphere density is a constant for any outer diameter.

b. The candidate materials that are potentially suitable in sphere form are listed in the second column in Table 5 in order of ascending optimum sphere densities at 13,500 psi external presssure.

The preceding conclusions are based on an analytical solution of a hollow sphere and were used as the basic guideline for choice. The final selection of the optimum suitable candidate will be based on the factors listed in Figure 4. These factors are discussed below.

Beryllia and silicon carbide, though having the lowest hollow sphere density, see Figure 4, are at present, both expensive and difficult to fabricate in the spherical shape. It was therefore decided to evaluate glass and alumina spheres first because of their lower cost and greater availability. The state-of-the-art of fabrication of these materials as hollow spheres appears to be more advanced than that for other lower density materials.

Some development effort will be required to meet or closely approach the assumed conditions listed in Figure 3 since limitations of present production methods may introduce some variations from ideal conditions. Variations between actual and theoretical test results will be taken into account during the evaluation phase of the program. The intent is to approach the "ideal" conditions as closely as possible.

HYDROSTATIC TEST OF LARGE HOLLOW GLASS SPHERES

Tests were made to determine how close to the theoretical the actual failure pressures was for large hollow glass spheres. Three inch O.D. hollow glass spheres designed for the 3000 to 8000 psi range were used because of their availability and low cost. It is believed that information obtained from these 3-inch O.D. spheres can be extrapolated to design spheres suitable for use at 13,500 psi hydrostatic pressure.

FINAL BASIS FOR SPHERE MATERIAL SELECTION

- ANALYTICAL SOLUTION
- AVAILABILITY AND COST OF MATERIALS
- FABRICATION TECHNIQUES
- EXPERIMENTAL RESULTS
- UNIFORMITY OF WALL THICKNESS
- SYMPATHETIC IMPLOSION
- INTEGRATION INTO MATRIX

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FIG.5

HYDROSTATIC TESTS - HOLLOW GLASS SPHERES

FAILURE PRESSURE, psi		
THEORETICAL*	ACTUAL	% DEVIATION
4,390	4,480	2.00
4,770	4,650	2.57
5,290	5,410	2.24
4,140	4,420	6.32
4,380	4,450	1.57
5,500	5,420	1.47
3,888	3,820	1.57
4,920	5,180	5.05
4,720	4,900	3.67
4,220	4,390	3.88

*NOTE: Based on NASL developed equation for a hollow glass sphere with nonuniform wall thickness.

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TABLE 6

A study was made to predict the actual failure pressure due to the variation of wall thickness in each sphere, which is one of the assumptions made in the theoretical analysis, see Figure 3. For each sphere, measurements were taken in both the latitudinal and longitudinal directions, to determine actual wall thickness at each point and variations in wall thickness throughout the sphere. These spheres, although not perfect, showed a reasonably high degree of sphericity. Each sphere was put into a pressure vessel, and the pressure was increased at a uniform rate until the sphere failed. Preliminary studies, which require additional verification, indicated that the following equation explains about 60 to 65 percent of the variation in Failure Pressure (F.P.) results:

$$F.P. = 134.82 \quad \bar{x} - 2S + 10496070(x^{-4}) + 42.69$$

F.P. - Failure Pressure

where: $\bar{x}$ = average thickness for specimen

S = within specimen standard deviation

Table 6 shows data for a selected group of spheres. It lists the theoretical and actual failure pressures, and the percentage deviation from the actual value for each sphere. The theoretical values shown are based on an Applied Science Laboratory developed equation for a hollow glass sphere with varying wall thickness, and differs from the theoretical equation reported and discussed in reference (3).

SYMPATHETIC IMPLOSION

When a hollow glass sphere fails in hydrostatic compression an implosion occurs. In working with glass and ceramic hollow spheres the phenomena of sympathetic implosion was observed and recognized as an important problem.

Sympathetic implosion may be defined as the effect of shock forces generated by the implosion of a shell causing implosion of another shell subjected to these forces either directly or by reflection. When a shell bursts abruptly inwardly, the potential energy in the shell coupled with the potential energy of the sea water in converting to kinetic energy, produces shock waves. The potential energy released at an environment pressure P, due to collapse of a cavity which had a volume Vo, at the surface is represented by PV_0 (references (4) and (5)).

The Applied Science Laboratory has conducted implosion tests on 3-inch O.D. hollow glass spheres of the type discussed under the previous section entitled Hydrostatic Test of Large Hollow Glass Spheres.

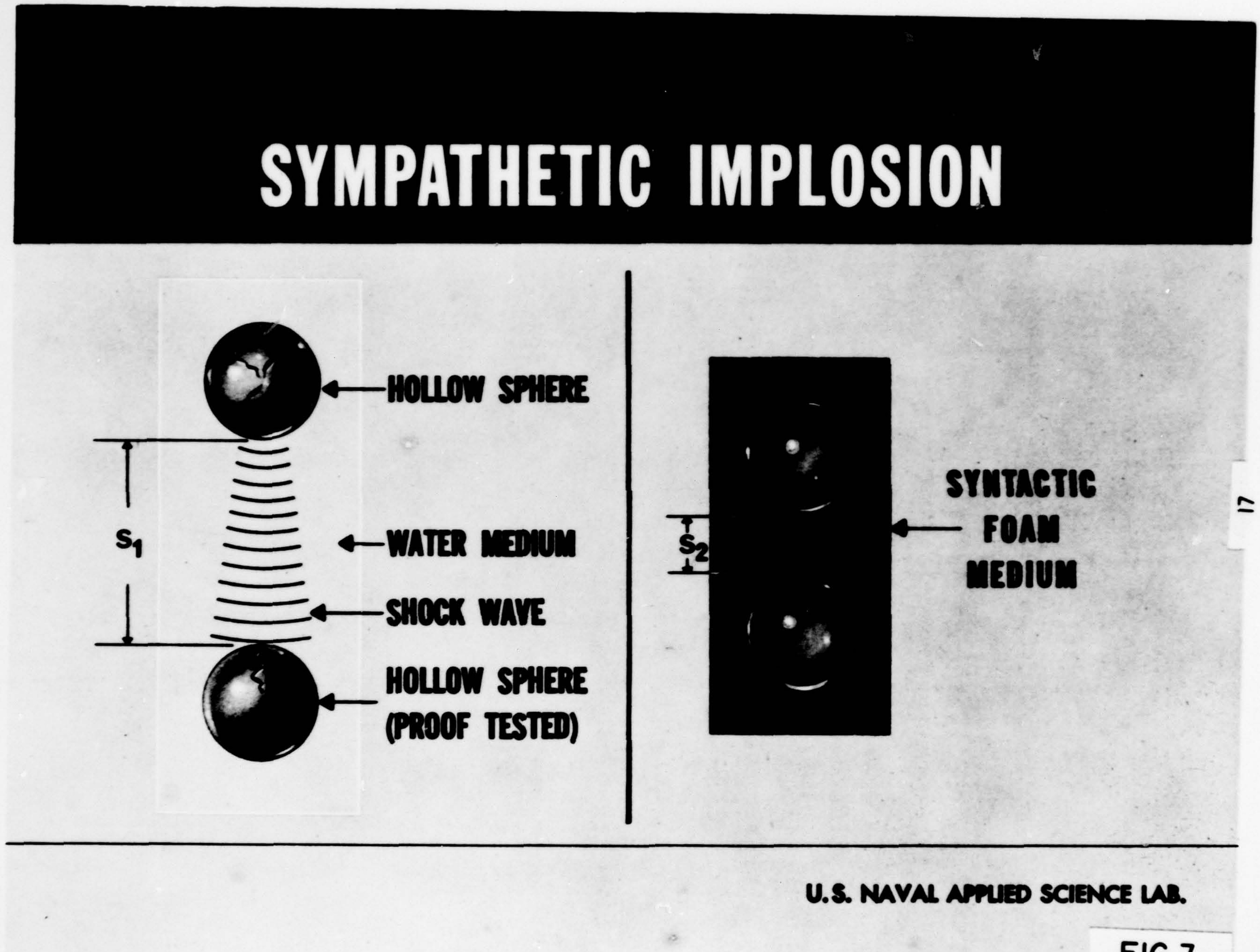
SYMPATHETIC IMPLOSION
HOLLOW SPHERE
S_1
WATER MEDIUM
SHOCK WAVE
HOLLOW SPHERE
(PROOF TESTED)
S_2
SYNTACTIC
FOAM
MEDIUM
U.S. NAVAL APPLIED SCIENCE LAB.

FIG.7

The test was performed on two spheres placed a specified distance apart in a pressure vessel. One thin walled hollow sphere, designed to fail at a low pressure was placed upstream. The second thicker walled hollow sphere, designed to fail at a higher pressure and proof tested was placed downstream. Pressure was applied and both spheres failed at the same low pressure. The assumption was that the failure of the "low pressure" sphere, by hydrostatic compression, produced a shock wave which caused the "higher pressure" sphere to fail. The phenomena of sympathetic implosion occurred at various distances between spheres up through 14 inches, which was the largest separation distance possible in the pressure vessel used.

The Applied Science Laboratory has tested a limited number of ceramic spheres and found that the problem of sympathetic implosion also exists with ceramic materials. The phenomena of sympathetic implosion occurring with spheres made of other materials has not yet been explored at the Applied Science Laboratory. From the literature and work conducted by other laboratories, references (6) and (7), this phenomena does not seem to be a problem with most metals. Thus the problem, if found critical enough in glass and ceramic types, may be a good reason for considering metal spheres as a component for the buoyancy module.

Underwater tests have been conducted at the Naval Ordnance Laboratory on large hollow glass spheres 10 inches in diameter, reference (8), which were exposed to explosions of 1 pound Pentolite charges, at a range of depths. One of the results reported shows that at greater depths the implosion problem is less critical but still occurs. In general, it can be seen that the major obstacle to the use of glass and ceramic hollow spheres for buoyancy is the development of a suitable cladding or matrix material that will insure adequate shock protection.

As part of a future program the Applied Science Laboratory will investigate the effect of sympathetic implosion of hollow glass spheres as well as hollow spheres made of other materials embedded in a syntactic foam matrix, see Figure 7. The initial study will be concerned with the critical spacing of two spheres in a syntactic foam matrix (a one dimensional array). This initial phase will be followed by a study of the spacing in a two or three dimensional array.

THE COMPOSITE MODULE

The integration of hollow spheres of glass or other materials in an array and the optimum design of the array are complicated and difficult problems. In this design the two important criteria are density and strength. Figure 8 shows an exploded view of a composite module. It may seem from the figure that a composite module has a particular size and geometry, size and material of hollow sphere and spacing in the matrix. If only the spacing is changed the corresponding changes in buoyancy can be determined from the parametric curve

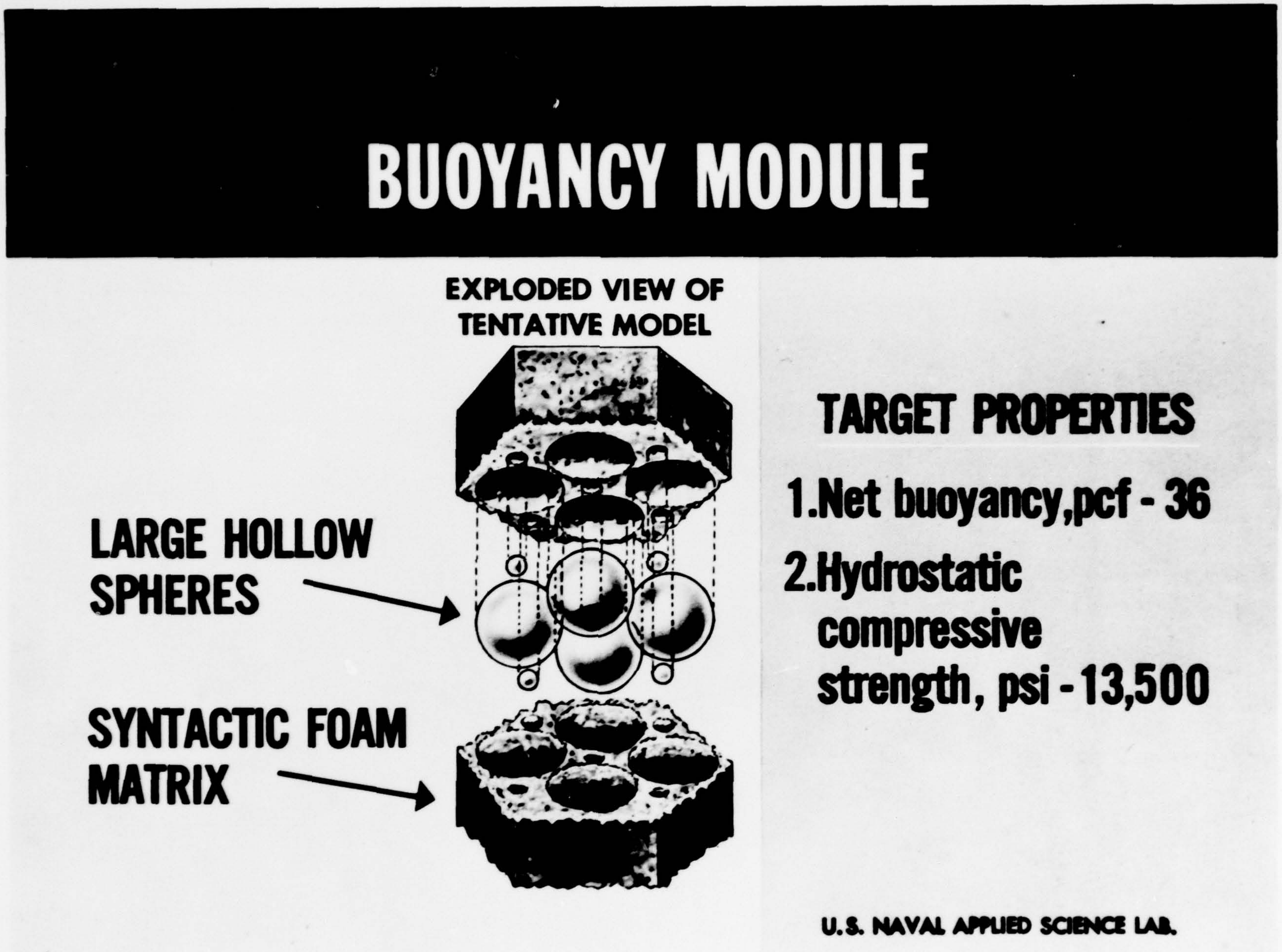
BUOYANCY MODULE
EXPLODED VIEW OF TENTATIVE MODEL
LARGE HOLLOW SPHERES
SYNTACTIC FOAM MATRIX
TARGET PROPERTIES
1.Net buoyancy,pcf - 36
2.Hydrostatic compressive strength, psi - 13,500
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FIG.8

PARAMETRIC GRAPH FOR MODULE DESIGN

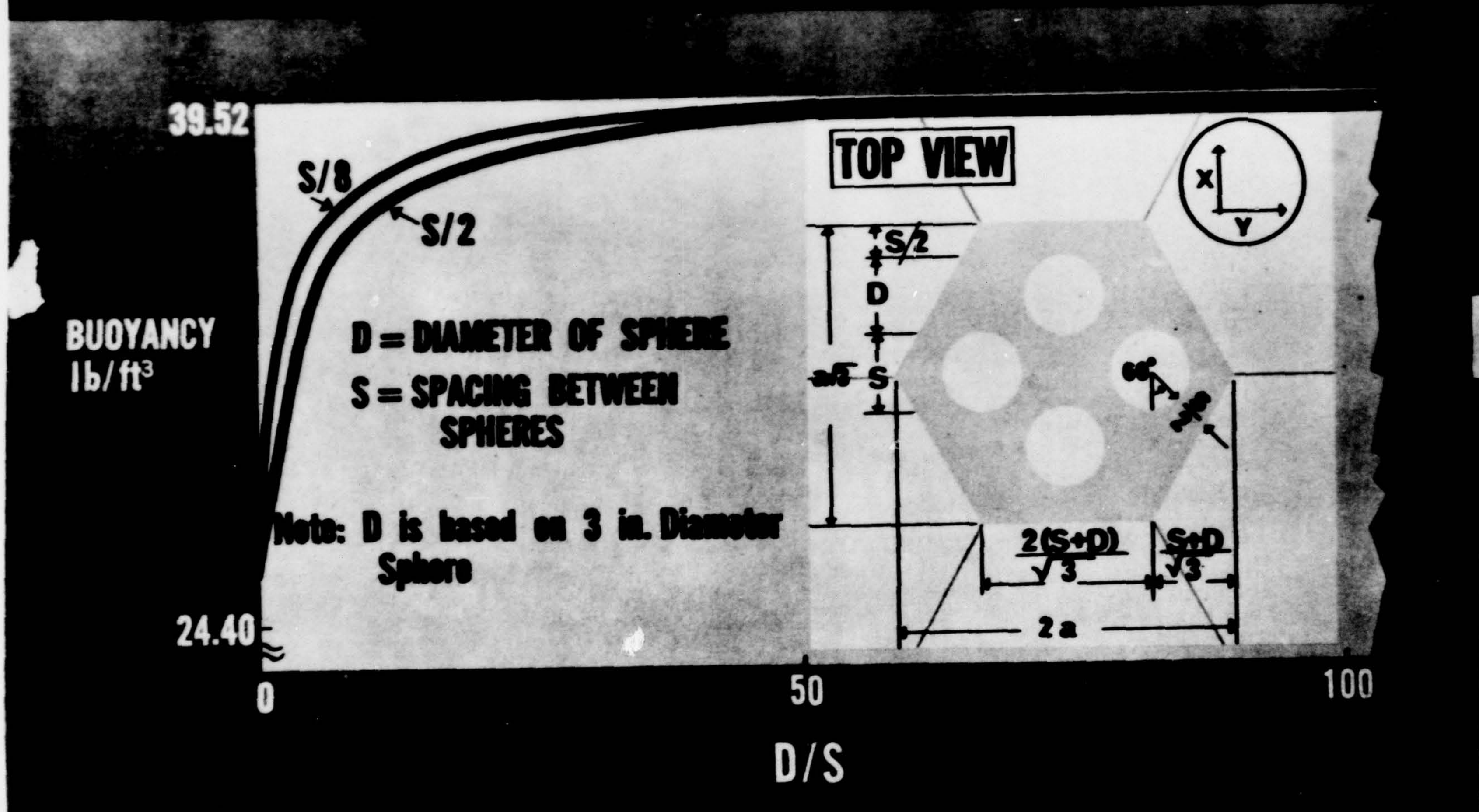

FIG.9

in Figure 9. Although it is not shown in Figure 9, changes in spacing would also produce changes in strength. Likewise, variations in diameter and material of the sphere, and geometry and size of the composite module will result in changes of buoyancy and strength. In evaluating the above criteria the following design parameters must be considered critical:

a. Failure Mode of Components. Determination of the best components which will yield the maximum strength and lowest density based on component material design failure mode and failure pressure.

b. Interaction of Components. The effect of interaction between two or more materials thus changing properties and possibly failure modes.

c. Stress Considerations. The design of a composite module using stress analysis to determine modes of failure for a multi-component system.

d. Packaging. The design of a geometric shape or shapes which would facilitate the best volume usage and be capable of being easily positioned and replaced.

e. Fabrication. Different methods of fabrication would result in different stress considerations and interaction of components.

f. Sympathetic Implosion. The determination of critical distances due to the shock wave problem for a particular level of reliability.

The final optimum system will only be optimum for a particular application; there will be different tradeoff points for different applications. In general the optimum system should be able to meet the particular strength application and have the lowest density possible for that application.

FORECAST OF FUTURE PROPERTIES

The Applied Science Laboratory prepared a report in 1964, reference (9), which presented the 1964 properties and costs for syntactic foam and forecast the values to be expected in 1970. Figure 10 shows three of the most important of these properties which are:

a. Ultimate compressive strength.

b. Net buoyancy, and

c. Cost per pound of buoyancy.

For each of the three properties shown are their corresponding values predicted at that time (in 1964), for 1970 as well as the present (1966) values. It can be seen that during the past two years the following occurred:

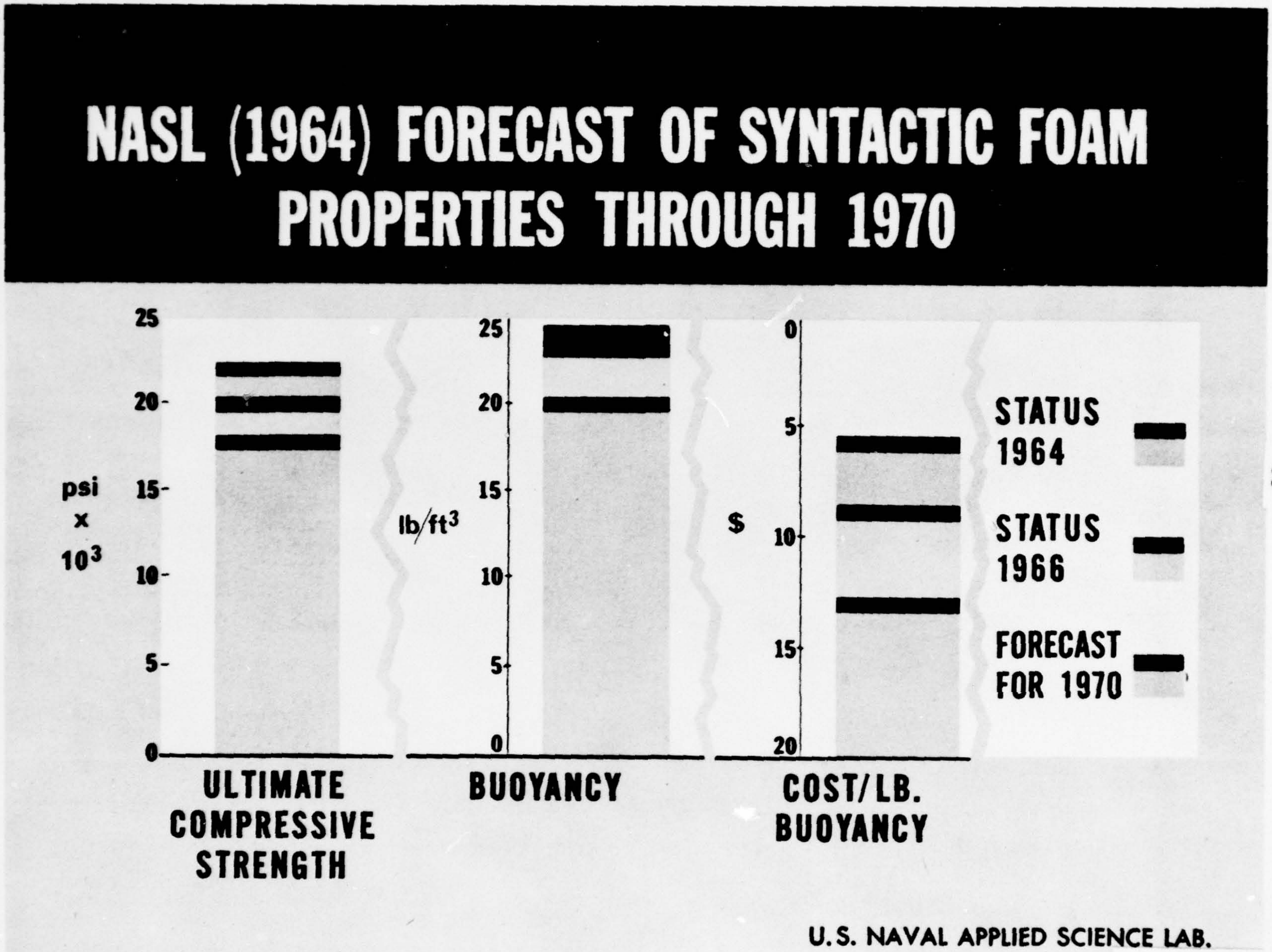
NASL (1964) FORECAST OF SYNTACTIC FOAM
PROPERTIES THROUGH 1970
psi
x
10^3
25
20
15
10
5
0
ULTIMATE
COMPRESSIVE
STRENGTH
lb/ft^3
25
20
15
10
5
0
BUOYANCY
$
0
5
10
15
20
COST/LB.
BUOYANCY
STATUS
1964
STATUS
1966
FORECAST
FOR 1970
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FIG.10

NASL (1966) FORECAST OF BUOYANCY MODULE PROPERTIES THROUGH 1970

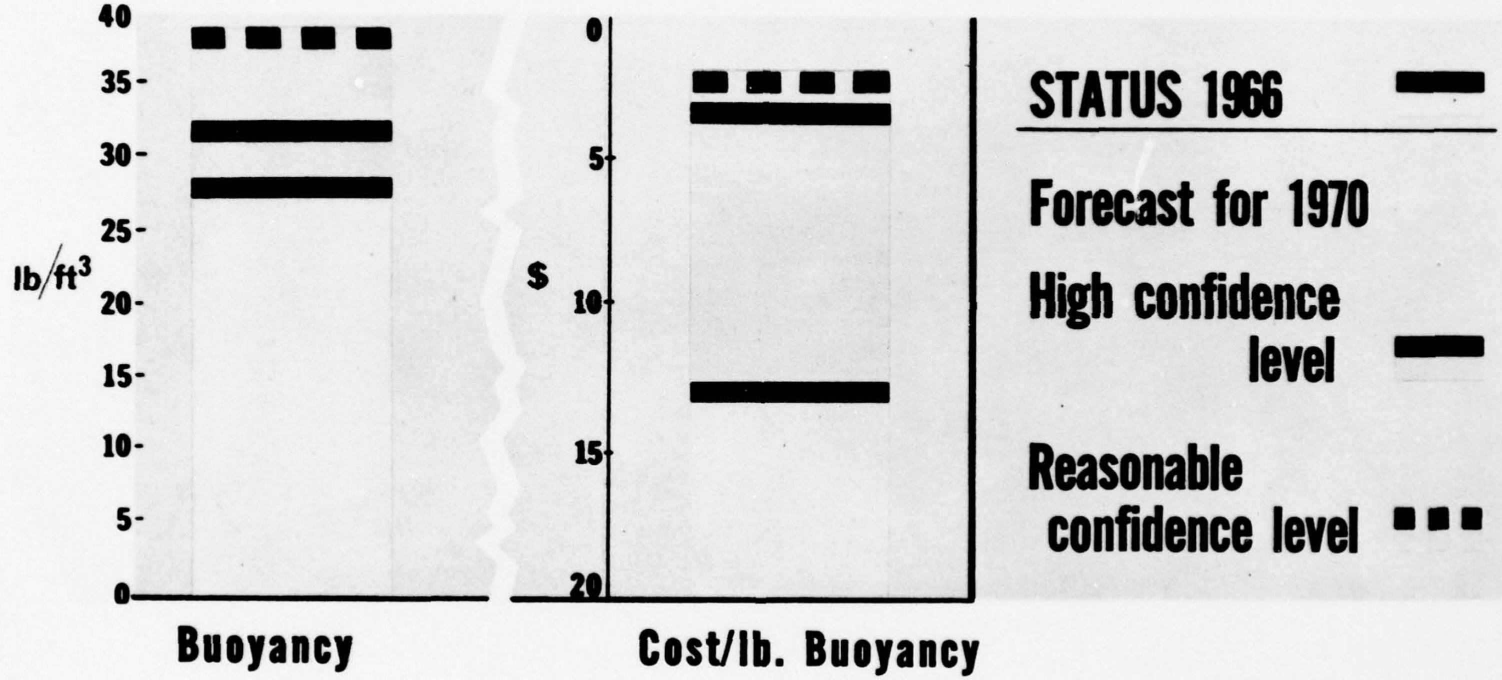

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FIG.11

Ultimate compressive strength has increased from 18,000 psi to 20,000 psi because of improvement in resin strength. This is half-way to the 1970 goal of 22,000 psi.

The net buoyancy of syntactic foam has increased from 20 to 24 lbs/ft^3 because of the availability of lower density microspheres. This goal forecast for 1970 has been reached in 1966.

The cost per pound of buoyancy has been reduced from $13 to $9 because of the reduction in cost of both the resin and the microspheres. The cost today is slightly less than that predicted for 1970.

It can be seen that the NASL forecast prepared in 1964 was conservative since for each of the values, the rate of improvement in properties is greater than the original forecast. Figure 11 shows the buoyancy and cost per pound of buoyancy which may be realized in a buoyancy module now. The figure also shows forecasts for both properties based on high and reasonable confidence levels. By 1970 it is expected, with a high level of confidence, that a module will be available which will supply 32 lbs/ft^3 of buoyancy and will be priced at about $3.50 per pound of buoyancy.

SUMMARY

Buoyancy materials are required to permit deep submersible vehicles to carry a payload and remain buoyant. At the 2nd U. S. N. Symposium on Oceanography, the U. S. Naval Applied Science Laboratory discussed the development and properties of syntactic foam which has a net buoyancy of 20 lbs/ft^3 and is capable of withstanding service pressures of 10,000 psi. With the new emphasis on greater depth oceanography a new target of strength and buoyancy is necessary. To meet this need, the Applied Science Laboratory is developing buoyancy modules consisting of large hollow spheres contained in a syntactic foam matrix.

The target buoyancy module will provide 36 lbs/ft^3 of net buoyancy and be capable of withstanding service pressures of 13,500 psi; it will be designed to withstand the effects of shock and sympathetic implosion. The properties and behavior of the syntactic foam matrix material after exposure to high pressure hydrostatic exposure is given. Also, a study was made of glass, ceramic and metal hollow spheres to establish criteria for candidate sphere materials. Hollow glass spheres were evaluated to determine the relationship between theoretical and actual collapse pressures. Analytical studies of optimum sizes and geometry of modules were initiated. Based on an analysis of the hollow sphere and matrix materials, significant improvements in increased buoyancy, strength, and reliability over present buoyancy materials may be expected.

ACKNOWLEDGMENT

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