become weight-limited at shallower depth, and evolution to new materials becomes urgent.

XIII Conclusions

An entirely new era in undersea research has been ushered in through the manned exploration of the ocean depths. Moreover, the third dimension of the sea invites attention as a means of providing versatility in combat submarine performance that could provide a favorable asymmetry to both offensive and defensive tactics.

One key to exploiting the medium lies in use of such new materials as metals as aluminum, fiberglass, and super-strength steels, with superior strength to density ratios. Other systems of construction such as sheathed cylinders and sandwich shells offer alternative solutions to the strength-weight impasse, for all operating depths, both shallow and deep.

With foreseeable achievements of stronger hulls for deep running without undue increase in weight by choices of new materials and construction techniques, the possibility exists that hulls for contemporary, shallow operating depths could be made proportionately lighter—by as much as 50 per cent. But the problem of evolving a hull structure depends on the payoff—penalty balance—but seems necessary if a new generation of compact submarines is to be feasible through future developments of higher density power plants or crew reduction.

XIV Acknowledgments

Acknowledgment should be made of foresight and initiative of the Committee on Undersea Warfare, National Academy of Sciences—National Research Council, for their initial sponsorship under auspices of the Office of Naval Research of the 1957-1958 feasibility studies of improved deep capabilities which lent substance to the promise of deeper diving submarines at a time when the mood for this research was dormant. Special recognition should be given of encouragement for this line of inquiry by Mr. George Wood, Secretary, CUW; Dr. Harvey Brooks, Chairman, CUW; and Rear Admiral A. McKee, USN (Ret), Chairman of the Submarine Panel.

The initial study reported herein was undertaken while the author was affiliated with Southwest Research Institute, and credit for assistance in conducting the numerical calculations should be extended to their staff.

XV References

5 Naval Ordnance Test Station unpublished report on Deep Diving Submarine for Oceanographic Research, 1959.
10 K. von Sanden and K. Günther, “Über das Festigkeitsproblem Quersteifte Holzländer unter Allseitig Gleichtässigen Aussen-
effects of reduced moduli on load-carrying capacity or appreciably greater margins between the elastic instability predictions and design collapse pressure than those suggested by the author. This is true not only for the ideal case of perfectly circular and initially stress-free cylindrical shell structures, but even more so for the actual case of those hulls fabricated according to prototype procedures. This point has been demonstrated beyond any doubt by recent studies conducted at the Model Basin in which machined and steam-relieved stiffened cylinders made of high-strength aluminum, and satisfying the criteria set forth by the author, have collapsed at pressures more than 15 per cent below those anticipated.

It is recognized that, in a feasibility study such as that presented by the author, assumptions invariably have to be introduced to make something like a strength-weight analysis tractable. However, extreme care should be exercised that such simplifications do not lead to results which prejudice certain basic parameters, such as materials considered in the present study. Specifically, the author’s assumptions (2) and (3) under Section VII are completely unrealistic, and result in the fact that HY-80 aluminum shows up much better than HY-200 steel throughout the practical range of positive buoyancy; this can be seen in Fig. 13. The use of more representative ratios for spacing of heavy frames and frame parameters permits the near doubling of the collapse pressures associated with the curve for HY-200 steel and in the region of 70 per cent excess buoyancy. Furthermore, it appears to the experienced eye that the author did not make use of his assumptions (2) and (3) in the development of the strength-weight curves in Fig. 13 for titanium and fiberglass.

In his discussion on sandwich construction, the author either fails to recognize or make mention of a basic and important difference in design philosophy between aircraft requirements and pressure hull requirements. Sandwich and other multi-layer shell structures, made of high-strength aluminum, and satisfying the criteria set forth by the author, have collapsed at pressures more than 15 per cent below those anticipated.

The author appreciates the interest by Messrs. Krenzke and Pulest in preparing their discussion, and in describing the scope and depth of current research which should go far toward putting meat on the bare bones of this feasibility study. Such progress is especially gratifying because stimulation of research was an important objective of the NAS Committee on Undersea Warfare in requesting the author’s study. Having determined that deeper operation deemed urgent for military reasons need not be frustrated by limitations of hull structure, findings with which the discussants seem to agree, research as outlined in Reference [1] becomes necessary to exploit the rich potential of new materials and systems of construction. The current Navy program is deserving of warm commendation, and it is hoped that the results will find prompt and fruitful application.

In calling attention to still classified studies conducted by the Bureau of Ships and the Model Basin “about the same time,” the discussants should inform the reader that both Navy feasibility studies were initiated to develop independent evaluation of the author’s findings. Antedating the author’s publication, both gravely cite Reference [1]; both support the author’s research proposals. A detailed account of research results, many of which are classified or proprietary, is not properly this author’s story to tell, but rather that of the many investigators who are now engaged in this effort. A comprehensive bibliography of relevant unclassified papers is appended to the author’s companion paper, Reference [6].

The exact origin of the sheathed construction concept is, in the author’s opinion, lost in history. Mr. Krenzke has on other occasions stated that TMB research was stimulated by the author’s December, 1958, briefing to the Navy on Aluminaut. At that time, the sheathed system which had been studied by Mr. John English of Reynolds Metals was described, together with a discussion of problems in full-scale fabrication that made it impracticable for immediate application to Aluminaut. It is to Mr. Krenzke’s credit that he has since developed the concept further and overcome certain practical limitations.

In stating that “... the mode erroneously referred to as axisymmetric yield collapse is in reality an inelastic buckling phenomenon,” the discussers appear to have overlooked References [6] and [11] wherein the author clearly identified this failure mode as a plastic instability and noted the inadequacy of available instability analysis.

The discussers apparently agree on the promise of sandwich construction proposed in Reference [1]. However, the relative merits of various sandwich systems depend on such factors as cost and ease of construction, so that selection cannot be made, as the discussers imply, on minimum weight arguments alone. Because the new high strength aluminum models that failed at 45 per cent less than anticipated pressure, the shell and general instability strengths should be arbitrarily chosen 40–50 per cent greater than shell yield strength until more rational design analysis becomes available.

With regard to high strength aluminum models that failed at 15 per cent less than anticipated pressure, the discussers do not explain their lack of correlation with DeHart’s extensive data from similar models that failed at higher than anticipated pressure. Without further details, interpretation is not possible. The author is aware, however, of one set of TMB models that failed prematurely, but understood that TMB now regards these as invalid because stiffener separation initiated from intense stress concentration along the juncures of outside T-stiffeners with the shell. These TMB results
are, nevertheless, instructive. Because radial stress at this juncture increases with hydrostatic pressure, the problem becomes more serious with deep-diving boats. If at all possible, stiffeners should be located inside so that radial stresses will be compressive rather than tensile; otherwise tension must be accommodated by careful attention to details to minimize the stress levels. The author’s findings of feasibility are predicated on diligent precautions to avoid stress concentrations of all types. Otherwise, with such a low safety margin, in the presence of cyclic loading, cracks and premature failure may occur, regardless of material. Application of these principles is reflected in Aluminaut concept, and in fatigue testing of Aluminaut hull models to confirm estimates of strength, a practice now widely adopted.