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SUMMARY OF
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SUMMARY OF AN INVESTIGATION OF TANDEM ROW HIGH HEAD PUMP INDUCERS

FINAL REPORT

By

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The following pages contain the summary, conclusions and references extracted from HYDRONAUTICS, Incorporated Technical Report 703-9 in fulfillment of the required separately bound summary. All figure numbers cited are those of the subject report which in its entirety contains 104 pages and 57 figures.

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5.0 SUMMARY

The suction specific speed (N_{ss}) is the parameter used to characterize the inlet operating conditions for a pump. For a given discharge, high suction specific speed results when either rotational speed is increased or NPSH is decreased. Both changes result in significant weight reductions when the pumps under consideration are fuel or oxidizer pumps in a liquid fueled rocket engine system. Prepumping stages called "inducers" are presently located ahead of the main fuel pumps. The inducers operate rather satisfactorily even with extensive cavitation and provide sufficient head rise so that the main pumps may operate non-cavitating.

A typical inducer consists of a high solidity axial flow impeller with a small number of blades operating on the same shaft and at the same rpm as the main pump. The blade form usually approximates a simple helix. While severely cavitating, cavitation damage and low efficiency are not particularly restrictive in "conventional" applications since the operating period is very short and the head generated by the inducer is only a small portion of the total. The problem of flow instabilities, however, is very significant as a limiting condition for acceptable inducer operation. Under certain conditions instabilities in the flow may cause engine thrust fluctuations. The resulting unsteady motions provide an unacceptable environment for delicate equipment and astronaut crews. In addition, low frequency oscillations may occur at or near the structural natural frequency.

The tandem row inducer has been suggested as one method for reducing or eliminating the instability problem. The first stage operates at the design suction specific speed but delivers only a fraction of the total head rise. The second stage thus operates at a lower N_{ss} and delivers the remaining head with greater stability.

The present study was conducted in water rather than the cryogenic fluids of the prototypes. Thermodynamic effects in cryogenics tend to make modelling in water a conservative procedure. For the same reasons, cavitation patterns in cryogenics will occur at lower bulk cavitation numbers, (higher N_{ss} values) than similar patterns in water.

A supercavitating first stage was chosen due to studies indicating that to produce the required head, cavities on the back side of the blades would be in excess of 30 percent of the chord length and unstable. Long cavities (supercavitation) are known to be a more stable operating condition.

A generalized theory of rotating stall (16) was chosen to determine the allowable head rise in the first stage of the tandem row inducer. Rotating stall was speculated to be another source of instability in addition to the unstable cavity lengths previously mentioned.

The performance of supercavitating cascades of constant pressure cambered foils was theoretically studied by the use of potential theory (18, 19). Using these results, a supercavitating first stage was designed using a free vortex-blade element approach (34,51,52) where the variation of head generated with radius is assumed to be constant.

The second or subcavitating stage was designed using the approach of (24) which requires no cascade data and which accounts for induced interference effects at the impeller blade as influenced by the other blades and the total pump vorticity.

An initial design for the two stage inducer utilizing a cylindrical 60 percent hub/diameter ratio, a two bladed constant pressure cambered supercavitating first stage (characteristic c/d = .540), and a six bladed high solidity (c/d = 2.43) second stage having NACA camber and thickness distributions was obtained. The design point overall performance requirements were:

flow coefficient, $\phi_o = 0.10$
head coefficient, $\psi = 0.25$
suction specific speed, $N_{ss} = 30,000$

The stability analysis (16) indicated that 15 percent of the total inducer head could be provided by the first stage at the design point and still maintain stable operation.

An experimental pump test loop (see Figure 4) was used to test the model. The loop had a plexiglas test section for observation of cavitating operation and the capacity to operate at reduced pressure to model N_{ss}. Direction sensitive velocity probes were used to provide radial surveys of the pressure, velocity and flow direction both upstream and downstream of the models. (see Figure 5). The test procedure adopted was to hold flow coefficient constant and to reduce NPSH (increase N_{ss}) until flow breakdown with data taken at arbitrary points along the performance curve.

The test program (34) indicated that for optimum performance both stages required empirical modification. Several modifications were tried and the final best performance was obtained by the use of a three-bladed first stage (c/d = .810) at the original design pitch and a six-bladed second stage at 10° less than the original design pitch. These stages were then tested in tandem with -6 inch and -1.5 inch overlaps (see Figures 7,8,9 and 10). Little difference was noted in the performance at the two overlaps. To compare the experimental performance to the original design requirement, the point at which the required head distribution (15 percent first, 85 percent second) occurred was chosen.

The tandem model produced more than the required head coefficient (.29/.25) at less than the design flow coefficient (.083/.100) and less than the design suction specific speed (22,000/30,000). The first stage cavity lengths at this point were approximately as required by the original design (1.50-1.75/ 1.50). Low frequency oscillations or instabilities were noted at breakdown but were attributed to unstable cavity lengths rather than rotating stall. In the stable region, pressure fluctuations over the range 0-10,000 cps were generally less than 5 percent of the head generated. The trade-off in head generation between the first and second stages produced a relatively flat ψ vs. N_{ss} characteristic.

The experimental performance, while not quite reaching the the design objectives, did indicate that the tandem inducer having a supercavitating first stage had definite potential as a high N_{ss} design concept.

Further manipulation of the pitch of the tandem inducer stages (in particular smaller pitch angles for Stage 1) may have reduced the head coefficient and increased the flow coefficient bringing each closer to the design values. This would probably have resulted in higher breakdown N_{ss} values because of the smaller angles of attack. It was concluded however, that with the constant pressure cambered blade shapes, it was doubtful that the design goal of 30,000 could be reached. One characteristic of constant pressure cambered cascades is that as the solidity is increased, the camber of the foil decreases approaching a flat plate. This is detrimental to the stability of the flow since flat plate profiles create a higher drag for the same lift than cambered profiles. The flat plate must rely entirely on angle of attack for lift generation. It was, therefore, apparent that the characteristics of supercavitating cascades having other than constant pressure camber were required. The second stage performance indicated the need for extension of the design capabilities of Reference 24. In particular, the velocities induced by a radial line vortex in an annulus (25) needed to be calculated for smaller axial and circumferential spacings and for larger hub/diameter ratios.

The theoretical performance of supercavitating cascades having other than constant pressure cambers was formulated (28) and the performance of numerous cascades calculated. The types of blades considered were those obtained by Johnson (27) and included circular arc, two-term, three-term and five-term cambers. The higher the number of terms in the camber distribution, the further aft the center of pressure is shifted. A comparison to the results of (18) indicated that the results of (28) were more conservative (i.e., more camber and angle of attack are required for the same lift than in the constant pressure results). This is in agreement with the experimental results on the Phase I models. A comparison of the results of (28) to experimental supercavitating cascade characteristics was difficult since almost no reliable data exists. A study of the influence of camber type on cascade performance indicated that the five-term cambered shape should be adopted for future first stage designs.

A formulation of the problem of partially cavitating cascades of cambered blades was conducted and published (36) for future use in the off-design performance of turbomachinery and for partially cavitating design use.

A theoretical study of the three-dimensional flow field generated by a radial vortex filament in a cylindrical annulus (42) was conducted as on extension of the second stage design capability. Considerable disagreement was found between these results and the results of Reference 25 except at mid radius. Sample streamline calculations showed that for hub/diameter ratios in excess of 0.70, the three-dimensional results are not required and a simpler two-dimensional approximation may be used.

A number of five-term cambered supercavitating first stage designs were considered using the theoretical results of (28) and the approach of free vortex design and blade element theory. The overall inducer requirements were taken to be the same as for the constant pressure cambered case previously described.

Among the five term cambered cases considered were two and three bladed designs using first order and approximate second order (26) results having:

(a) specified linear C_L variation with radius
(b) constant chord length with radius
(c) constant solidity with radius (radial leading and trailing edges)
(d) specified linear chord length variation with radius

The two bladed, second order, constant chord length design was chosen. Lining up the trailing edges in a radial direction results in a swept leading edge. The swept leading edge has been shown (4) to have certain advantages with regard to stability and in addition has definite structural advantages. The swept or spiral leading edge has also been used in a number of operational rocket engine inducers including the J-2 and F-1 engines for the Saturn V launch vehicle. The design, assigning 15 percent of the total head rise to the first stage was shown to be marginally stable at the design point and mid-radius using the criteria of (16).

A helical back surface was used for the model and structural consideration based on chordwise bending stresses at 20 percent of the chord from the leading edge showed structural compatibility with prototype inducers having the diameter and rpm ranges of the Saturn V inducers when the prototype design stress is 50,000 psi.

Using the newly calculated results for the radial vortex filament in an annular space (42), numerous second (subcavitating) stage designs were considered using the design technique of (24). The design chosen utilized 5 blades and a 0.70 hub/diameter ratio. Six vortices per blade were used in the design procedure and the NACA 65 series camber and 16-009 thickness function were used to arrive at the final blade profiles (see Figure 24).

The two bladed, five-term cambered first stage was manufactured and tested in the pump test loop (see Figure 22). Significant improvement was achieved over the performance of the constant pressure cambered first stage previously investigated (see Figure 26). The design head coefficient (15 percent of .25) and suction specific speed (30,000) were both achieved but at a flow coefficient of only 80 percent of the design value.

A large region of partially cavitating (spanwise direction) flow was noted with the tip becoming supercavitating before the hub. Tip cavities were sometimes separate and sometimes merged to the base cavities (see Figures 28 and 30). In either case, they tended to collapse at the same point as the base cavities. The variation in the base cavity length when fully cavitating was such that the closure of the cavity paralleled the leading edge of the following blade. A region of severe, instabilities and regions having various cavitation patterns including some face cavitation were found to be present (see Figure 26).

From the experimental results on the two bladed five-term model it seemed apparent that the design goal head coefficient and suction specific speed could not be met with this model at the required flow coefficient of 0.10. However, significant improvement over the best first stage model having constant pressure camber was achieved. Most notably, the operating N_{ss} value increased from 22,000 to 30,000.

A first stage model having the same blade profiles but with three blades was constructed in the belief that the higher solidity blades might improve overall head generation and thus delay breakdown to a higher N_{ss} value at a higher flow coefficient. The blades were also reduced in pitch by 1° to increase the flow coefficient operating range. The resulting three bladed five-term cambered first stage was manufactured and tested in the pump test loop. The addition of the third blade greatly increased the head generation at low N_{ss} values, but reduced the breakdown N_{ss} value at all flow coefficients (see Figure 35). The region of face cavitation was increased in spite of increased head generation and the base cavity lengths before breakdown were reduced. The phenomenon of unequal cavity lengths was also noted for this model.

Near the design flow coefficient (.10) the outlet axial velocity profiles were rather non-uniform with the velocity increasing from hub to tip with some boundary layer effects modifying the distribution. Suction specific speed had little effect on axial velocity profile but flow coefficient influenced it quite strongly. At lower flow coefficients where the flow was fully supercavitating the axial profile was much more uniform (see Figure 40). Typical total head generations varied by 15 to 25 percent with radial location with the higher values near the tip.

Analysis of the blade element performance of the two and three bladed five term cambered models at the midspan of the blade when operating in the fully supercavitating mode indicated that the theory (28) reasonably calculates the cascade lift performance when the basic assumption (fully supercavitating) is met. (See Figures 44, 45, 46 and 47). The partially cavitating or non-cavitating data at midspan indicates higher lift coefficients than when supercavitating as would be expected. Face cavitating conditions resulted in lift reduction.

Using the stability analysis techniques of (16) the experimental data for the two and three-bladed, five-term cambered models was analyzed at midspan. According to (16) the onset of rotating stall type instabilities should occur when the ratio of the parameters M/M_L approaches 1.0. If this type of instability is responsible for the regions of instabilities noted in the model tests, the ratio M/M_L should thus approach 1.0 or at least steadily increase as the boundary of the unstable region is approached. This was not found to be so. It was thus concluded that the criterion of (16) did not adequately predict the onset of incipient instabilities in the cavity flows under consideration and, therefore, that the rotating stall mechanism was not responsible for the large magnitude, low frequency oscillations observed in the cavitating inducers studied.

Analysis of the cavity length data for both models indicated that, provided the flow coefficient was below a certain critical value, the region of severe oscillations corresponded to that operating condition where the cavity collapsing from one blade extends back to or slightly beyond the leading edge of the adjacent blade. The oscillation of the flow in the unstable region appears to be of the limit cycle type, but the exact mechanism is uncertain. From the analysis, however, it may be concluded that the oscillations are probably due to the interaction of the cavities with adjacent blades at critical cavity lengths and thicknesses. Because of the complex flow at the entrance to the gap formed by the adjacent blade, the cavity length-head relationship may be inherently unstable leading to cavity length oscillation between fixed boundaries.

In the large "stable" region of operation, an analysis of the magnitude and frequency of oscillations in the 0-100 cps range indicates that peaks occur in the vicinity of 20 cps and 85 cps. Neither pressure peak exceeded 10 percent of the head generated by the first stage and the N_{ss} values of 22,000 or less neither exceeded 5 percent. Correlation with ℓ/c indicated a minimum at about $\ell/c = 1.40$.

No tandem tests were conducted using a five-term cambered first stage, however, the results of pressure fluctuation measurements on tandem tests during Phase I indicate that the overall pressure fluctuation level in the tandem configuration will be much lower when expressed as a percentage of total inducer head. This is due to the relatively smaller fluctuations of the second stage and the higher portion of the total head generated by that stage.

It is concluded that a tandem inducer using a supercavitating first stage and subcavitating second stage may be designed to operate over a fairly wide range of suction specific speeds (models operated at 10,000 - 30,000 in water) and flow coefficients (models operated at .12 - .07) with pressure fluctuations of less than 10 percent of the head generated.

The influence of the remainder of the hydraulic system (including main fuel pump) on damping or amplifying this level cannot presently be predicted. In addition, the number of inducer models tested has been quite limited and these have been tested only in room temperature water. The thermodynamic effects of cavitation in cryogenic fluids will raise the range of operating suction specific speeds to higher values.

Appendix A provides a summary of the inducer performance characteristics during a flight of the Saturn V launch vehicle using the data available. Appendix B discusses the shuttle vehicle inducer performance characteristics based on some preliminary and highly speculative data. The problems relating to stresses and cavitation damage to the impeller and casing are considered to be very serious and require careful attention. The effect of cavitation damage on a conventional (short life) rocket inducer is minor since the operating time is only a matter of minutes. The shuttle, however, with the required reusable characteristic presents serious material problems in the turbomachinery system.

6.0 CONCLUSIONS

Based on the work reported, the following conclusions may be drawn:

1. Based on the Phase I tests the constant pressure cambered supercavitating cascade theory (18) tends to be overly optimistic in predicting the lift performance of high stagger angle cascades.

2. The theory for supercavitating cascades of cambered foils (28) appears to agree rather well with the test data provided that the flow is nearly two-dimensional and that supercavitating conditions exist.

3. The complex three dimensional flow field present in an actual inducer almost assures that empirical modifications to the design will be required. The design technique as developed (26,34) is admittedly less sophisticated than might be desired, however, it appears to be an adequate first step which should be built upon. A new rationale for determining head distribution among stages is needed.

4. The constant pressure cambered foil profile is considered inferior to the five-term cambered shape for cascade applications. The shift of the center of pressure further aft is advantageous.

5. Due to the various off-design operating conditions encountered, the theory formulated for partially cavitating cascades might prove especially valuable and should be further studied.

6. The swept leading edge configuration is apparently both hydrodynamically and structurally superior to the radial leading edge design.

7. The improved second stage design capability made possible primarily through the investigation of the radial vortex filament in a cylindrical annulus (42) should result in much improved second stage designs. In particular, the larger hub/diameter ratios such as in the designs discussed should improve performance. No model tests, however were conducted on second stage models after the improved design information was available.

8. In tandem, a two stage model demonstrated a flat N_{ss} vs. ψ curve with a larger percentage of the total head being assumed by the second stage as N_{ss} is increased. In addition, the tandem model (7.0 inch diameter) was affected only slightly by a change in overlap from -6.0 inches to -1.5 inches.

9. While not totally eliminating the unstable region, the tandem inducer configuration with a supercavitating first stage did produce a large "stable" operating range where the total fluctuating head was typically less than 5 percent of the total head generated.

10. The originally proposed stability criterion of (16) did not appear to correlate well with the observed onset of flow instabilities in the model.

11. The mechanism for flow instability in the models tested appeared to be related to cascade-cavity interference. The base cavity is predominant in this interference, the effect of the tip cavity being secondary. When the flow coefficient is below a critical value (dependent on the geometry of each inducer) and the suction specific speed is high enough that the cavity extends back to or slightly beyond the leading edge of the adjacent blade, limit cycle type cavity oscillations may occur. In this region it is believed that the cavity-length-head relationship for the impeller may be inherently unstable with the cavity length and head oscillating between fixed boundaries.

12. It is apparent that tandem inducers using a supercavitating first stages and subcavitating second stages may be designed to operate over a fairly wide range of suction specific speeds (models operated at 10,000 - 30,000 in water) and flow coefficients (models operated at .12 - .07) with pressure fluctuations of less than 10 percent of the head generated.

13. The influence of the remainder of the hydraulic system (including main fuel pump) on damping or amplifying the pressure fluctuation level cannot presently be predicted. In addition, the number of inducer models tested has been limited and these have been tested only in room temperature water. The thermodynamic effects of cavitation in cryogenic fluids will raise the range of operating suction specific speeds to higher values.

14. The type of inducer investigated might well be an alternative to the simple helical types presently used. This approach would appear to be even more attractive as future performance requirements become more severe with regard to higher speeds, lower flow coefficients, and higher total head generation requirements. It seems likely that more than two stages may be required for such applications.

15. Cavitation damage to the models and test section and previous research into cavitation damage and related phenomena indicates that serious materials problems may be expected for future high performance turbomachinery systems having long life requirements such as for the proposed space shuttle vehicle. These problems will be present regardless of the inducer configuration finally chosen.

REFERENCES

1. Daily, J. W., "Theory of Turbomachinery," Chapter 8 in Engineering Hydraulics, H. Rouse, Ed., Wiley, 1961.

2. Ross, C. C and Banerian, G., "Some Aspects of High Suction Specific Speed Pump Inducers," Transactions ASME, Vol. 78, Number 8, 1956.

3. Pinkel, I. I., et al., "Conference on Selected Technology for the Petroleum Industry," NASA SP-5053, Chapter 6, Pump Technology, December 1965.

4. Acosta, A. J., "An Experimental Study of Cavitating Inducers," Trans. 2nd Symp. on Naval Hydrodynamics, ONR Publication ACR-38, 1958.

5. Hartmann, M. J., and Soltis, R. F., "Observations of Cavitation in a Low Hub-Tip Ratio Axial Flow Pump," ASME Paper No. 60-Hyd-14, March 1960.

6. Iura, T., Discussion of Ref. 4 by Acosta, Trans. 2nd Symp. on Naval Hydrodynamics, ONR Pub. ACR-38, 1958.

7. Soltis, R. F., "Some Visual Observations of Cavitation in Rotating Machinery," NASA TN D-2681, July 1965.

8. Crouse, James E. and Sandercock, Donald M., "Blade-Element Performance of Two Stage Axial Flow Pump with Tandem Row Inlet Stage," NASA TN D-3962, May 1967.

9. Sandercock, D. M., and Crouse, J. E., "Design and Overall Performance of a Two-Stage Axial-Flow Pump with a Tandem-Row Inlet Stage," NASA TN D-2879, March 1965.

10 Soltis, R. F., Urasek, D. C., and Miller, M. J., "Blade-Element Performance of a Tandem-Bladed Inducer Tested in Water," NASA TN D-5562, November 1969.

11. Soltis, R. F., Urasek, D. C., and Miller, M. J., "Overall Performance of a Tandem-Bladed Inducer Tested in Water," NASA TN D-5134, May 1969.

12. Eisenberg, P. and Tulin, M. P., "Cavitation", Chap. 12 in Handbook of Fluid Dynamics, V. L. Streeter, Ed. McGraw-Hill, 1961.

13. Stripling, L. B., and Acosta, A. J., "Cavitation in Turbo-Pumps, Part I," ASME Hydraulics Division Paper No. 61-WA-112, November 1961.

14. Acosta, A. J., and Hollander, A., "Remarks on Cavitation in Turbomachines," CIT Report 79.3, October 1959.

15. Wade, R. B., and Acosta, A. J., "Investigation of Super-cavitating Cascades," ASME Journ. Basic Engr. Paper 66-WA/FE-25, December 1967.

16. Yeh, H., "An Actuator Disc Analysis of Inlet Distortion and Rotating Stall in Axial-Flow Turbomachines," Journal of the Aeronautical Sciences, Vol. 26, No. 11, 1959.

17. Auslaender, J., "The Linearized Theory for Supercavitating Hydrofoils Operating at High Speeds Near a Free Surface," HYDRONAUTICS, Incorporated Technical Report 001-5, June 1961.

18. Yim, B., "Supercavitating Cascades with Constant Pressure Cambered Blades," HYDRONAUTICS, Incorporated Technical Report 703-2, July 1967 (NASA CR-90426).

19. Yim, B., "The Higher Order Theory of Supercavitating Cascades with Constant Pressure Cambered Blades," HYDRONAUTICS, Incorporated Technical Report 703-3, October 1967. (NASA CR-91444).

20. Emery, James C., Herrig, L. Joseph, Erwin, John R., and Felix, A. Richard, "Systematic Two-Dimensional Cascade Tests of NACA 65 - Series Compressor Blades at Low Speeds," NACA Report 1368, 1958.

21. Numachi, F., "Cavitation Tests on Hydrofoils Designed for Accelerating Flow Cascades/Report 1," Report No. 125 of the Institute of High Speed Mechanics of Japan, April 1959.

22. Numachi, F., "Cavitation Tests on Hydrofoils Designed for Accelerating Flow Cascades: 3-Five Profiles Generated from Prescribed Pressure Configurations of Types 1 and 3," ASME Paper No. 63-WA-74, November 1963.

23. Barr, Roderick A., "Study of Instabilities in High Head Tandem Row Inducer Pumps," HYDRONAUTICS, Incorporated Interim Technical Report 703-1, February 1967.

24. Bowerman, R. D., "The Design of Axial-Flow Pumps," Trans. ASME, Vol. 78, No. 8, 1956.

25. Tyson, H. N., Jr., "Three-Dimensional Interference Effects of a Finite Number of Blades in an Axial Turbomachine," C.I.T. Report E19.1, November 1952.

26. Etter, R. J., and Hsu, C. C., "An Investigation of Tandem-Row High-Head Pump Inducers - Interim Report Phase II," HYDRONAUTICS, Incorporated Technical Report 703-8, February 1970.

27. Johnson, V. E., Jr., "Theoretical and Experimental Investigation of Supercavitating Hydrofoils Operating Near the Free Water Surface," NASA Technical Report R-93, 1961.

28. Hsu, C. C., "On the Flow Past a Supercavitating Cascade of Cambered Blades," HYDRONAUTICS, Incorporated Technical Report 703-5, February 1969. (NASA CR-100773).

29. Tulin, M. P., "Steady Two-Dimensional Cavity Flow about Slender Bodies," David Taylor Model Basin Report 834, May 1953.

30. Cohen, H. and Sutherland, C. D., "Finite Cavity Cascade Flow," Rensselaer Polytechnic Institute, Department of Mathematics, Report No. 14, April 1958.

31. Acosta, A. J., "Cavitating Flow Past a Cascade of Circular Arc Hydrofoils," California Inst. of Tech., Report No. E-79-2, March 1960.

32. Betz, A., and Petersohn, E., "Application of the Theory of Free Jets," NACA TN 667, April 1932.

33. Hsu, C. C., "Supercavitating Lifting Hydrofoils--Second Order Theory," HYDRONAUTICS, Incorporated Technical Report 121-6, March 1966.

34. Contractor, D. N., and Etter, R. J., "An Investigation of Tandem Row High Head Pump Inducers, Interim Report-Phase I," HYDRONAUTICS, Incorporated Technical Report 703-4, May 1969.

35. Pearsall, J. S., "The Use of Potential Flow Methods in Designing Cavitating Pumps," in 1968 ASME Cavitation Forum, ASME Fluids Engineering Conf., May 6, 7, 1968, Philadelphia, Pennsylvania.

36. Hsu, C. C., "On Flow Past a Cascade of Partially Cavitating Cambered Blades," HYDRONAUTICS, Incorporated Technical Report 703-6, March 1969.

37. Wade, R. B., "Flow Past a Partially Cavitating Cascade of Flat Plate Hydrofoils, California Institute of Technology Engineering Report No. 79-4, 1963.

38. United Aircraft Research Laboratories Report G910254-50 "Systematic Two Dimensional Cascade Tests of Double Circular-Arc Hydrofoils," 1968.

39. Lewis, George W., et al., "Cavitation Performance of an 83° Helical Inducer Operated in Liquid Hydrogen," NASA TM X-419, March 1961.

40. Soltis, Richard F., et al., "Investigation of the Performance of a 78° Flat Plate Helical Inducer," NASA TN D-1170, March 1962.

41. Montgomery, J. C., "Analytical Performance Characteristics and Outlet Flow Conditions of Constant and Variable Lead Helical Inducers for Cyrogenic Pumps," NASA TN D-583, March 1961.

42. Etter, R. J. and Van Dyke, P., "Three Dimensional Flow Field from a Radial Vortex Filament in a Cylindrical Annulus," HYDRONAUTICS, Incorporated Technical Report 703-7, December 1969. (NASA CR-102560).

43. McMahon, J., "On the Roots of the Bessel and Certain Related Functions," Annals of Math. Vol. 9, No. 1, pp 29, 1894.

44. Titanium Metals Corp. of America, "Titanium Engineering Bulletin No. 1 - Properties of Ti-6Aℓ-4V," New York, February 1965.

45. Scott, Russell, B., Cyrogenic Engineering, D. Von Nostrand Company, Princeton, N. J., 1959.

46. Lieblein, S., Schwenk, F. C., and Broderick, R. L., "Diffusion Factor for Estimating Losses and Limiting Blade Loadings in Axial-Flow-Compressor Blade Elements," NACA RM E53D01, June 1953.

47. Tulin, Marshall P., "Supercavitating Propellers - History, Operating Characteristics, Mechanism of Operation," 4th Symposium on Naval Hydrodynamics, ONR Publication ACR-92, 1962.

48. "Aerodynamic Design of Axial-Flow Compressors," Volumes I, II and III, NACA RME56B03, August 1956.

49. Acosta, A. J., and Wade R. B., "Experimental Studies of Cavitating Hydrofoils in Cascade," CIT Report, February 1968.

50. Wood, G. M , "Visual Cavitation Studies of Mixed Flow Pump Impellers," ASME Paper No. 62-Hyd-12, 1962.

51. Wislicenus, F. G., "Fluid Mechanics of Turbomachinery," Volumes I and II, Dover Publications, New York, 1965.

52. Stepanoff, A. J., "Centrifugal and Axial Flow Pumps," 2nd Ed. John Wiley and Sons, N. Y., 1967.

53. Raleigh, Lord "On the Pressure Developed in a Liquid During the Collapse of a Spherical Cavity, Philosophical Mag., Vol. 34, 1917.

54. Thiruvengadam, A. and Preiser, H. S., "On Testing Materials for Cavitation Damage," HYDRONAUTICS, Incorporated Technical Report 233-3, December, 1963.

55. Thiruvengadam, A. and Waring, S., "Mechanical Properties of Metals and Their Resistance for Cavitation Damage," HYDRONAUTICS, Incorporated Technical Report 233-5, June 1964.

56. Eisenberg, P., Preiser, H. and Thiruvengadam, A., "On the Mechanisms of Cavitation Damage and Methods of Protection," SNAME Transactions Vol 73, 1965.

57. Thiruvengadam, A., "The Concept of Erosion Strength," HYDRONAUTICS, Incorporated Technical Report 233-9, December 1965.

58. Thiruvengadam, A., "On Modelling Cavitation Damage," HYDRONAUTICS, Incorporated Technical Report 233-10, August 1966.

59. Thiruvengadam, A., "Theory of Erosion," HYDRONAUTICS, Incorporated Technical Report 233-11, March 1967.

60. Eisenberg, P., "Cavitation and Impact Erosion Concepts, Correlations, Controversies," Symposium on Characterization and Determination of Erosion Resistance, ASTM Annual Meeting, 1969, Atlantic City, N. J.