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PUMP AND OTHER COMPONENT CAVITATION COMPARISONS BETWEEN ALKALI LIQUID METALS AND WATER

by

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Abstract

The presently existing and available world data on cavitation performance and damage in alkali liquid metals, particularly as it pertains to cases where water tests of the same or identical components are available, has been surveyed. It is generally concluded that there exists no difference in cavitating (or non-cavitating) performance between water and alkali liquid metals of such components as pumps or venturis observed within the various pertinent experimental inaccuracies. Hence, for most engineering purposes, ordinary water tests may be taken as an approximate indication of sodium results. More precise results will require tests wherein the gas content of both fluids, including the size and population spectra of entrained nuclei, has been measured. However, within the usual engineering range of interest (moderate gas contents) gas content is apparently not of over-riding importance.

Long-term operation of liquid metal powerplant pumps within or near the cavitating range is impractical from the viewpoint of damage. However, design of complex truly cavitation-free liquid metal components is not within the present state-of-the-art without a sophisticated research program involving visualization and aimed at a particular component.

I. Introduction

As recently discussed by the author (1), for the design and specification of complex fluid handling machinery such as centrifugal pumps, e.g., in cases where cavitation is limiting, it may actually be necessary for optimum results, to test the prototype machine under prototype conditions. However, in many cases such as those involving either very large machines or machines handling difficult fluids (such as sodium), this may not be feasible. Both the above conditions may be present to some extent in the case of the coolant pumps for large sodium-cooled reactors. It is quite possible that the pump manufacturer may not be able to fully test the full-scale unit in his own laboratory even in water, and certainly not (at least in most cases) in sodium. Hence it is necessary to know reliably the relationship between cavitation performance of the unit in question in ordinary water and in sodium (or other alkali liquid metals, assuming that there is little important difference between these different coolant liquids). While only relatively limited pertinent information is yet available, that which exists, and is pertinent to centrifugal pumps, will be surveyed in this report. Conclusions pertinent to the present state of knowledge and recommended future research will then be drawn.

At the present, there are three sources of information, pertinent particularly to centrifugal (or axial and mixed-flow) pumps, which will be discussed. These are the studies made by the following groups:

1. Pratt and Whitney Aircraft - CANEL
2. Oak Ridge National Laboratory
3. French AEC
4. NASA

II. Pertinent Applications and Data

A. Pratt and Whitney Aircraft - CANEL

1. <u>General Background Information</u> (1-8)

The program at Pratt and Whitney Aircraft's Connecticut Advanced Nuclear Engineering Laboratory (CANEL), primarily in the early 1960(s), was aimed at the development of alkali liquid metal turbopumps primarily for use in the SNAP-50 program. Fluids to be pumped were sodium, potassium, NaK, and lithium. Since this program was oriented toward the development of space hardware, minimization of volume and weight of machinery was of predominant importance. Thus, turbopum speeds were to be maximized and suppression pressures minimized. For these reasons, pump cavitation became a limiting parameter. Since long machinery life was also a requisite (one year of unattended operation for example), cavitation damage could not be tolerated, as opposed, e.g., to rocket turbopumps, where life requirements are sufficiently short that cavitation damage is not a major problem. Thus, the CANEL SNAP-50 requirements are rather similar to those of the present fast reactor coolant pumps in that both cavitation damage and performance effects are important. These applications differ in that space and weight minimization for the SNAP-50 pumps are relatively very important, so that a more aggressive design philosophy with respect to cavitation is required for these pumps. Hence, one of the major goals of the CANEL work (and also that of NASA, to be discussed later) was to determine how much cavitation was tolerable in light of the particular life requirements.

The CANEL program involved complete and comprehensive testing of the same pump impellers in both water and liquid metals, eventually including some cavitation damage testing of one of the same impellers in potassium. I assume at this point that there is no difference in kind between the various alkali liquid metals with respect to cavitation performance, so that sodium, potassium or NaK tests when compared directly with water, are equally valid for the present purpose.

The pumps involved are of the mixed-flow type (part radial and part axial) with specific speed of about 8200, and are designed for maximum cavitation performance, with inlet sections something like the conventional "cavitating inducers" used in rocket turbopumps. They are "unshrouded", i.e., the outer tips of the blades run with close clearance to the casing, thus providing a small leakage flow between casing and blade tips, where the first evidence of cavitation is often found. Nevertheless, this type of pump (unshrouded) has been found to be more resistant to cavitation than the conventional shrouded design (3), perhaps because of the reduced degree of restraint applied to the fluid. One difficulty with the unshrouded design, for the study of cavitation performance in different conditions, is the fact that performance depends closely on the value of tip clearance. This parameter proved difficult to maintain when comparing pump performance in water and liquid metal tests. These CANEL impellers perform excellently with regard to cavitation, being operable at suction specific speed (S-value) ~ 20,000. This compares with S of perhaps 7000 maximum for conventional reactor coolant pumps.*

The CANEL program included first the very careful testing of a group of quite similar open-shrouded impellers of the type described above in a water tunnel constructed for the purpose, wherein water could be deaerated to some extent and total air content measured. The pump casings were of plexiglass so that high-speed pictures of the flow could be taken, and the first appearance of cavitation accurately measured. In addition

*S=6700 and 5200, e.g., for primary and secondary sodium pumps for the British 250 MWE Prototype Fast Reactor (18). Hydraulic Institute recommends S $\leq$8140 for cavitation-free performance (15), e.g.

acoustic measurements were made to correlate cavitation noise with other observable flow parameters, and the location of later cavitation damage was determined by using an acrylic coating easily removed by the beginni of cavitation attack.

Once the impellers had been so "calibrated" in the water tunnel it wa planned that they would be operated in high-temperature liquid metal, an their full cavitation performance obtained. Later, long duration cavitat damage tests would be made at selected S-values, to determine how much cavitation could be tolerated in the SNAP-50 system. Actually this rathe ambitious program was never completed due to curtailment of the entire CANEL operation. However, one of the impellers which had been very carefully tested in water was calibrated in high-temperature potassium for cavitation performance, and then was operated under cavitating conditio (S=20,000) for 350 hours, after which some head fall-off occurred and vibrations increased markedly so that the test was terminated. It was then found that considerable cavitation damage occurred under this condition.

The direct comparison of cavitation in water and potassium is unfortunately weakened by the fact that the piping leading up to the impeller i the potassium and water loops was not identical, and also that the blade tip leakage flow may not have been properly modeled. This clearance was quite pressure-sensitive in the water-loop because of the deflection of the plexiglass housing under pressure. Also it was temperature-sensitive in the high-temperature potassium loop, but not appreciably pressure-sensitive since the casing there is of stainless steel.

2. Actual Tests and Results (1-8)

a. Cavitation Performance in Water and High-Temperature Potassi

Fig. 1 shows the comparative cavitation performance curves obtained for the same open-shrouded impeller tested in partially deaerated cold water and in potassium at 1400°F. For the liquid metal test only "constant throttle" operation for the driving gas-turbine was feasible, so for comparative purposes a similar test was run for water. This is not precisely the conventional constant flow test, but the flow variation is relatively small. A comparison between results for the constant flow and constant throttle test for water is shown in Fig. 1.

From the present viewpoint of comparing cavitation performance in water and alkali liquid metals, the most important result of this test must be that the 3% drop-off point from maximum head (usually defined as the "cavitation inception point" in commercial pump tests) for potassium occurs at an NPSH ("net positive suction head" $\cong (P_{in}-P_v)/\rho V^2/2g_o$) which is approximately twice that required for water, i.e., from this particular test it appears that potassium cavitates <u>much more readily</u> than water in the same pump impeller, indicating that tests in water are <u>not</u> "conservative." This trend is also verified if the start of head falloff from the maximum head is called the cavitation inception point. This is in fact an alternative method for defining the inception of cavitation. Inspection of Fig. 1 indicates that in this case the ratio between inception NPSH for potassium and water would be about $60/35 \cong 1.7$. However, as will be developed later, this result disagrees with other pertinent information, and in fact there seems to be no theoretical reason to believe that the trend it indicates is valid.

There are other interesting features indicated in Fig. 1. For example, the water and potassium curves are <u>not similar</u>, probably indicating that there exists some significant difference in the test geometry. According to the authors (1,2), this is inevitable in that the arrangement of inlet and discharge piping in the water and liquid metal loops is not identical. The differences are also partly the result of differences in the blade tip to casing clearance between the water and liquid metal tests. In the water tests this clearance, which is very important in determining pump head, increases significantly with pressure, i.e., NPSH, due to the significant deformation of the plexiglass casing because of the relatively small elastic modulus of plexiglass. On the other hand, in the potassium test, the tip-casing clearance is significantly temperature-dependent, and is thus not precisely known, since it is impossible to measure at operating temperature. For these reasons, the observed difference in NPSH between water and potassium may not be meaningful.

b. Detailed Cavitation Performance in Water (1-8)

The CANEL water cavitation studies, using the same impellers for which the potassium test was made, are among the most detailed and comprehensive presently existing, and in themselves shed important light on the problem of designing "cavitation-free" sodium coolant pumps. The CANEL tests used transparent pump casings (only useful with the unshroud type of impellers used) so that high-speed photography could be used to observe carefully the first appearance of vapor, i.e., the initial onset of "cavitation", long before it affects measurably pump head or flow Whether or not such "micro-cavitation" is damaging is another presently unresolved question, but it is certain (19,e.g.) that it will provide a characteristic bubble-collapse noise signal, no doubt making difficult the acoustic determination of boiling nucleation.

In the CANEL tests it was found (5) that micro-cavitation appeared at an NPSH about 8 x that corresponding to the conventional NPSH inception point as defined by a 3% pump head fall-off. Similar results (multiplying factor of $\sim$3.5) were found in the NASA tests (9). In my opinion, these results are probably typical of most pumps, so that today, in my opinion and that of others (18,e.g.), it is probably beyond t state of the art to design a true "cavitation-free" pump for a given application (without considerable research) which is not prohibitively conservative otherwise, i.e., the S-value would have to be extremely low (perhaps order of 3000-4000 for a typical case). This would require a costly, large and bulky unit, operating at low speed with high inlet pressures.

c. Cavitation Damage Tests (1-3,7-8)

As previously indicated, one of the primary objectives of the CAMEL experiments was to determine the maximum degree of cavitation which could be tolerated consistent with the SNAP-50 objectives, i.e., the maximum S-value for these impellers suitable for long-term operation in high-temperature liquid metal. Also as previously indicated, the impellers were first "calibrated" in water to determine a degree of cavitation which appeared feasible for long-term operation, at least from the viewpoint of noise, vibration, and head (or efficiency) fall-off. In addition, an acrylic coating was used in the water tests to determine the location of probable cavitation attack and obtain at least some idea of its intensity. As a result of these water tests it was decided that an NPSH corresponding to S=20,000 was likely to be successful from all the above viewpoints. The 1400^{o}F potassium test was hence performed under this condition. However, during the first 350 hours of operation a significant pump flow and head fall-off occurred. During the first 250 hours operation was entirely normal. At 350 hours a sudden jump in vibration level caused the test to be terminated at that point.

Upon disassembly (1) it was determined that the cause of the vibration was rubbing between the impeller and casing. No cause for this could be assigned. Cavitation damage was fairly general over the blade surfaces, reaching a maximum depth of about 0.050 in. Full details on the form and distribution of damage are given in ref. 1. The impeller was of cast type 316 stainless steel. It was a general conclusion from this damage test that a long-term operating condition corresponding to an S-value of 20,000 is too optimistic for this type of coolant pump (1).

B. Oak Ridge National Laboratory

1. General Background Information

The program at the Oak Ridge National Laboratory (ORNL) was motivated at first by the (since abandonned) nuclear aircraft project in the 1950(s). In fact a small reactor (10,11) of 2.5. MWt, the Aircraft Reactor Experiment (ARE), was actually constructed at Oak Ridge and operated in the late 1950(s). This was a "molten-salt" cooled reactor, wherein the primary molten salt* (11,12) coolant exchanges heat with a helium heat-dump loop. Also, the reflector is sodium-cooled, also heat-exchanging with a helium heat-dump loop. The ORNL pump group program was then aimed primarily at the development of pumps for both alkali liquid metals (Na, NaK, and K) and molten salts. Once the aircraft nuclear project was curtailed during the 1950(s), the same work may have been partially motivated by the SNAP-50 system development (which also motivated the CANEL work already described). Eventually a molten salt reactor project for possible central station reactors was commenced (during 1960(s)) and has resulted in the construction and continued operation of the Molten Salt Reactor (MSR) at ORNL. The MSR has thus profitted from the initial and continued pump work at ORNL involving molten salt pumps.

As in most pump development projects, particularly those utilizing fluids for which great amounts of previous experience are not available, one of the primary problems to be researched is that of cavitation. The work at Oak Ridge involves the following pertinent items:

1) Direct comparison of cavitation NPSH for the same pump operated in water and also in NaK (13).

*Density $\cong$ 3.25 g/cc; i.e., $\sim$4 x sodium density. Salt is NaF - ZrF_4 - UF_4 (50 - 46 - 4 mol %).

2) Long-term operation of centrifugal pumps under cavitating conditions in molten salt and in sodium (12,14).

3) Venturi cavitation tests with sodium (15), but no direct comparison to water.

4) Cavitation tests with EM pumps in potassium with argon cover gas and simple potassium vapor pressurization, noting differences in cavitation inception due presumably to entrained gas (16,17).

2. Actual Tests and Results

a. Comparison of Cavitation NPSH - Water and NaK (13)

The cavitation tests at ORNL differ from those at CANEL in that the pumps are more or less purely centrifugal pumps of conventional (shrouded) design, rather than the axial-mixed-flow units tested at CANEL. Mechanically, the ORNL pumps are vertical sump-type units with shaft overhung from relatively conventional bearings. A gas space separates the liquid metal from a mechanical shaft seal.* The specific speed of the pumps is of the order of 1000 (vs. $\sim$ 8,000 for the CANEL pumps), and the suction speed the order of 2000-3000 (vs. $\sim$20,000 for the CANEL pumps), i.e., they are relatively very poor pumps from the viewpoint of cavitation suppression, but are probably closer to commercial design in this regard than are the CANEL designs.

For the specific comparison of cavitation inception performance between water (150-200°F) and NaK (1495°F), a pump of specific speed, N_s= 955 with impeller of $\sim$10 inch diameter running at 3150 RPM, 290 foot head and 450 GPM was used. The cavitation inception NPSH was defined as that NPSH below which a continuous drop in pump head is produced. This point was found graphically as the intersection of lines tangent to the generally horizontal portion of the NPSH vs. head curve to that tangent to the generally vertical portion of this curve. Typical NPSH values in

*A dynamic shaft seal ("vortex seal") was used in the CANEL SNAP-50 pumps since their operations specified conditions included negative "g".

these tests are the order of 20-35 ft. The cover gas for the water test was air, and helium for the tests in NaK.

Five tests were made for both water and NaK, respectively, in the sa loop with the same instrumentation. The effect of pump speed over the range 2600-3400 rpm was explored. Correcting for the differences in vapor pressure for the different fluids, it was found that there was le than a 6% difference between the NPSH values required for the two fluid in each pair of tests. However, as in the previously discussed CANEL tests, the required NPSH for NaK was greater (on the average, though no always) than that for water. However, the difference was so small as to be considered negligible (and perhaps within experimental error) in my opinion ($\sim$1 ft. in general). According to the author (13) there was in fact a possible error in the potassium NPSH values of about 1 ft. due t lack of precision in control of the temperature. The detailed results are summarized in Table 1 (reproduced from the original paper - (13)). Table 2 shows the suction specific speed values from these tests, indicating in general that it is not constant, but increases markedly with pump speed ($\sim$20%) for a speed change of $\sim$30%. Such an increase of S with N is quite common for pumps of this specific speed range (20, e.g.) but there is some indication that S will maximize and then reduce with further increase of N (21, e.g.). Similar results have been observed for venturis, e.g. (23,24). This result is simply one of the numerous fairly major departures from the "classical" laws of cavitation scaling, described in the literature as "cavitation scale effects," and largely of unresolved origin and unpredictable magnitude, thus adding only to the general uncertainties concerned with cavitation tests (22,23,24, e.g.). While it is fairly well verified from all the tests here described, as well as other miscellaneous sources (25, e.g.) that the non-cavitating liquid metal performance of a given alkali metal pump can be predicted accurately by water tests, the indications regarding cavitating performance are only those herein discussed.

In summary, from the ORNL centrifugal pump cavitation inception comparison between water and NaK, it can be concluded that the inception NPSH (or S) is virtually identical between the two fluids (within about 6% for NPSH or about 4.5% for S), with the water test being "non-conservative." However, the experimental error is at least of the same order as the observed difference.

b. Cavitation Damage Tests (12,14)

Long-term cavitation damage tests were conducted at ORNL (12,14) with molten salt and sodium, using centrifugal pumps of somewhat different type for the two fluids (N_s=1900 for sodium and 4300 for molten salt and the head rise for sodium is 132 ft. and 40 ft. for molten salt). One test (2575 hours) was run with sodium at 1400°F at the 3% drop-off point, in this case corresponding to S=3200, i.e., the pump is not well-designed for cavitation resistance. Two tests were run in pumps of somewhat different design in molten salt: the first for 3550 hours, again at the 3% drop-off point, but in this case S=9300. The second was for 25,000 hours but at an NPSH about 1.5 x that for the 3% drop-off point, corresponding to S=7000 in this case. The temperature for the sodium test was varied in 516 continuous thermal cycles over the range 1050-1250°F throughout the test, whereas for molten salt the temperature was held at 1200°F throughout, for the longer test. The temperature was varied over the range 1100-1400°F in 652 thermal cycles for the shorter of the molten salt tests. The material from which the pumps are constructed in all cases is Inconel, and the molten salt is of the same components previously described. Table 3 directly reproduced from ref. 12 gives full details of the tests.

Considerable cavitation damage occurred in all cases, thus being consistent with the previously described CANEL tests to the extent that operation of liquid metal pumps well within the cavitating region (3% drop-off, e.g.) is generally not feasible from the viewpoint of damage. In the ORNL tests (as opposed to those at CANEL) there was no measurabl performance deterioration due to cavitation damage. However, in all the ORNL tests pits of depth greater than $\frac{1}{4}$ in. were found. Thus damage was relatively very substantial, since the impeller diameters were of the order of 6 in. Considering the low S-values involved, these pumps are certainly not optimum from the viewpoint of cavitation design, and this fact may be partly responsible for the rapid accumulation of cavitation damage.

An interesting point concerning the 25,000 hour test, which was performed at an NPSH-value 1.5 x that corresponding to the conventionally defined (3% drop-off point) cavitation inception point, was that even f this "non-cavitating" point, substantial damage is accrued in a long-te test, i.e., continuous operation for about a 3-year period. Presumably, this operating condition, as well as those of the shorter tests, would then be prohibitive for sodium-cooled or molten salt reactor powerplant

c. Venturi Sodium Cavitation Tests (15)

Part of the effort of the ORNL pump group consisted of cavitation te in sodium in a venturi with 7° diffuser cone-angle (15). Unfortunately, there was no direct comparison made with water in the same facility. However, the cavitation performance of the venturi was roughly as expected, in that cavitation was found at the venturi throat at a pressure ~1.4 ps above vapor pressure, thus probably* indicating an ample supply of en-

*Another possible partial explanation may be that the minimum pressure was not measured, and that the friction drop downstream of the pressure tap may not have been properly included. However, this is estimated at only about $\frac{1}{4}$ psi.

trained gas. No measurement of entrained gas was made and of course that capability is still undeveloped. It is presumed that the gas originated from the centrifugal sump-type pump with argon (and sometimes helium) blanket, which was used to drive the loop. It is mentioned that there is also a large sodium-gas interface in one of the loop tanks. Although it was investigated, no change in cavitation sigma was found due to changing from argon to helium as pressurizing gas. This observation is at variance with those made by a French AEC group (Cadarache) working with cavitating orifices and nozzles with helium and argon as pressurizing gas. This work (26,27) will be described later. No indication of actual sodium conditions such as velocity, pressure, or Reynolds' number are given. The venturi throat diameter is ~ 1 in. $T = 1215-1475^{\circ}F$.

d. Cavitation Tests with Potassium in Electromagnetic (EM) Pumps (16,17)

Cavitation tests were made on 3 electromagnetic (EM) pumps in potassium at temperature ranging from 800-1300°F. The pumps were of different types. Argon pressurization was used and cavitation results compared with another system where pressurization was provided by potassium vapor alone, heated to attain the desired vapor pressure in a tank included for this purpose and connected to the loop through a small-bore tube. Thus, in the argon-pressurized tests, at least a small supply of entrained gas nuclei was available, whereas these were apparently nearly absent in the vapor-pressurized tests. These tests are of interest in the present context in showing the dependence of cavitation inception sigma* upon entrained gas nuclei content.

The result of these tests is that cavitation could not be attained at all in the vapor-pressurized runs (within the capabilities of the equipment), and in fact negative NPSH-values up to -7 psi were found (with no cavitation). For the argon-pressurized tests, on the other

~~*As do the~~ French AEC tests described later (26,27).

hand, the NPSH for cavitation inception was up to +3 psi. For directly comparable tests, the difference (due presumably only to the method of pressurization) is ~8 ft. It is not possible to compute sigma, since no inlet velocity is given. However, the total pump head rise is high, ~ 750 ft. The significance of these tests from the present viewpoint is the demonstration of the potential major importance of entrained nuclei content in the liquid metal fluids.

C. French Atomic Energy Commission Tests - Cadarache (28) and Electricité de France (EdF) (26,27)

1. General Background Information

A program has existed in France over the past several years to investigate cavitation in sodium, motivated by their fast reactor program. One facet of their sodium work has been to evaluate the applicability of water cavitation inception data to sodium. In this connection both water and sodium (26,27) cavitation tests were made in a venturi which was identical in flowpath to one used by our own laboratory for cavitation studies. No significant difference in inception sigma between the fluids was found, although there was fairly considerable data scatter (as is common with cavitation inception tests) as well as strong dependence on velocity (or Reynolds' number), amounting, however, in total to a variation in NPSH of only ~6 ft. Hence, perhaps this difference is negligible from the engineering viewpoint. The water data obtained in the French venturi tests was consistent with that obtained with water in our own tests on the similar unit. These tests are summarized in Fig. 2-5 (reproduced directly from ref. 26,27). The experimental results and the venturi flow-path are shown.

To try to resolve the somewhat inconclusive results of the above tests and to obtain additional pertinent data, a further test program has been undertaken by the French Atomic Energy Commission in their laboratory at Cadarache. So far they have measured cavitation sigma in orifices and converging nozzles (28). It is planned eventually to cavitation-test these same components in water, and perhaps extend the program to others, but comparative results are not available as yet. The sodium results (28) alone, however, are of interest in showing (as did the EM pump tests at ORNL) the importance of gas nuclei content in substantially affecting the cavitation inception sigma. This leads them to conclude: (as translated) "This is why it seems important to rapidly start a program to develop an apparatus to measure...(gas nuclei)..." I fully agree that this is in fact the key issue needing resolution before further substantial progress in the prediction of cavitation inception in sodium can be made. There is such an active program at Cadarache now.

2. Specific Results

The Electricité de France - University of Michigan venturi tests in water and sodium are reported in detail in our previous report (26), and the results repeated here for convenience, Fig. 2-5. The major result is that inception sigma for water and sodium lay within the same scatter band of data, which, even considering the substantial effects of velocity or Reynolds' number, is still small enough to be considered negligible from an engineering viewpoint. Since entrained gas nuclei spectra were not measured for either water or sodium (for which no practical instrument is yet available), no further light can be shed on the subject from these tests. However, the additional tests conducted by Cadarache do further emphasize the substantial importance of knowing these gas nuclei spectra (size and population density).

In the Cadarache tests in sodium on orifices and nozzles (28), it was found that sigma for inception (defined as first intermittent cavitation noise), as well as sigma corresponding to cavitation characterized by the first steady noise, depended significantly on whether argon or helium were the pressurizing gas used in the expansion tank to control the overall loop pressure level. Gas was entrained in the sodium from this source rather than from the driving pump, since it was a freeze-seal unit rather than the sump-type pump often used in such loops. Test results show that inception sigma is greater by about 0.3 for both orifices and nozzles when argon is the cover gas than in cases when this is helium. This difference amounts to an NPSH difference of about 6 ft. (2 psi), which is about the magnitude of overall scatter of the results in the previously discussed EdF tests. From an engineering viewpoint, the differences may often well be negligible in both cases.

In addition, it was found that inception sigma was modified by the pressure level in the expansion tank for a given flow rate. The variati in sigma in this case was about 0.1 for argon. The same phenomenon was noted for helium. Finally, the slope of the sigma vs. Reynolds' number curves appears to be somewhat steeper with helium than with argon.

The larger sigma for argon as compared with helium appears to imply a greater quantity of entrained gas in the sodium when argon is the cover gas. These results may be related to different solubilities of th two gases in sodium, but they are generally unexplained at this point. Their importance in the present context is the definite demonstration that entrained gas effects are of major importance in determining cavitation sigma, so that it appears impossible to make further significant progress in this field without the development of a technique for measuring entrained microbubble spectra in sodium. This is also the stated opinion of the authors of the Cadarache report (28).

D. NASA Program and Results (9,29-32)

1. General Background Information

A substantial program of liquid-metal turbopump development existed primarily during the 1950(s) at the Lewis Research Laboratory of NASA in support of the SNAP programs, particularly SNAP-50. The NASA program was rather similar to that at CANEL, already discussed, and involved especially work with the alkali liquid metals. Tests in both water and liquid metals were included. The studies included cavitation performance effects as well as damage, and involved primarily axial-mixed-flow pumps of high specific speed, somewhat like those tested at CANEL.

2. Specific Results Obtained

a. Water Pump Cavitation Study (9)

Unshrouded impellers somewhat similar to those used at CANEL in transparent housings were studied photographically under cavitating conditions. As in the CANEL work, it was found that cavitation first developed from the tip-clearance flow. In the NASA tests "micro-cavitation" of this type developed at NPSH about 3.5 x that corresponding to the 3% drop-off point (vs. about x8 in the CANEL tests). The appearance of the first photographically visible cavitation occurred at S=6650 vs. S≅15,000 for the 3% drop-off point. Hence, it is again emphasized that the development of a truly "cavitation-free" pump is beyond the present state-of-the-art without a fairly extensive development program.

b. Cavitation Damage Studies (29-31)

Quite comprehensive cavitation damage studies in sodium at various temperatures and with various materials have been conducted by the NASA-Lewis group (29-32). A special unshrouded axial-mixed-flow impeller was constructed with removable blades for this study. Tests were run on materials such as René-41 (a nickel-chromium-based superalloy), and 316 and 318 type stainless steels (29). Of these materials, 316 SS was the least resistant to cavitation damage, and René-41 the most. Tests were conducted at 1000°F and 1500°F. It was found that the rate of damage was virtually independent of temperature over this range. Thus, these tests do <u>not</u> agree with vibratory damage tests in this regard. There, there is a very great fall-off of damage for 1500°F sodium vs. 1000°F (22,33,e.g.) presumably due to the "cavitation thermodynamic effects" as they are termed in the literature. Of course this "built-in" fluid effect is countered to some extent by the reduced strength of the materials as temperature is increased, particularly in a high-temperature range such as 1000-1500°F. In the vibratory tests (33,e.g.) the fluid "thermodynamic effect" great outweighed the material weakening effect. However, this was apparently not the case for the NASA tests (29-31). This "paradox" merely emphasiz the difficulty of transferring cavitation test results from test model prototype, etc, which exists in many cases.

The NASA cavitation tests were generally of 200-300 hours duration, and considerable damage was produced on all the materials. In at least one case (29) the test duration for which significant damage was produc was only 32 hours. It was determined (as expected) that the rate of dam age increases very rapidly with pump speed for tests at constant S (29) Hence, suction specific speed alone cannot be used as a predictor for damage. It was also found (29) that the NPSH corresponding to a given point on the cavitation curve (the 3% fall-off point, e.g.), was much l at 1500°F than at 1000°F (13 ft. in one case), due primarily also to "thermodynamic effects." Thus, for this case, an NPSH decrease of about 15% occurs at higher temperature, corresponding to an increase in S of about 11%.

In summary, the NASA damage tests appear to prove, as did those at CANEL and at ORNL, that operation within or near the cavitating region i not practical for liquid-metal powerplant pumps.

c. Cavitation Performance Comparisons with Different Fluids

Over the past decade or so there has been a continuous program at NASA-Lewis (partially in conjunction with NBS, Boulder, Colo.) to study cavitation inception in various fluids, using a venturi-type geometry for the studies (32,e.g.). Comparisons between water and cryogenics hav been emphasized rather than liquid metals, but in so far as basic theor ical models are evolved (as they have been to some extent), this work is also applicable to liquid metals.

III. Conclusions

The major conclusions which can be drawn from the present study follow.

A. Cavitation Inception in Water and Alkali Liquid Metals in Identical Components

Available evidence, where direct comparisons between water and alkali liquid metal cavitation tests exist, show <u>in general</u> that there is no major difference in inception sigma for pumps of venturis (the only components for which there is experimental evidence) between water and any of the alkali liquid metals. It is also reasonable to assume that there is no significant difference in this regard between sodium and the other alkali liquid metals. The above statements are confirmed by tests at ORNL and Electricité de France (coordinated with University of Michigan tests). Tests at Pratt and Whitney Aircraft (CANEL) disagree in showing that the NPSH required for a potassium pump may be twice that for the same pump in water. However, there are special reasons pertinent only to this work and explained in detail in this report, which lead to the conclusion that this result is invalid. Furthermore, there is no theoretical reason to believe that Na, NaK, or K should cavitate more easily than water. Theoretical reasoning leads, in fact, to the opposite conclusion.

B. Non-Cavitating Performance Comparisons between Water and Alkali Liquid Metals

Non-cavitating performance of alkali liquid metal pumps and other flow components can be accurately enough predicted by water tests, applying the conventional scaling laws.

C. Detailed Cavitation Inception Comparisons between Water and Alkali Liquid Metals

Detailed differences between cavitation performance with water and alkali liquid metals, pointed out in all the tests here reviewed, can only be further resolved if complete gas content measurements are made in all the fluids involved, i.e., size and population density spectra c entrained gas "microbubbles" must be measured as well as total (or dissolved) gas. Though there exist in general no relatively available inst ments for this purpose for any fluid, such measurements are being made routinely now in various laboratories (including our own) for water, ar apparently feasible techniques exist for liquid metals. The best approa for sodium at present to obtain such spectra is through the use of an ultrasonic absorption or scattering technique using high-temperature transducers of a type already developed at ANL, and already used in 12C sodium.

Within practical engineering limits, applicable at least in most cas but not always if good precision is required as it might sometimes be, the effect of gas content (judging from a vast amount of water data (24 e.g.)) appears to be small within a moderate range of gas contents (not very high or very low), applying to most actual large scale machines. These results for both cavitation inception sigma and for cavitation damage are summarized in Fig. 6-a,b (reproduced for convenience from re 24). The results so far available for alkali liquid metals seem to indi that the same general situation applies, at least for cavitation as it affects component performance, but probably not such phenomena as noise or boiling superheat.

D. Cavitation-Free Operation

It is sometimes desired that completely cavitation-free operation be specified for sodium reactor components. However, the design of complex fluid-flow components which are truly "cavitation-free," i.e., no bubbles capable of producing noise or damage exist, is probably not within the present state-of-the-art without sophisticated research programs, involving model tests and flow visualization, aimed at that particular component. This is the case at present for any liquid including water and all liquid metals. These statements are based on the NASA and CANEL work.

E. Cavitation Damage

It is in general impractical to operate liquid metal pumps over long periods in or near the conventional cavitation zone due to the rapid accumulation of damage. This has been observed in various cases for tests as short as 100-500 hours.

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TABLE 1

Comparison Centrifugal Pump Cavitation Inception Test Results

ORNL (13)

Water Tests						Sodium-Potassium Tests								
	N_{av} (rpm)	Q_{av} (gpm)	T (^oF)	H_{ci} (ft abs)	H_{vp} (ft)		N_{av} (rpm)	Q_{av} (gpm)	T (^oF)	H_{vp} (ft)	Estimated H_{ci} (ft abs)	Alloy Test H_{ci} (ft abs)	Difference (ft)	Difference (%)
Run 1	3375	306	188	45.1	21.3	Run 1	3390	308	1490	40.5	64.3	63.3	+1.0	+1.6
Run 2	3374	436	138	39.5	6.4	Run 2	3383	435	1501	43.0	76.1	79.8	-3.7	-4.7
Run 3	3003	306	188	43.2	21.3	Run 3A	3018	310	1502	43.2	65.1	68.0	-2.9	-4.3
						Run 3B	3030	305	1497	42.1	64.0	65.5	-1.5	-2.3
						Run 3C	3047	307	1500	42.7	64.6	65.0	-0.4	-0.6
Run 4	2999	436	138	37.0	6.4	Run 4A	3000	432	1493	41.2	71.8	75.4	-3.6	-4.8
						Run 4B	3000	432	1503	43.5	74.1	79.0	-4.9	-6.2
						Run 4C	2985	435	1503	43.5	74.1	77.6	-3.5	-4.5
Run 5	2603	304	188	40.2	21.3	Run 5	2601	303	1481	38.5	57.4	59.0	-1.6	-2.7

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TABLE 2

ORNL Pumps Suction Specific Speed, S

N (RPM)	Q GPM	NPSH Ft.	S
3390	308	63.3	2610
3383	435	79.8	2640
3030	307	66.0	2310
3000	433	79.0	2360
2601	303	59.0	2130

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TABLE 3

Pump Operating Conditions

ORNL (12)

	Sodium pump test	Molten salt pump test 1	Molten salt pump test 2
Test fluid	Sodium	Molten salt*	Molten salt*
Temperature, F	1050–1250	1100–1400	1200
Shaft speed, rpm	3550	2700	2700
Pump flow, gpm	~440	~645	645
Static suction head, ft abs	61–69	14.1–14.8	21
Total head, ft	~132	~40	40
Design specific speed	1900	4300	4300
NPSH, ft abs	60–65	14.1–14.8	21
Average suction specific speed	3200	9300	7000
Impeller relative inlet velocity, ft/sec	53.1	37.7	37.7
Test duration, hr	2575	3550	25,000

* $NaF-ZrF_4-UF_4$, 50-46-4 mole %.

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WATER AND POTASSIUM

TURBOPUMP CAVITATION PERFORMANCE COMPARED AT CONSTANT FLOW AND CONSTANT THROTTLE (Ref. 1)

(Pratt and Whitney Aircraft - CANEL)

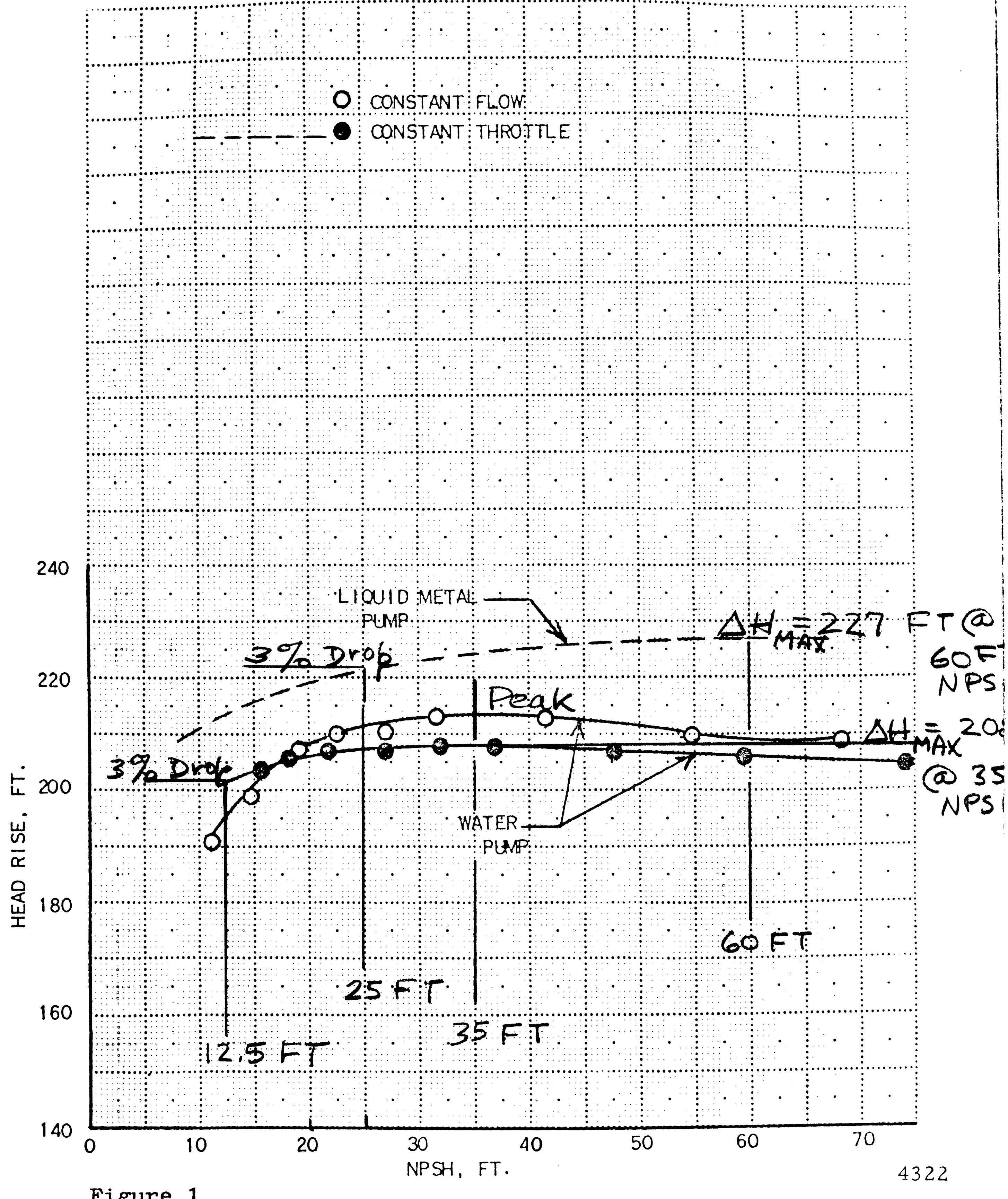
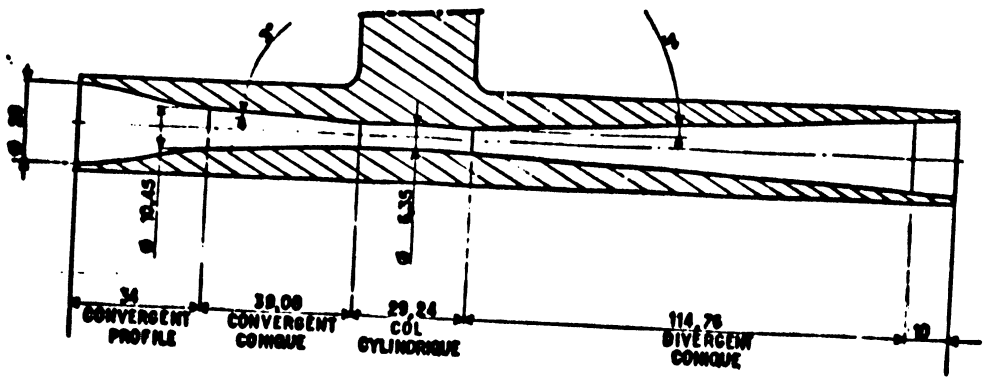


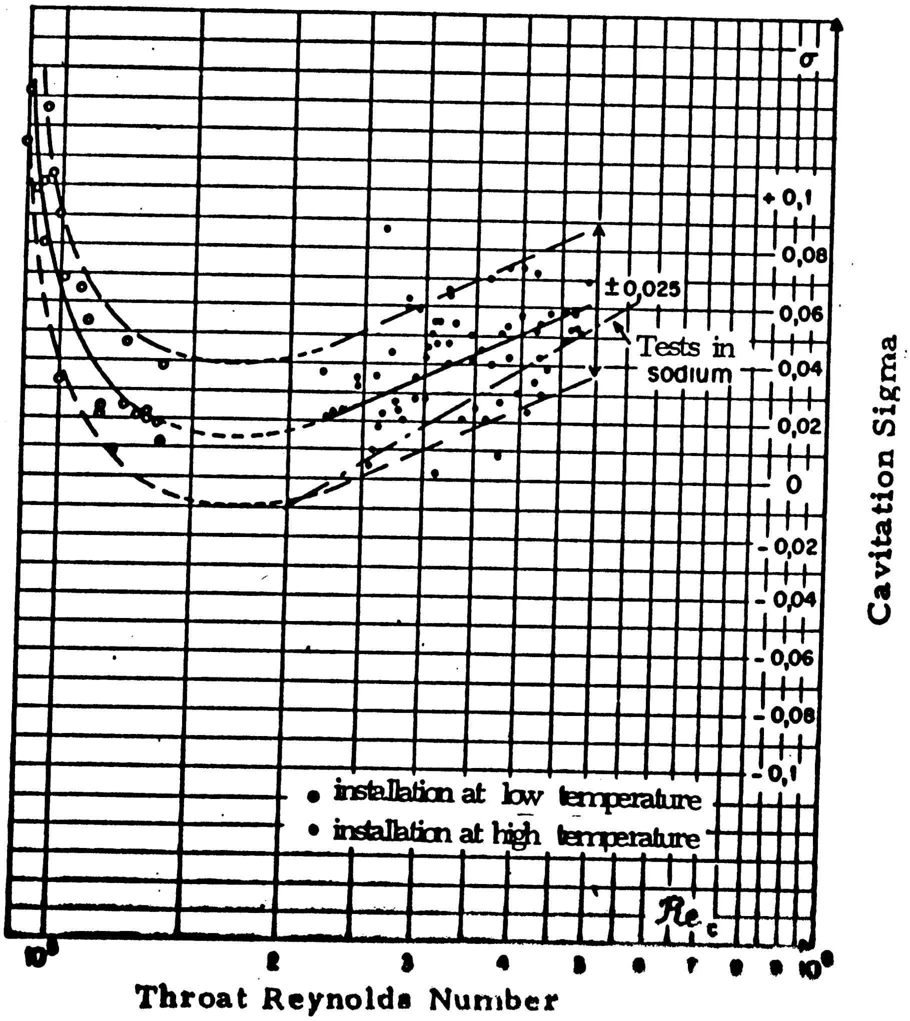
Figure 1



4916

Fig. 2 Schematic of Venturi Tube (Dimensions in mm.)

Electicité de France Tests (27)



4917

Fig. 3 Water Cavitation Inception Tests
Electricite de France (27)

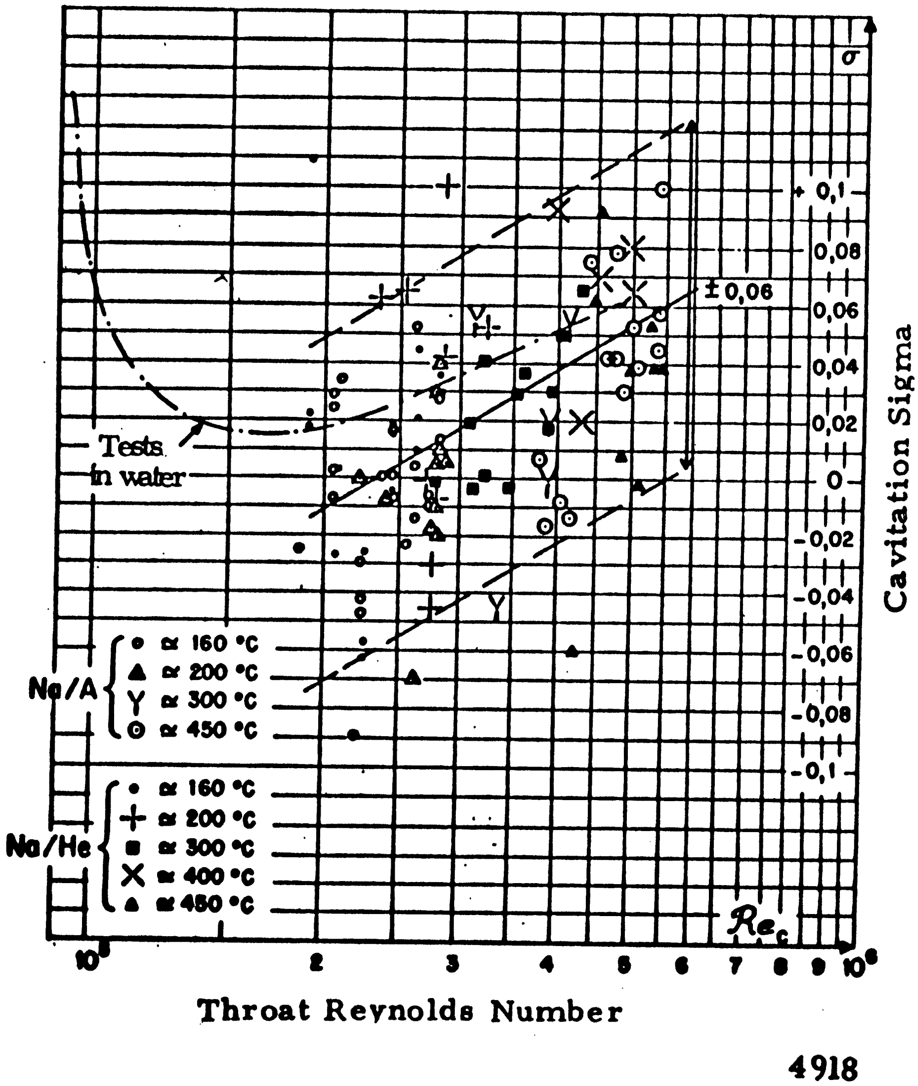
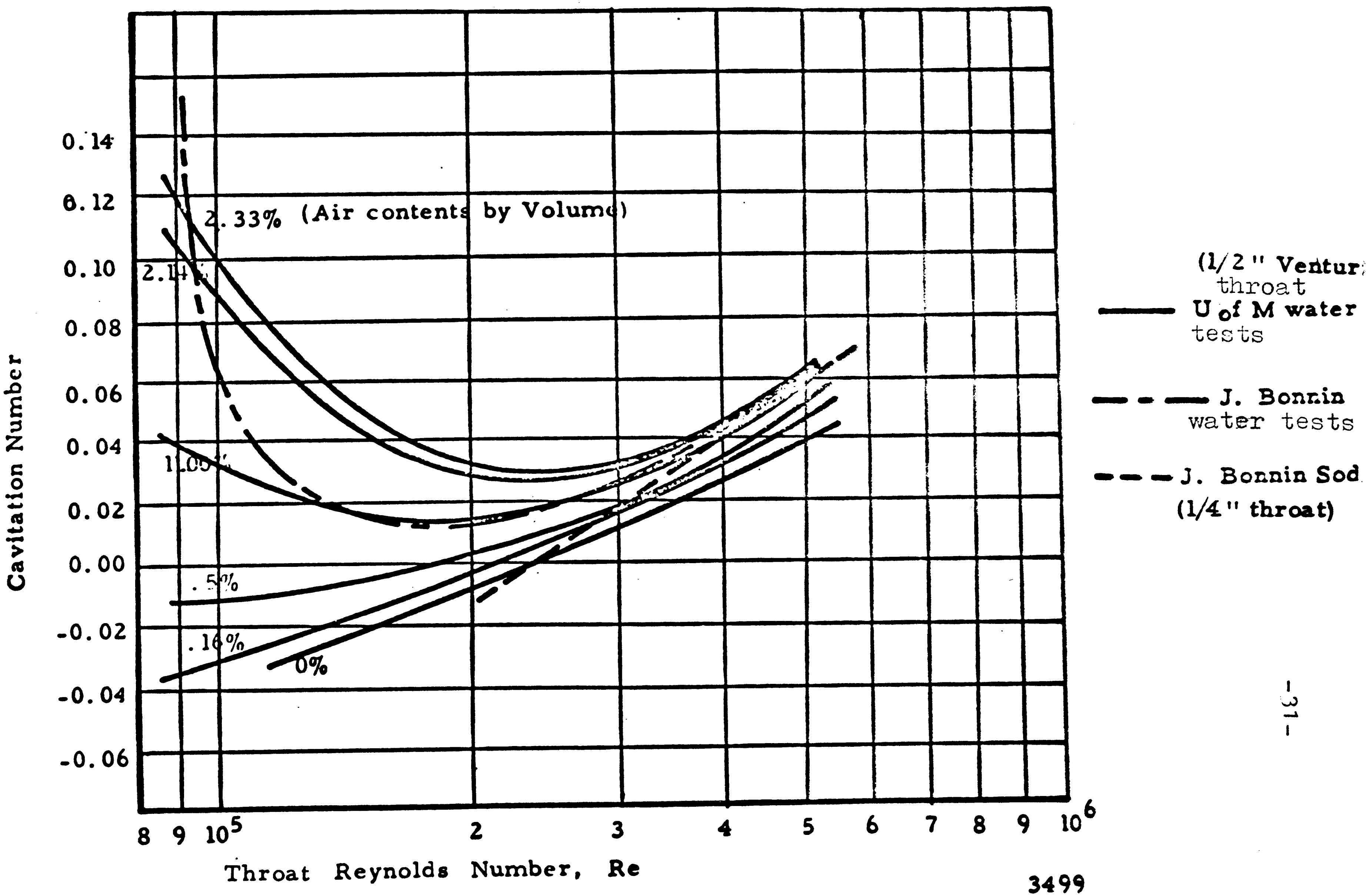


Fig. 4 Sodium Cavitation Inception Tests

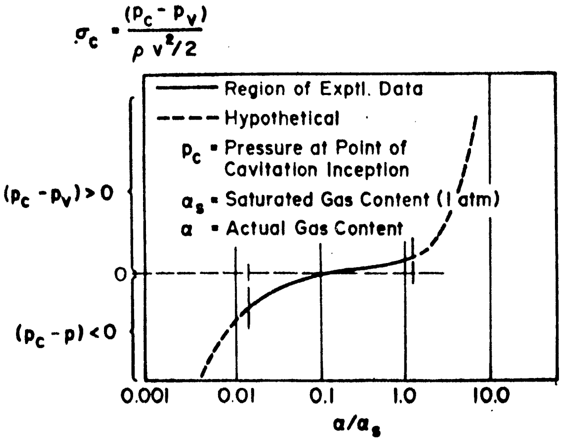
Electricité de France(27)



3499

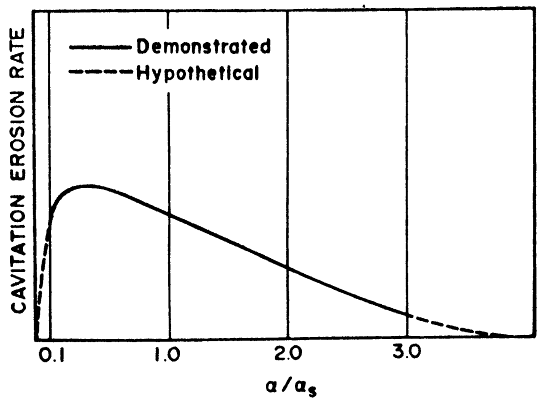
FIG. 5 CAVITATION SIGMA VS. REYNOLDS NUMBER IN VENTURI FOR WATER AND SODIUM

Electricite de France[27] and University of Michigan[23, 24]



p_c = pression au seuil de cavitation
α_s = teneur saturante en gaz
α = teneur en gaz

a. Inception Sigma vs. Relative Air Content (hypothetical example).
σ de début en fonction de la teneur relative en air



b. Erosion Rate vs. Relative Air Content (hypothetical example).
Vitesse d'érosion en fonction de la teneur relative en air

Fig. 6. Hypothetical Overall Dependence of Inception Sigma and Erosion Rate on Relative Air Content.

σ et taux d'érosion en fonction de la teneur en air (extrapolation des résultats d'expérience).

(Ref. 24)

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