THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

OBSERVATION OF CAVITATION SCALE AND THERMODYNAMIC EFFECTS IN STATIONARY AND ROTATING COMPONENTS

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NOMENCLATURE

p	absolute static pressure
p_v	vapor pressure
g_c	mass to force conversion factor
v	fluid velocity
v_t	fluid velocity in throat
ρ	mean fluid density
σ_c	cavitation number $= \dfrac{p_{min} - p_v}{\rho v_t^2/2g_c}$
σ_L	venturi loss coefficient $= \dfrac{p_{in} - p_{out}}{\rho v_t^2/2g_c}$
σ_T	Thoma cavitation parameter $= \dfrac{NPSH}{\Delta H_p}$
ΔH_p	pump head rise in non-cavitating condition
S	suction specific speed $= \dfrac{RPM\sqrt{GPM}}{(NPSH)^{3/4}}$
NPSH	net positive suction head $= \dfrac{p - p_v}{\rho}$ at impeller inlet referred to elevation of impeller centerline and assuming mean velocity equal to pipe velocity.

I. INTRODUCTION

It has become increasingly evident of late that significant departures from idealized cavitation similarity relations, as for example the concept of the Thoma cavitation parameter or suction specific speed, exist. These are of importance in that they can easily invalidate model tests both with respect to fluid-dynamic performance and, certainly, cavitation damage if they are not fully understood. It is the purpose of this paper to present some new data regarding variation from idealized relations of cavitating performance for both stationary and rotating components, and to attempt to rationalize these variations as far as present theoretical knowledge will permit.

II. OBSERVATIONS ON A STATIONARY COMPONENT (VENTURI)

A. Description of Component and Cavitation Conditions

Cavitation performance tests using water as the test fluid have been run on two geometrically similar venturi plexiglass test sections of 1/2 and 1/4 inch nominal throat diameter. Each has a cylindrical throat of length equal to about four diameters, followed by a diffuser which tapers on a straight-line $6°$ included angle out to the nominal 1-1/2" pipe diameter. The nozzle taper to the throat entrance is also a straight-line $6°$ included angle, with a well-rounded entrance from the pipe diameter. Detailed drawings are shown in Reference 1.

Several cavitation conditions were defined for these venturis:

1) Sonic Initiation: first appearance (or disappearance*) of audible sound.

* No cavitation hysteresis was observed in these tests between disappearance and appearance of cavitation. Perhaps this is due to the fast recirculation of water and absence of a settling tank.

2) Visible Initiation: first appearance (or disappearance*) of complete visible ring of cavitation.

3) First Mark Cavitation: cavitation cloud appearing to end at "first mark," i.e., one inch downstream from end of cylindrical throat portion in small venturi; geometrically similar location in large venturi.

4) Second Mark Cavitation: analogous to above.

Variation in the cavitation condition for a given throat velocity and fluid temperature is achieved by adjustment of upstream and downstream valves. In addition, throat velocity for a given cavitation condition can be varied in this closed loop facility from about 55 to 95 feet/second, and fluid temperature from about 60°F to 160°F with the plexiglass venturis. The facility, designed for liquid metal tests, is described in detail in Reference 1.

Gas content can be controlled between approximately 30% of saturation and slightly supersaturated. It was found in initial tests that within this range gas content was not a significant variable. This observation is also reported by Kermeen _et_ _al_.(2) For the venturi and pump tests the water was generally settled over a period of several hours to at least remove gross entrained air, and had total gas content of the order of 2/3 of saturation at room temperature and one atmosphere.

B. Scale and Thermodynamic Effects for Different Degrees of Cavitation

For the purposes of this paper, and as partially substantiated by its results, it is assumed that deviations from the idealized relations

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* See footnote, page 1.

can be grouped into "scale effects" encountered with changes in velocity or dimensions, and "thermodynamic effects" from changes in the thermodynamic properties of the fluid as brought about by a temperature change.(3)

1. Scale Effects at Different Degrees of Cavitation

Previous papers have considered scale effects as related to the cavitation number for either the first appearance or the final disappearance of cavitation.(2,4) This paper presents new data relating to cavitation initiation (or disappearance*) and also data for various degrees of well-developed cavitation. In all cases a significant scale effect has been observed such that the cavitation number (defined with respect to the minimum static pressure existing in the venturi, and the throat velocity) decreases with increasing throat Reynolds' number, approaching the theoretical value of zero and becoming negative at high Reynolds' number. The well-defined trend with Reynolds' number is striking in that the tests comprise a range of about 2:1 in throat diameter, viscosity, and velocity. (Figures 1, 2, 3, and 4 --Revised from Reference 1)

Figures 5 and 6 show the same data in two typical cases plotted against throat velocity rather than Reynolds' number. It is noted that there is a clear differentiation according to venturi size so that two separate curves are required.

The figures show the approximate standard deviation of the data computed on the basis of repetitive runs for typical points. It is noted that this is sufficiently small so that the trends shown are meaningful, and also that the scatter of points around the curves shown is far beyond

* See footnote, page 1.

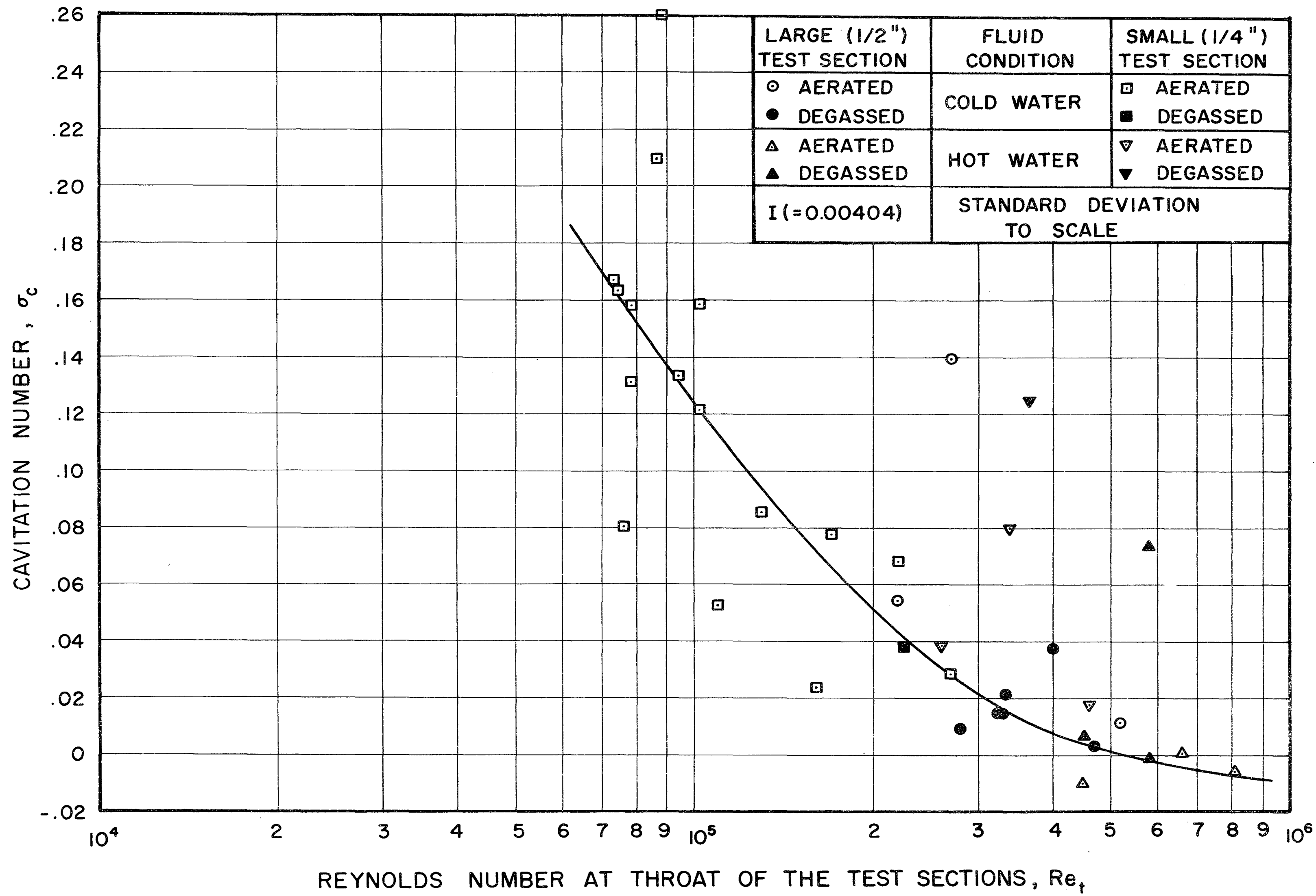

Figure 1. Cavitation Number vs. Throat Reynolds' Number in a Cavitating Venturi for Sonic Initiation.

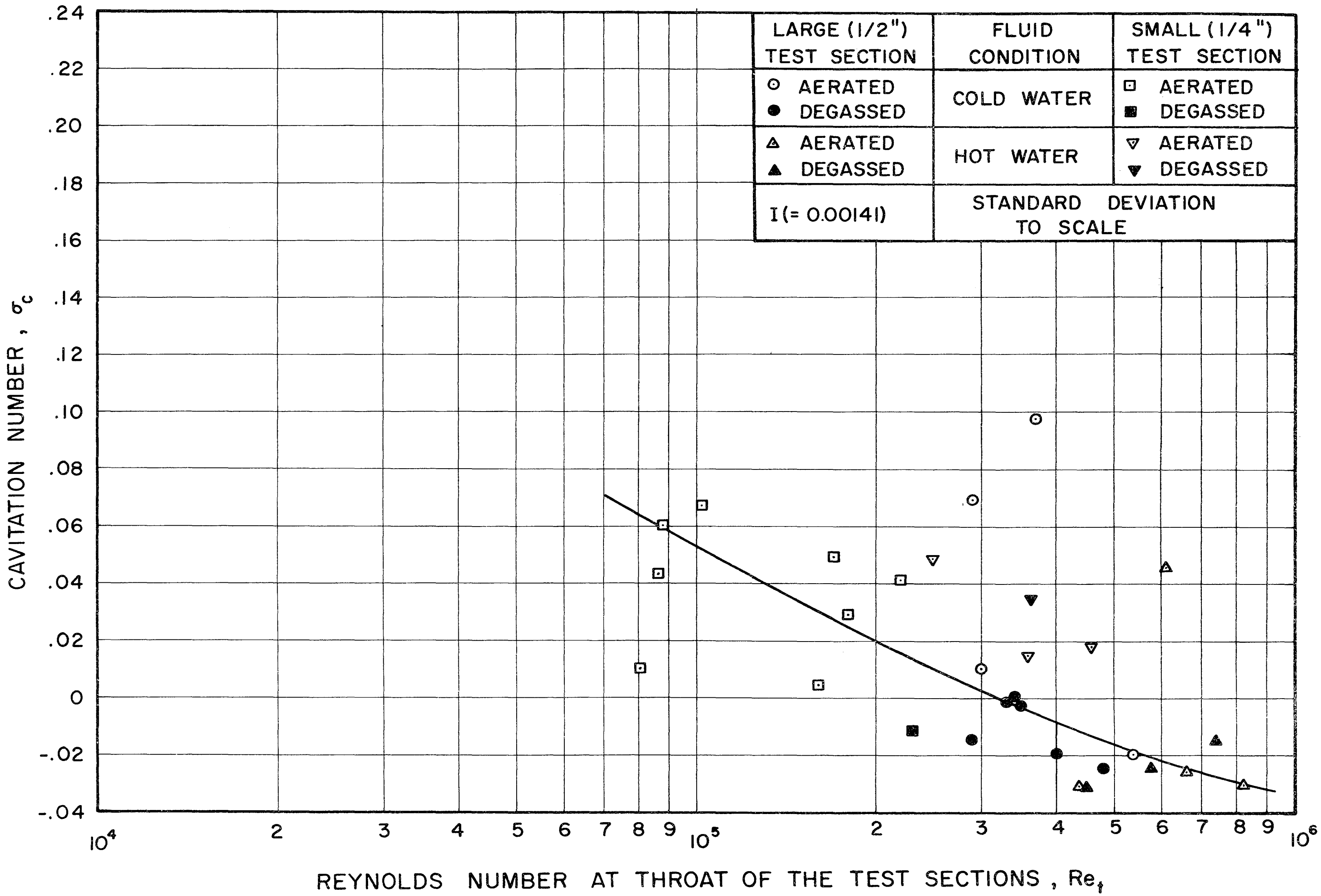

Figure 2. Cavitation Number vs. Throat Reynolds' Number in a Cavitating Venturi for Visible Initiation.

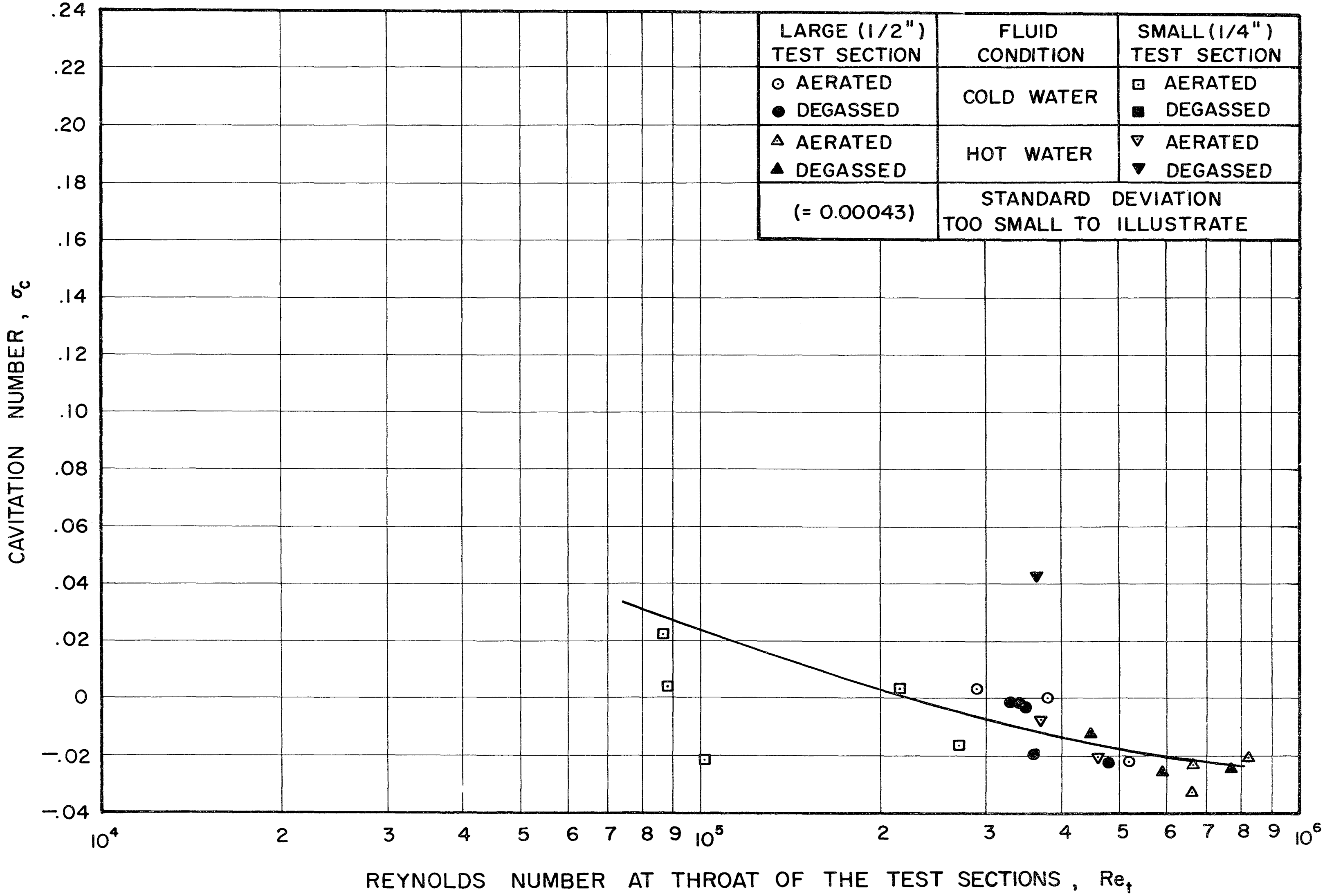

Figure 3. Cavitation Number vs. Throat Reynolds' Number in a Cavitating Venturi for Cavitation to First Mark.

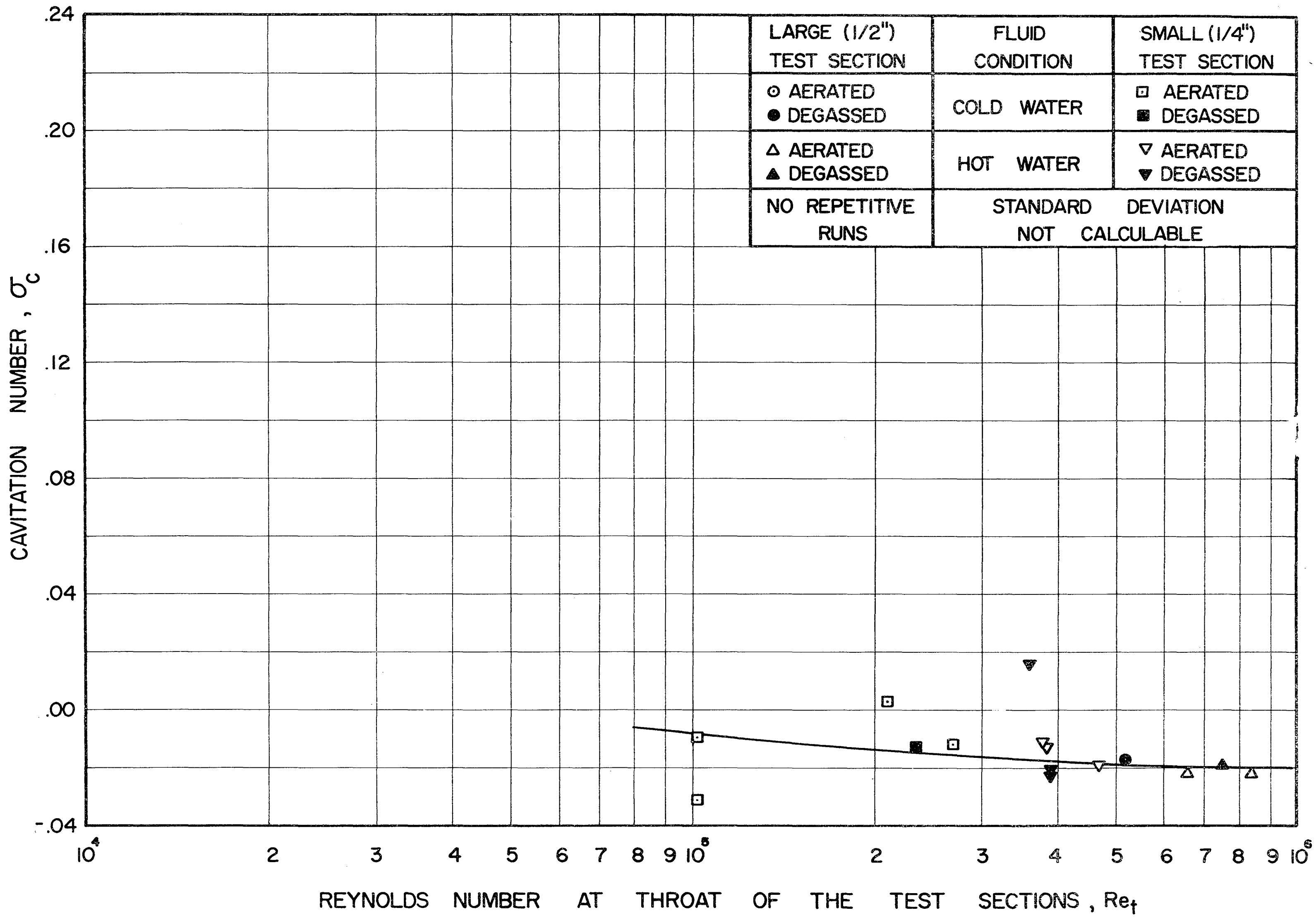

Figure 4. Cavitation Number vs. Throat Reynolds' Number in a Cavitating Venturi for Cavitation to Second Mark.

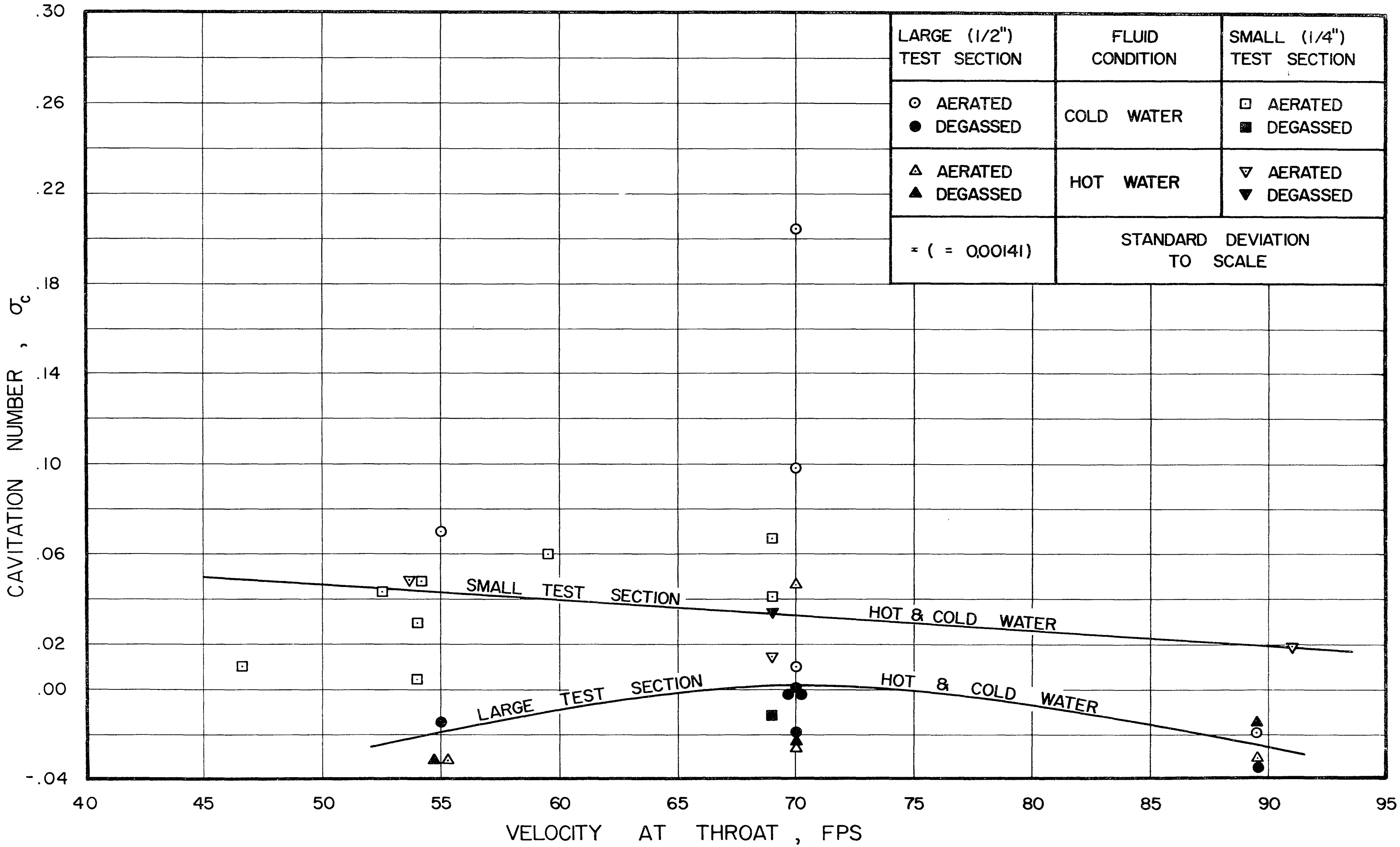

Figure 5. Cavitation Number vs. Throat Velocity in a Cavitating Venturi for Visible Initiation.

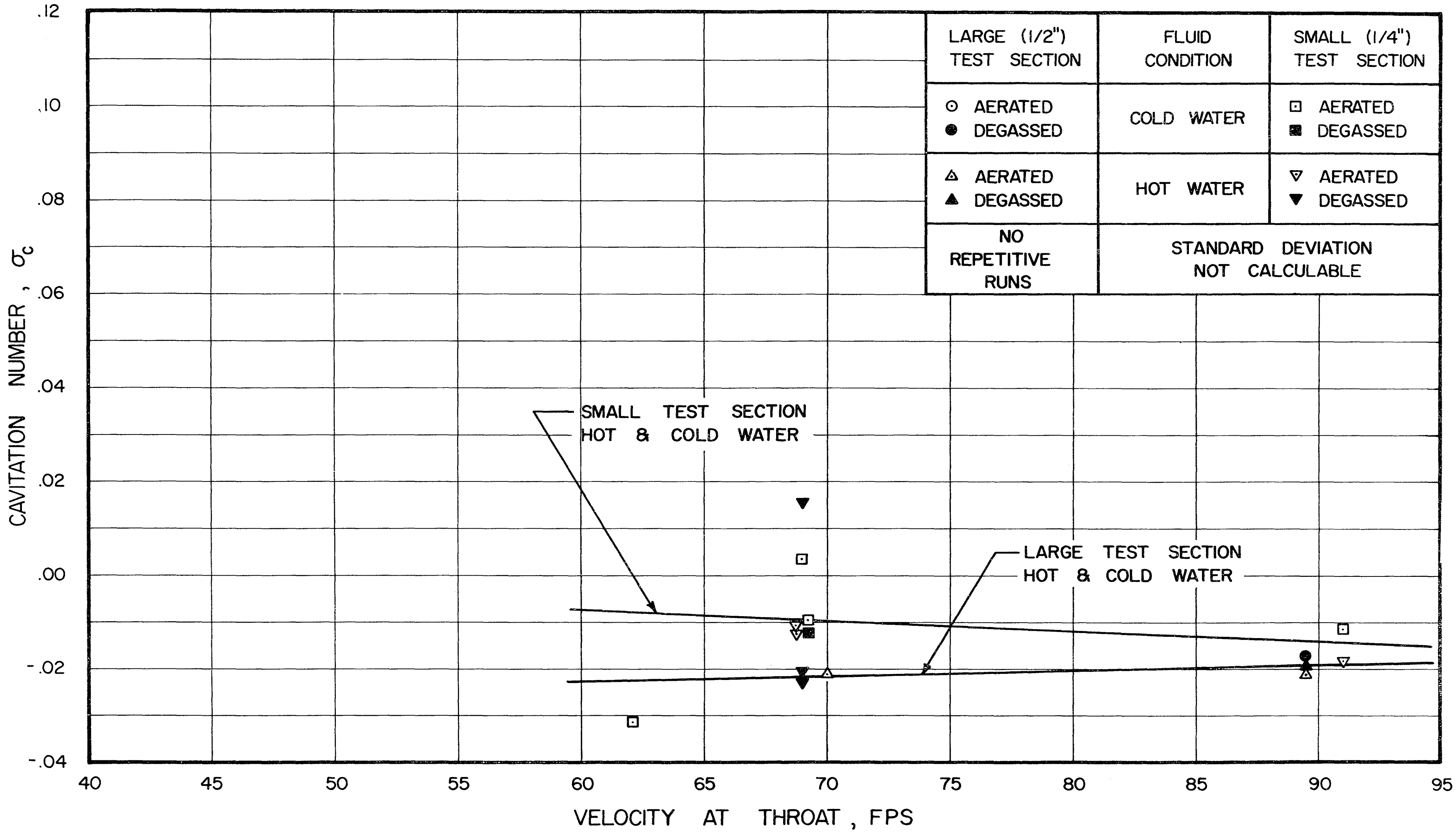

Figure 6. Cavitation Number vs. Throat Velocity in a Cavitating Venturi for Cavitation to Second Mark.

experimental error for both velocity and Reynolds' number plots. Hence, it appears likely that other parameters are significant. What these may be and how they enter cannot be specified without a better understanding of the bubble growth and nucleation process. However, some further indications of the interrelations do exist.

2. Thermodynamic Effects

Examination of Figures 1 through 6 discloses no thermodynamic effects per se in that both hot and cold water points, for cavitation number, are equally correlated by a single curve.

However, a fluid-dynamic parameter other than cavitation number which might be considered to characterize the cavitating flow in a venturi is the loss coefficient; i.e., the ratio between overall pressure loss across the venturi to pressure differential between inlet and minimum pressure point. Since it is much more sensitive to degree of cavitation than is the cavitation number, it might be taken as a more sensitive indication of significant correlating parameters.

Figures 7 through 9 (revised from Reference 1) show this parameter plotted against Reynolds' number, using data from the tests previously described, for the various cavitation conditions. The same data is replotted against velocity in Figures 10 through 12.

For the loss coefficient vs. Reynolds' number plots (Figures 7 through 9) the following significant points are evident:

1) For visible initiation (or sonic initiation which is not included since it is nearly identical) there is no differentiation between hot and cold points or between points from the

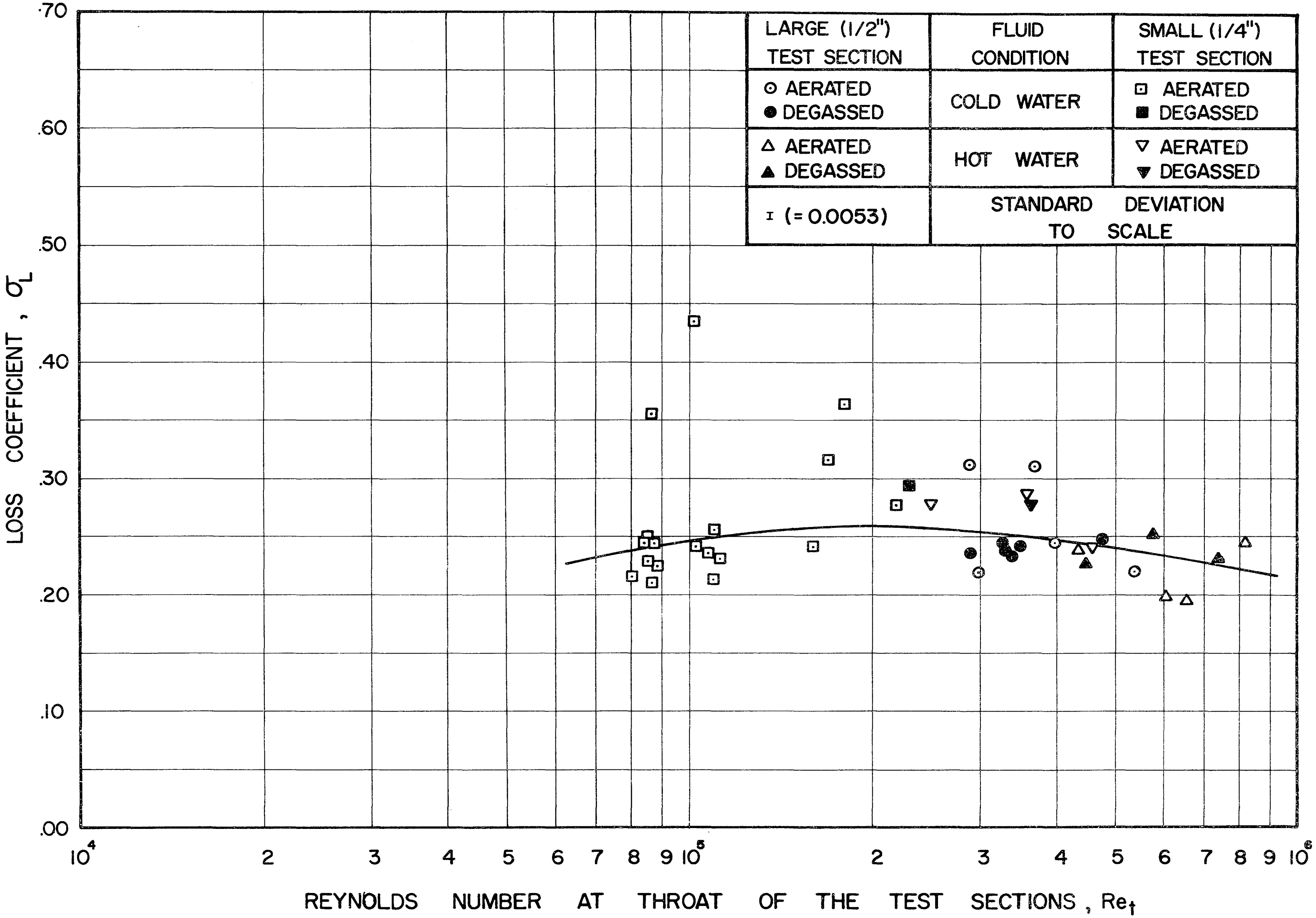

Figure 7. Loss Coefficient vs. Throat Reynolds' Number in a Cavitating Venturi for Visible Initiation.

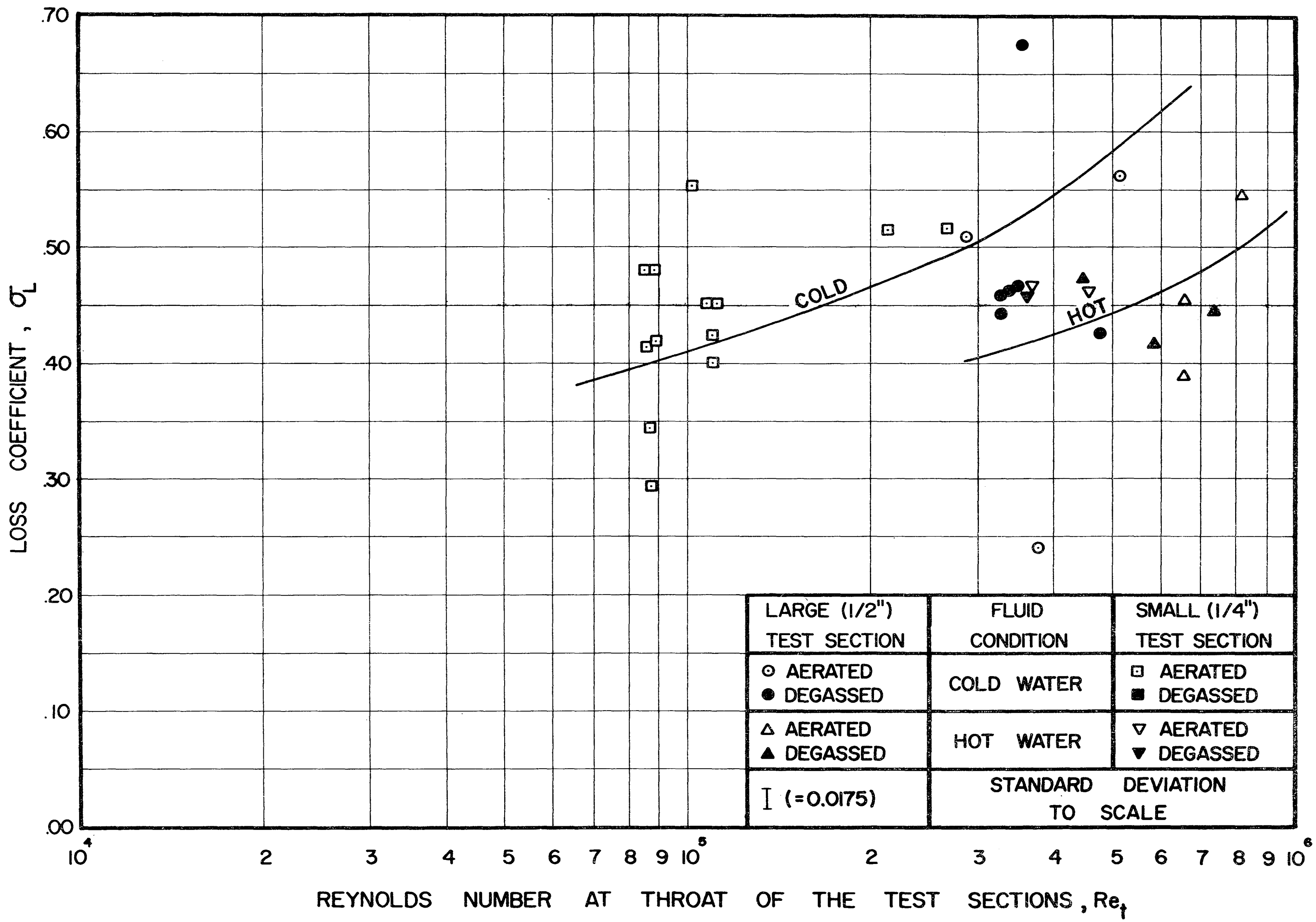

Figure 8. Loss Coefficient vs. Throat Reynolds' Number in a Cavitating Venturi for Cavitation to First Mark.

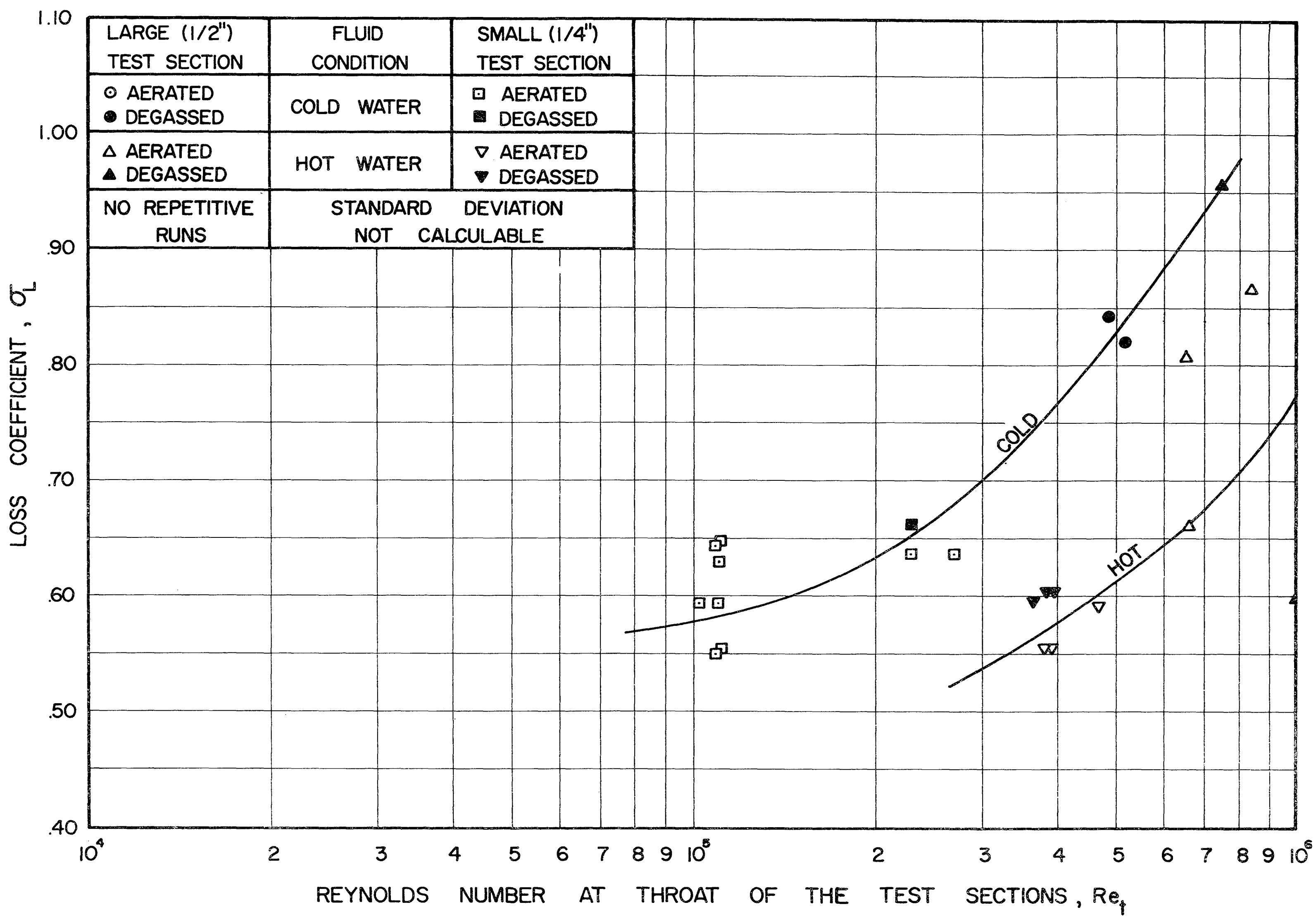

Figure 9. Loss Coefficient vs. Throat Reynolds' Number in a Cavitating Venturi for Cavitation to Second Mark.

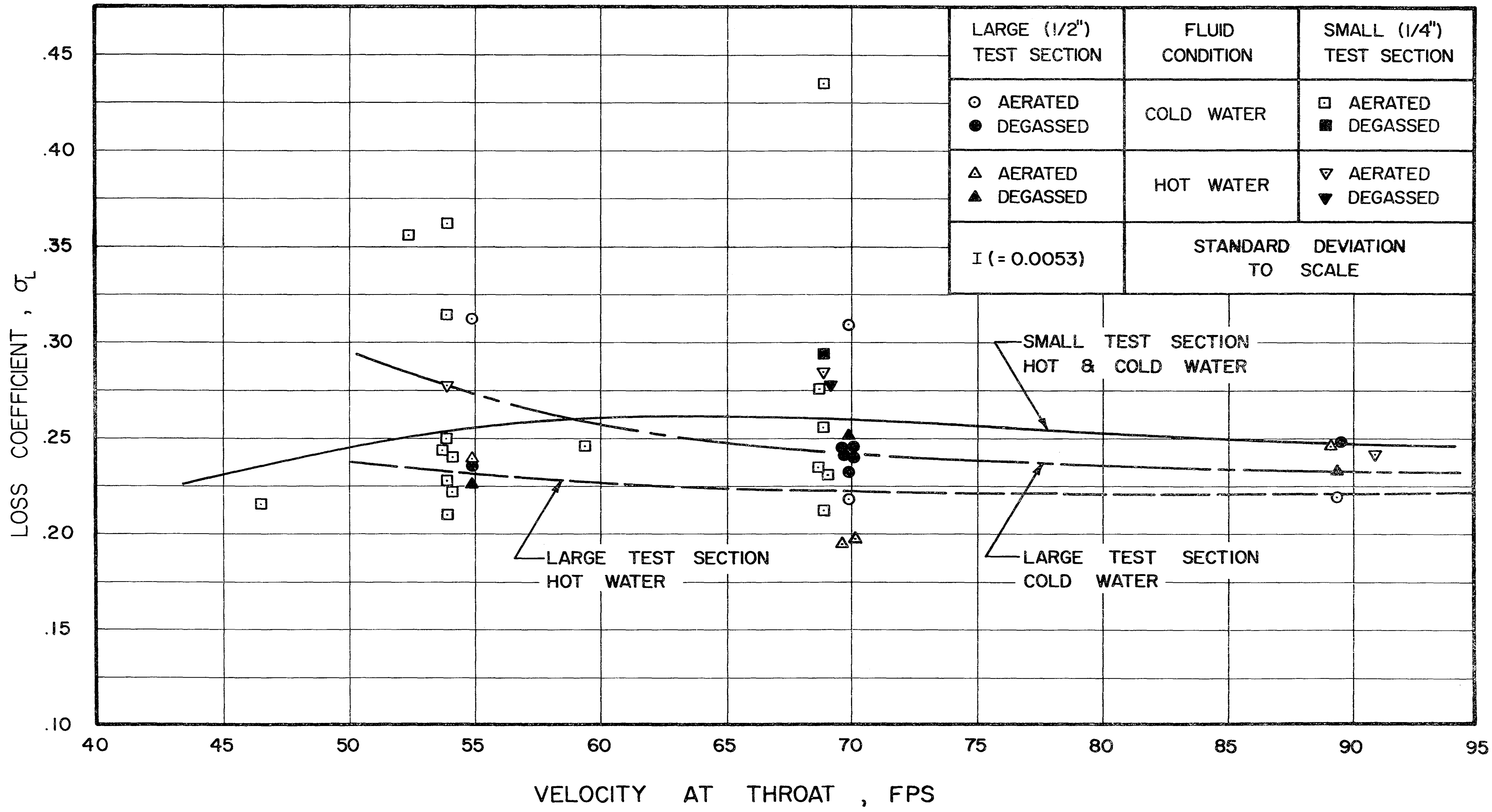

Figure 10. Loss Coefficient vs. Throat Velocity in a Cavitating Venturi for Visible Initiation.

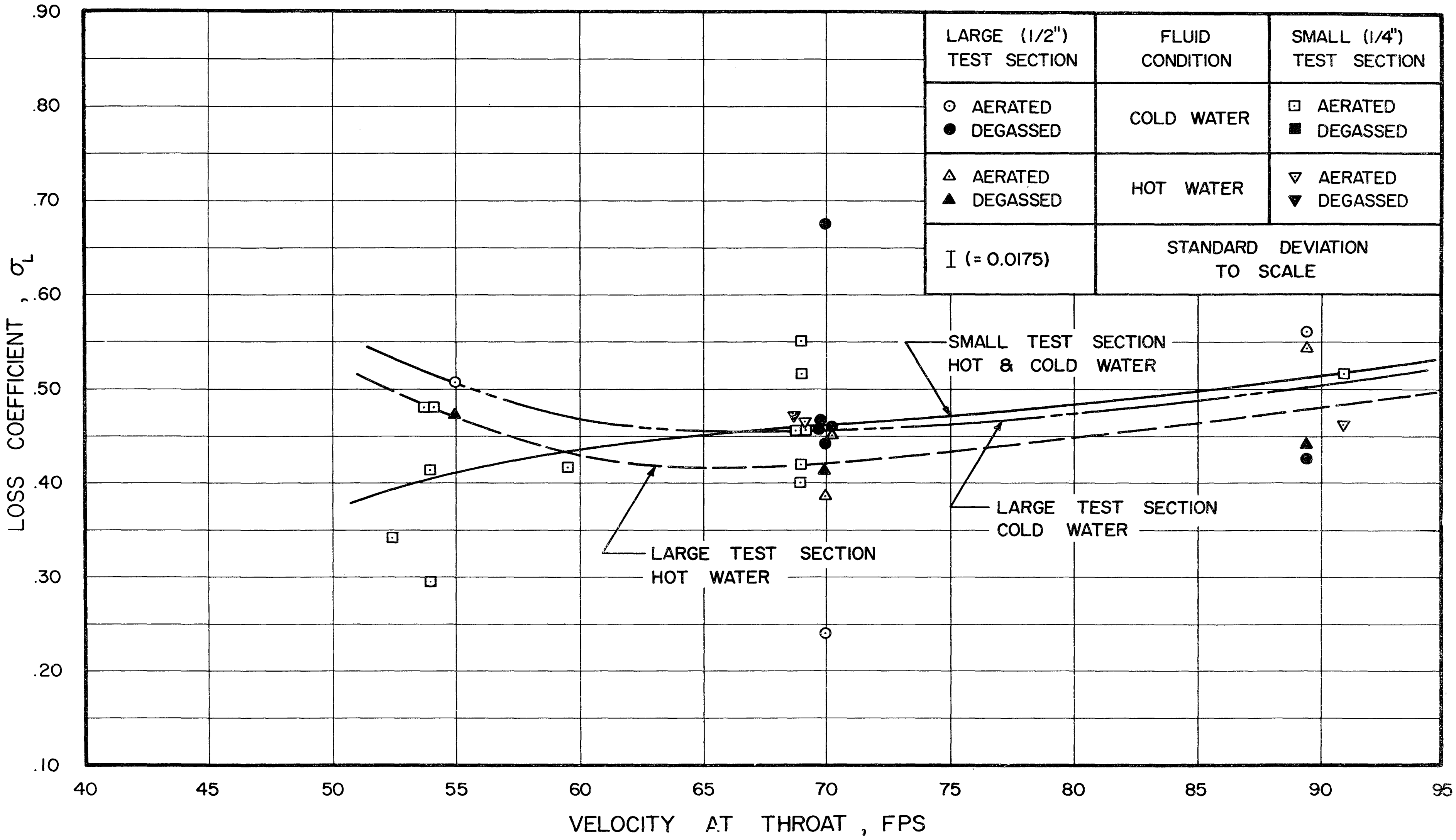

Figure 11. Loss Coefficient vs. Throat Velocity in a Cavitating Venturi for Cavitation to First Mark.

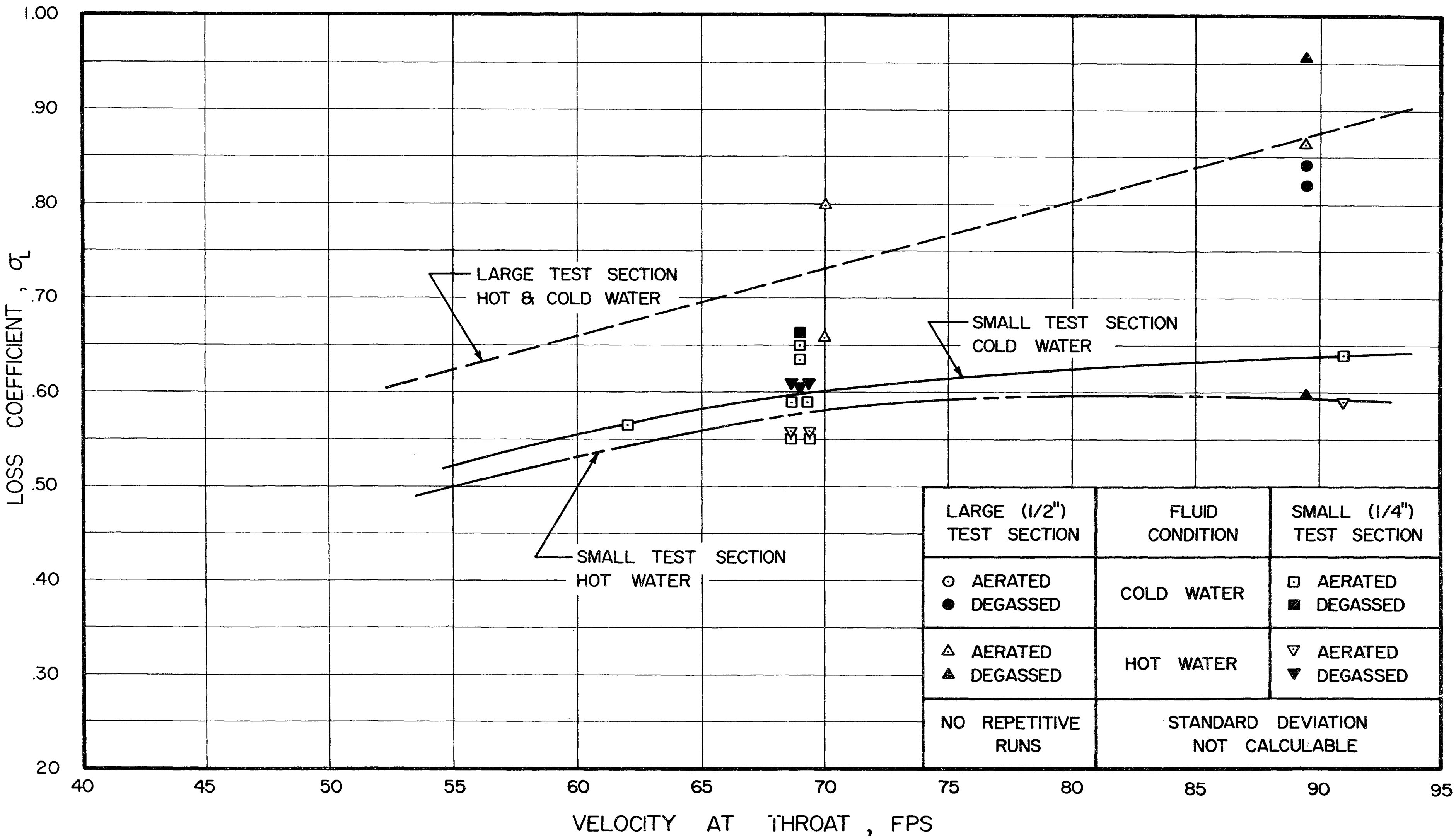

Figure 12. Loss Coefficient vs. Throat Velocity in a Cavitating Venturi for Cavitation to Second Mark.

large and small venturi. The data correlate fairly well in terms of Reynolds' number. This is not surprising since the degree of cavitation is too small to affect the overall flow pattern very significantly.

2) For substantial cavitation (first and second mark) Reynolds' number does not correlate all the points; rather, the cold and hot water points are separated.

3) The loss coefficient for cold water is higher than for hot water where a differentiation is possible. The direction of the differential is as predicted from consideration of the thermodynamic parameters, as first suggested by Stahl and Stepanoff.[3]

4) For first and second mark cavitation, the loss coefficient increases significantly with Reynolds' number, and the rate of increase accelerates for higher Reynolds' numbers. Examination of the standard deviations shown on the figures indicates that the trends mentioned are significant.

When loss coefficient is plotted against throat velocity (Figures 10, 11, and 12) separate curves must be used for throat diameter and temperature of fluid, even for initiation conditions (Figure 10). Thus it is apparent that Reynolds' number at least partially accounts for changes in diameter and temperature as well as velocity.

The situation is complicated for the more developed cavitation conditions (Figures 11 and 12), since it was shown in the Reynolds' number curves (Figures 8 and 9) that thermodynamic effects in themselves were important. Hence in the velocity plots, there is a temperature effect both thermodynamically and through Reynolds' number. The direction of curve separation indicated by each of these effects is the same. It is noted that in all cases the loss coefficient for cold water is greater than for hot at a given velocity as would be expected.[3]

The loss coefficients for developed cavitation generally increase with velocity as well as with Reynolds' number.

III. OBSERVATIONS ON A ROTATING COMPONENT (CENTRIFUGAL PUMP IMPELLER)

A. Description of Component and Cavitation Condition

Cavitation performance effects have also been observed on a single-stage sump-type centrifugal pump used to power the cavitation loop of specific speed equal to 740 in GPM units (manufactured by the Berkeley Pump Co.)

In this system,[1] pump cavitation can only be obtained by reducing the sump pressure to near vacuum, balancing vacuum pump capacity against stuffing-box leakage. The rather large scatter of the data is probably a result of the required test procedure, even though high-response-rate pressure transducers were used.

A long-radius elbow immediately upstream of the pump suction is partially responsible for the low suction specific speed values. In addition, the pump was designed for high-temperature liquid metal performance rather than good cavitation behavior.

The data points presented (with one exception) are the result of several repetitive runs (varying from 2 to 6). In each case the standard deviation was calculated and an average value computed. As noted, data of sufficient precision to be statistically meaningful has been obtained (Figures 13, 14, and 15). The onset of cavitation is defined as sufficient cavitation to cause a decrease of 5% in the pump head at a fixed speed and system resistance. It is considered that this small amount of cavitation is probably more nearly similar to the visible initiation condition in the venturi than any other, and hence comparisons are made with this condition.

B. Pump Test Results

Pump speed is varied in the pump test runs over a range of about 1.7; flow (i.e., ratio of actual to design flow) over a range of 1.3; and fluid temperature over the range from about 90°F to 160°F. Tests were run at three distinct speeds, presented in the figures as ratios of actual to design speed, two flow ratios, and three temperatures (including the extremes of the range above).

The resulting Thoma cavitation parameters are presented in Figures 13 and 14 plotted against normalized Reynolds' number and normalized pump speed, respectively. The figures disclose:

1) The data can be correlated reasonably well either in terms of Reynolds' number or pump speed, i.e., velocity.
2) The data divides naturally according to the flow ratios, i.e., the Thoma parameter for the higher flow ratio (somewhat above design flow) is higher than for the lower (close to design flow), for the same N/N_o or Re/Re_o.

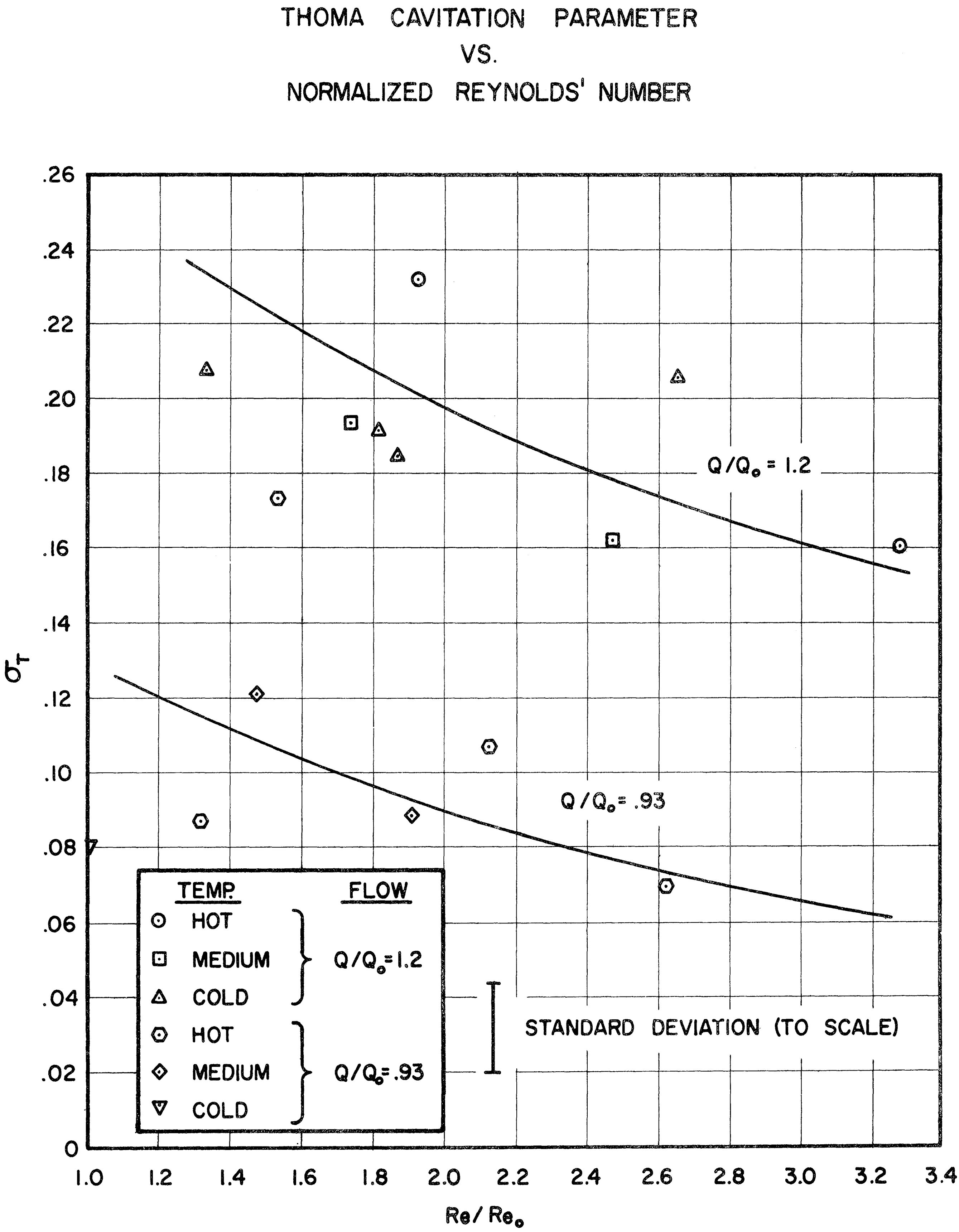

Figure 13. Thoma Cavitation Parameter vs. Normalized Reynolds' Number.

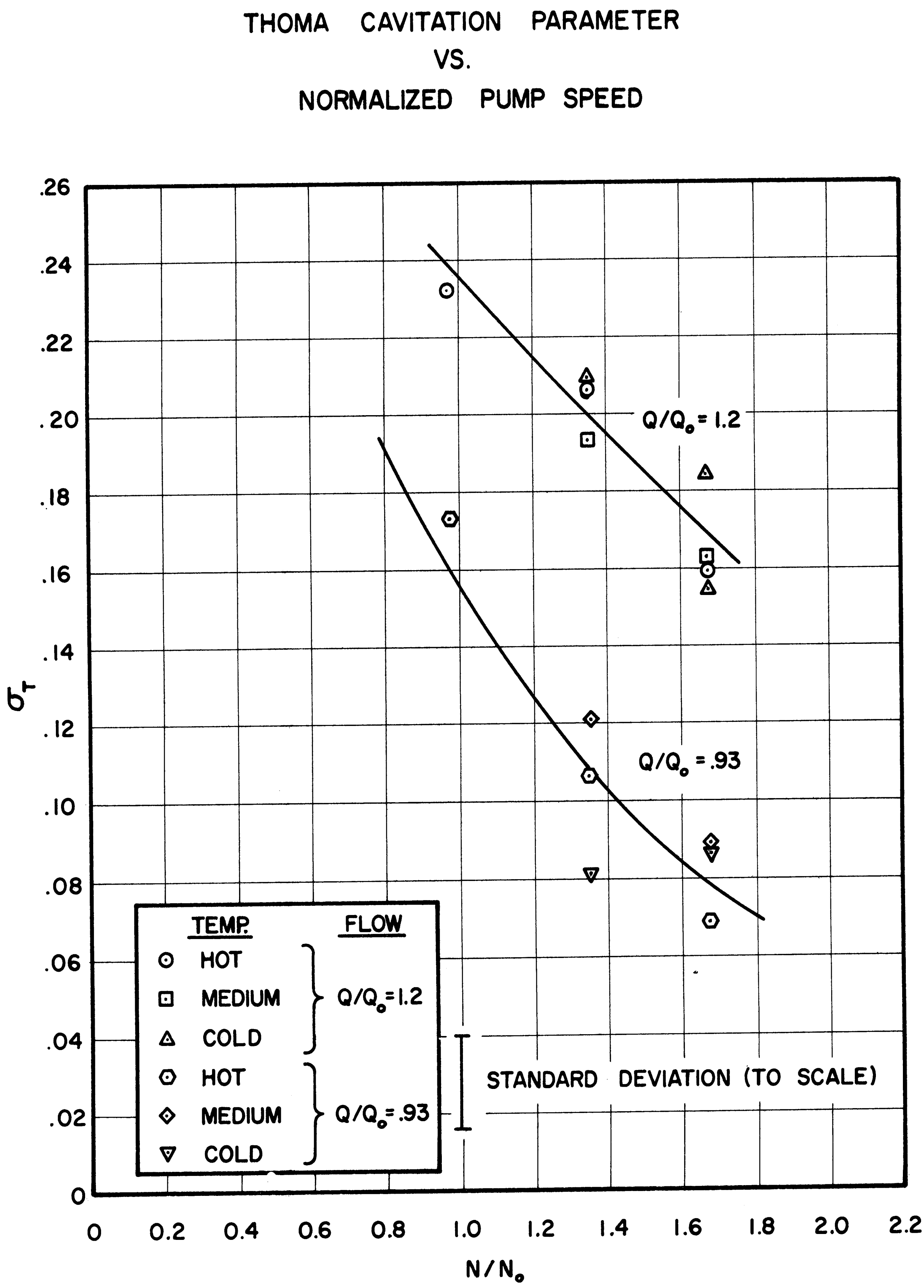

Figure 14. Thoma Cavitation Parameter vs. Normalized Pump Speed.

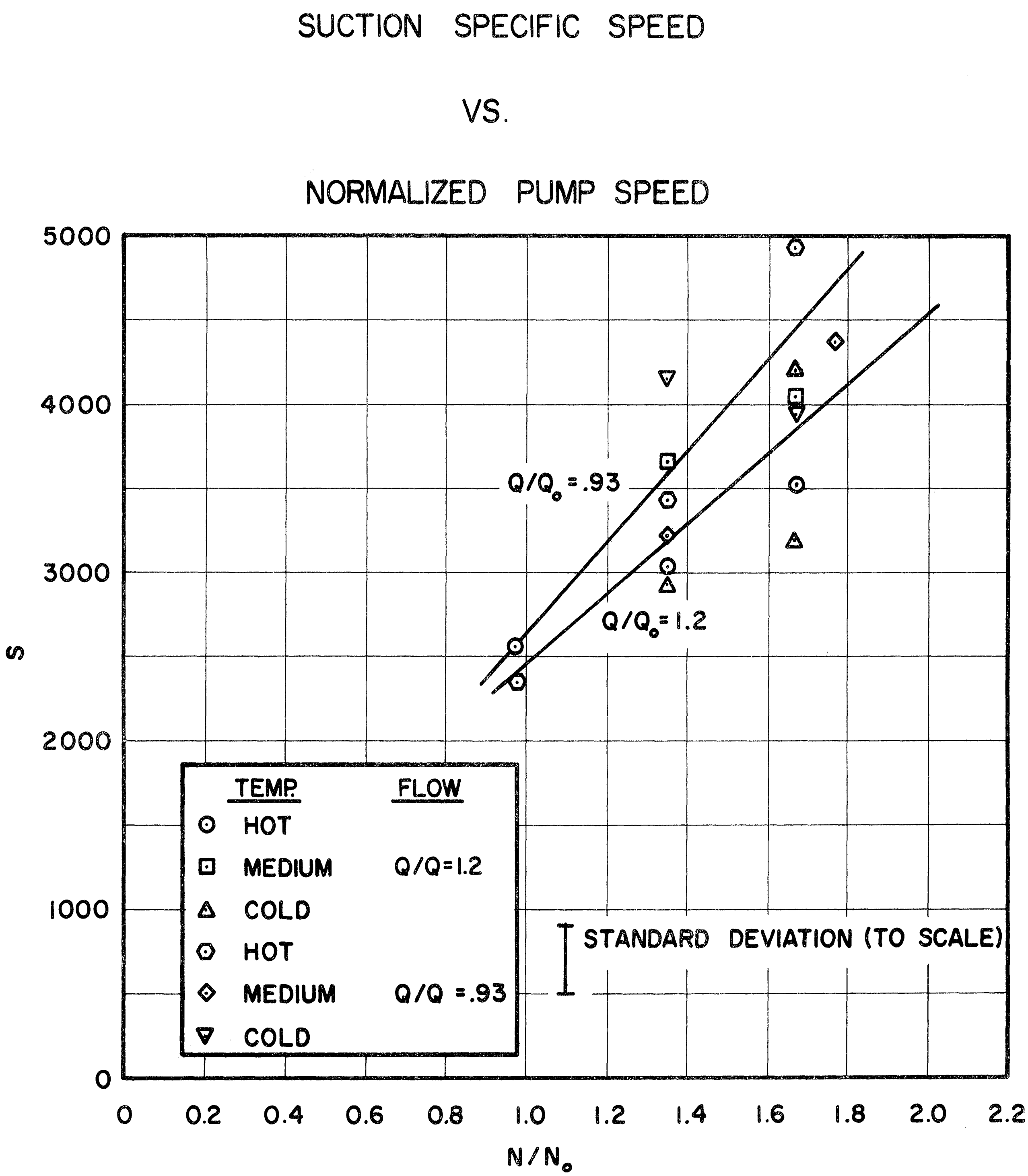

Figure 15. Suction Specific Speed vs. Normalized Pump Speed.

3) There is no significant separation within the precision of the data as plotted against either velocity or Reynolds' number. In the case of velocity curves there is no substantial separation of the points; hence there must be such separation in the case of Reynolds' number, as Figure 13 shows. However, it is not in the direction anticipated from a consideration of the thermodynamic parameters.[3] The indicated separation of the curves is small as expected from consideration of the venturi results since the pump cavitation condition corresponds only to initiation. Thus, only a single curve is warranted within the precision of the data.

4) There is a substantial decrease in Thoma cavitation parameter as the Reynolds' number or velocity is increased (30-50% for a speed increase of 75%).

The data from Figure 14 are replotted in Figure 15 in terms of suction specific speed which varies over almost a 2:1 range, from about 2500 to 4500. The direction of variation and the relation between high and low flow curves of course follows from the previous curves.

IV. DISCUSSION OF RESULTS

Since the cavitation condition in the venturi tests is based on visual extent of cavitation, and that in the pump on proportionate head loss, a direct comparison of results is not necessarily meaningful. However, the following points of similarity exist between the results from the venturi and those from the centrifugal pump (Figures 1, 2, 3, 4, 14, 15):

1) In both cases, there is a substantial decrease in cavitation number (or Thoma parameter) as either velocity or Reynolds' number is increased.

2) In both cases, for the cavitation number curves, for conditions of initiation, no significant thermodynamic effects are indicated.

3) In both cases, for the cavitation number curves, the data can be correlated to some extent in terms of either Reynolds' number or velocity, although the velocity plots for the venturi can be conveniently divided in terms of temperature and size. The Reynolds' number correlation is very much better for the venturi and appears to take care of the size variation between the different venturis as well as the temperature variation to some extent. The velocity correlation, however, is somewhat better for the pump, where there is no size variation.

Other points of major significance are:

4) In the case of the venturi, substantial scale effects exist for well-developed as well as initial cavitation. No data for equally well-developed cavitation with the pump as compared through proportionate head losses is available, but it is presumed that the venturi results would qualitatively apply.

5) The scale effects for the venturi apply to both cavitation number and to loss coefficient (see also Figures 7, 8, 9,

10, 11, 12). However, the latter is much more sensitive to degree of cavitation than the former.

6) A substantial thermodynamic effect, in the anticipated direction,[3] is found for the loss coefficient, but only for well-developed cavitation.

A. Theoretical Considerations

Fairly clear-cut arguments can be advanced to explain a dependence of cavitation number or loss coefficient on Reynolds' number and on the thermodynamic parameters, and also, perhaps to a lesser extent, on other parameters. A summarization of the arguments follows.

If it is considered that cavitation bubbles originate in the boundary layer[4] and also that local under-pressures in the fluid are a function of degree of turbulence, it is not surprising that Reynolds' number should, to some extent at least, correlate cavitation data. Other possible parameters[5] include Froude number, Mach number, Weber number, and Peclet number (i.e., "thermodynamic effects"). Also, the influences of absolute time and pressure on the microscopic nucleation process may be significant in themselves. Of these, the author believes it most likely, within the range of parameters of the present tests, that Weber number and "thermodynamic effects" are of greatest importance, aside from Reynolds' number. A variation of cavitation number with Reynolds' number has, in fact, recently been derived by Oshima[6] by considering only inertial, pressure, and surface tension effects. However, the predicted variation is in the opposite direction to that observed in the present tests.

1. Thermodynamic Effects

In the pump tests, the cavitation conditions are defined as those producing a pump head reduction of 5%. As suggested by Stahl and Stepanof[3,7] and Jacobs,[8,9] tentatively this can be taken to mean a given vapor volume within the pump. Again, as originally suggested by Stahl and Stepanof[3,7] and Jacobs[8,9] and discussed and corroborated by Salemann,[10] considerably greater local head depression for hot than for cold water, at least under equilibrium conditions, is required to abstract the sensible heat from the surrounding liquid for production of the requisite vapor. If, as previously discussed by the present author,[11] the applicable parameter is defined as the equilibrium ratio of vapor volume formed to liquid volume per unit head depression, it is found to vary by a factor of about 5 over the temperature range of the present tests. In other words, under equilibrium conditions, a head depression, 5-fold increased over the cold water tests, is required to produce the same proportionate head reduction in the hot water tests. It is apparent that this is not quantitatively meaningful in the present case, since the head depression for the cold water tests is of the order of 4 feet, and does not differ greatly for the hot water tests. Qualitatively, however, the trend characterized in the current literature as "thermodynamic effects" has been shown to exist by the test results of Stahl and Stepanoff,[3,7] Jacobs[8,9] and Salemann,[10] as well as the present data for the loss coefficient of the venturi with well-developed cavitation. In most of these tests it has also been shown that a quantitative prediction from the equilibrium considerations is not meaningful.

The fact that no thermodynamic effects were found for the pump or venturi cavitation number is in apparent agreement with the results listed by Stepanoff[7] and Salemann.[10] The vapor pressure values for the present tests are far below those which they considered, and extrapolation of their data indicates that the thermodynamic effect would not be appreciable in the present tests. Jacobs' tests were with cryogenic fluids for which the equilibrium vapor/liquid volume ratio is so much different from the present tests that no comparison can be made. However, he observed a very strong thermodynamic effect for those fluids.

That a significant thermodynamic effect in the anticipated direction (i.e., less loss for a given visual extent of cavitation region for hot than for cold water) was found for the venturi loss coefficient with well-developed cavitation may be the result of the fact that this parameter is much more sensitive to changes in the flow than is the cavitation number.

2. Reynolds' Number Effects

Assuming on the basis of the previous discussion that thermodynamic effects are negligibly small in the present tests with the single exception mentioned, there are three groups of data to be considered for Reynolds' number and velocity effects: (a) Thoma cavitation parameter for the pump tests (which is in effect a cavitation number), (b) cavitation number, and (c) loss coefficient for the venturi tests.

Without exception, the cavitation number, both for pump and venturi, and for all degrees of cavitation tested, decreased substantially for increased Reynolds' number or velocity. An examination of the existing literature regarding scale effects in pumps and on stationary objects[2,3,5,6,7,8,9,10,12] shows that the cavitation number sometimes increased with increased Reynolds' number or velocity and sometimes decreased.

The only pump tests found in the literature, aside from the present results, giving constant temperature data at different speeds are those quoted by Stepanoff[7] from a Russian paper.[12]* These results are quantitatively almost identical to those of the present tests. Also, some of the other results quoted by Stepanoff[7] to substantiate the existence of thermodynamic effects could be taken instead to show, at least partially, Reynolds' number effects. They show a decrease of cavitation number for the impeller with increased temperature for a given fluid at fixed pump speed. Since the viscosity decreases rapidly with increasing temperature, these effects could be attributed to an increase of Reynolds' number as well as to a change in thermodynamic parameters. Other results, shown by the same authors, concern the comparison between water and organic fluids. For these, the thermodynamic effects unquestionably predominate.

A summarization of the scale effects for stationary bodies is presented by Holl and Wislicenus.[5] Data for CIT reported by Kermeen _et al._[2] and from Pennsylvania State University are included. It is reported that results from a low pressure coefficient body

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* Similar results are available from unpublished sources.[13]

(an NACA 16012 hydrofoil) show a decrease of cavitation number with increased Reynolds' number or velocity as do the present tests. On the other hand, a high pressure coefficient body such as an ogive shows the opposite trend. The hydrofoil and the present venturi, being well streamlined bodies, seem somewhat comparable, as do the hydrofoil and the blades of a centrifugal pump. Hence, the results of the present tests seem in at least quantitative agreement with the literature. However, it should be mentioned that the previous scale effects results reported,(2,5) as opposed to the present results, involve mainly variation of velocity and size. The tests of Reference 2 do include a small temperature variation (from 55° to 77°F).

As previously noted, Figures 7 through 9 show that the venturi loss coefficient cannot be correlated in terms of Reynolds' number alone except for the case of cavitation initiation which is virtually single-phase flow. This may be taken to indicate the basic inadequacy of Reynolds' number as a unique correlating parameter.

3. Velocity, Weber Number, and Time Effects

The reasoning behind the expectation of a correlation in terms of Reynolds' number has been previously discussed. However, the use of velocity *per se*, for a given fluid, as a correlation parameter can also be justified. Such a presentation would also tend to include Weber number effects as discussed below.

For a constant cavitation number, both the time of exposure to the region of underpressure, and the amount of this underpressure, are functions of velocity; one inversely as the velocity, the other directly as the velocity squared. It may not be unreasonable to assume that the gross cavitation pattern is largely controlled by the nucleation process, which is itself not as yet entirely understood. It is not inconceivable that the nucleation process may depend upon time of exposure to underpressure and absolute value of this underpressure in such a way that the effects are not cancelled for constant cavitation number.

The Weber number, for a given fluid and over a moderate temperature range, is almost entirely a function of velocity since surface tension does not change substantially over such a range. Therefore, nucleation effects which, from a slightly different viewpoint might be considered as Weber number effects, are uniquely related to velocity under these conditions.

V. CONCLUSIONS

The following significant conclusions can be drawn:

1) Significant scale effects have been observed in stationary components for various degrees of cavitation and substantial variations in velocity, size, and temperature. Also such effects have been observed in rotating equipment over a range of velocity and temperature. The direction of these effects is consistent with the present literature.

2) The cavitation numbers, for stationary and rotating components, can be correlated either in terms of Reynolds' number or velocity if size and temperature

is not varied. Reynolds' number appears to account adequately for size variation, and partially for temperature variation in the stationary component (venturi). No size variation was available for the rotating component (pump impeller).

3. Venturi loss coefficient cannot in general be correlated solely in terms of Reynolds' number or velocity.

4. Thermodynamic effects are significant in the present tests only for the venturi loss coefficient for well-developed cavitation. Over the temperature range tested, this is not inconsistent with the existing literature.

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