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European Trip Report - F. G. Hammitt

European Sodium Cavitation Research - State-of-Art

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I INTRODUCTION

This report reviews the present state-of-the-art and probable future course of sodium cavitation research with particular application to FBR programs in Europe and Britain as understood by the author. The information has been gleaned ~~primarily~~ to a large extent from conversations and other unpublished documentation resulting from the author's visits during the past summer to atomic energy laboratories in France, England, and Holland. This extended visit in Europe was primarily as a Fulbright to the French atomic energy laboratory in Grenoble (CENG)*, as well as a week spent at the French laboratory at Cadarache. Later and shorter visits were also made to the fast reactor pump groups at Risley and at Neratoom (Holland). The contact with the French has been extended over a period of 5 - 10 years, starting with a Sabbatical to Electricité de France (EdF), a 6-month leave to the French private hydraulic research company in Grenoble (SOGREAH), and finally the Fulbright to CENG. In addition for several years my laboratory at Michigan has been engaged in a series of sodium cavitation tests under contract from Cadarache. These tests are now complete, and have examined the effects upon damage rates of varying sodium temperatures and pressures on a variety of materials of interest including SS-316. The final report is not as yet written, and the data is not yet cleared for release. In connection with this work primarily I have been a consultant to the French AEC for several years. The present report will cover the pertinent work in all these countries as I know it, and will list published references where possible. It will start with the work in France, since this is the most extensive.

*Centre Energie Nucleaire de Grenoble

I Status of European Work & Trip Report

A. French Sodium Cavitation Research

1. General Background

In both France and England, the FBR program, as compared to that in the U.S., has advanced rapidly toward the production and use of "demo-reactors", so that, in my view, highly practical problems such as cavitation acheived early prominence and attention. As far as I know, ~~this~~ serious research on this problem seems to have started probably sooner in France than in Britain. In any case the potential problems with cavitation lie primarily under the following headings:

a. Cavitation Inception - Can ordinary cold water tests on pumps and other components adequately predict inception performance of the same components in reactor temperature sodium?

b. Cavitation Damage - Can limited cavitation be tolerated in a sodium reactor system without prohibitive damage, as it normally is in water systems?

c. Acoustic Performance - In some FBR systems (such as French Rapsodie and Phenix, and British PFR) it is expected that acoustic instrumentation around the core will be utilized to detect boiling as an important part of the safety system. Since the acoustic signature of sub-cooled boiling and cavitation bubbles is essentially very much the same, the use of such acoustic boiling detection pre-supposes the complete absense of cavitation during normal operation. This imposes a much more stringent requirement on the design of pumps and other types of components such as flow restrictions than has been faced previously in other flow systems, and in fact may be almost beyond the present state of the art.

2. Electricité de France (EdF) and University of Michigan (U-M) Program

Cavitation tests have been conducted with tunnel systems, mostly on venturis, in our laboratory at the University of Michigan, in both water and mercury, to determine the ~~variation~~ dependence of cavitation inception sigma ~~with~~ on such parameters as velocity, Reynolds number, diameter, temperature, gas content, etc starting in the early 60(s). This work has been extensively reported (1, eg.), and hence provided a basis for comparison for later French tests using precisely the same venturi geometry. Tests were thus made by EdF in cooperation with Cadarache, and ourselves in providing the detailed drawings of the venturis used and the data obtained. The French tests were in both water and sodium, the data including the dependence upon velocity and Reynolds number agreeing quite closely with our own. This agreement was only for the cases of air-saturated water, which was the situation in the French tests, where air content was not ~~mentioned~~, measured. Our data, including a wide variation in air content, showed a substantial difference in trend with velocity between low and high air content. The pertinent curves are here attached for convenience (Fig. 1-4), and were also attached to my letter to Dr. Hoppenfeld of October 12. The following major conclusions result from this work in my opinion.

a. Inception sigma depends substantially on velocity and/or Reynolds number, and there is considerable experimental scatter for both fluids. However, water and sodium fall within the same scatter band. The variation with velocity (or Reynolds number) for either fluid is more important than any difference between sodium and water.

b. From an engineering viewpoint all the scatter and variations mentioned above are relatively small, in that the design of ~~such~~ components such as pumps would not be substantially affected.

The results of the above tests are reported in various references in the open literature starting in 1971 (3-6, eg.), including a 1972 ASME paper (4).

A summary of the result of these tests, and similar ones at Cadarache, from the French viewpoint is found in ref. (7), 1970 ASME Cavitation Forum. To quote, "Presently available results seem to indicate no difference (between water and sodium), within measurement accuracy, but other tests will be performed to check whether factors such as argon content in sodium, its purity, and its temperature level may influence inception of cavitation." These later tests at Cadarache will be discussed in the following.

3. Cadarache Sodium Cavitation Research

Approximately parallel time-wise with the venturi sodium and water cavitation inception tests of EdF with the U-M venturis discussed above (late 60s) a similar program was undertaken by Cadarache. ~~Both~~ Neither EdF nor Cadarache tests involved the building of special loops for cavitation studies, but rather the attachment to existing large loops of a smaller cavitation bypass loop, into which venturis, orifices, etc. could be installed. In all these cases (as in our own mercury tests) cavitation inception was determined acoustically, being the only feasible method. The Cadarache tests included orifices and other components as well as venturis, and I believe the comparative water tests were done in well-established water tunnel facilities at SOGREAH in Grenoble. These tests also included investigating the difference between argon and helium as pressurizing gas, and surprisingly it was found that there was a substantial difference between inception sigmas obtained with these different gases. This may be due to different solubilities of the two gases in sodium. It is somewhat reminiscent of results obtained with an EM potassium pump loop at Oak Ridge (8), where different indeption results were obtained depending upon whether argon or ~~sodium~~ metal vapor were used for pressurization. (potassium in this case).

To my knowledge the results of the above sodium and water cavitation inception tests at Cadarache have not been published in the open literature. In a letter to myself in 1970 (in translation), "it seems that the threshold of cavitation for an orifice depends upon the operating conditions of the loop", i.e., the type of pressurizing gas, and perhaps other factors of which I am unaware. In any case, these results were considered sufficiently unsatisfactory and unsettling, that Cadarache decided to build a new large sodium tunnel especially for the investigation of cavitation (designed by SOGREAH I believe). This facility is now complete, and its operation is expected to commence this autumn. It will be used for both inception and damage tests. It is expected that entrained gas microbubble spectra will be measured acoustically in a cooperative program with the group at Risley. Their work will be described later. The Risley instrumentation for determination of entrained gas content in sodium has already been used in a cooperative endeavor with the French on a heat transfer boiling loop at CENG (Grenoble), and the entrained bubbles were successfully measured. These results have not yet been published to my knowledge.

4. French and U-M Cavitation Damage Research

In the U. S., liquid metal cavitation damage tests in vibratory facilities have been made by NASA (Lewis Research Laboratory) (9), at Hydronautics Inc. (10), and by our own laboratory (11, etc.) over the past decade. Tests have been with lithium, lead-bismuth alloy, and mercury (11), sodium and mercury (9), and sodium (10). Much of this early work was financed by NASA for the SNAP-50 program. Sodium ~~or~~ kali liquid metal cavitation damage tests were also made in the U.S. by CANEL and Oak Ridge. This work is summarized in a report by myself recently written for ANL (12), and in the open literature (6).

The only recent sodium cavitation damage tests to my knowledge are those contracted to ourselves by Cadarache, conducted in a vibratory facility over ranges of pertinent temperature and pressure. These results are not yet cleared for publication, but hopefully will be in a few months. However, the general trends found are similar to those also found by NASA (9), and generally applicable to all fluids (12, eg). For all fluids, damage rates decrease very substantially at high temperature (even though materials may also be substantially weakened) due to "thermodynamic" restraints on bubble collapse which become operative at high vapor densities existing at high temperature. As a result, cavitation damage does not appear to be a very prevalent phenomenon in pumps or other components handling water under PWR or BWR conditions, as compared to cold water pumps. However, the results presently available do not indicate that the same will be true of reactor temperature sodium components, since reactor temperature sodium is much more nearly comparable to cold water than to PWR temperature water.

5. French Acoustic Work

As previously mentioned the Rapsodie and Phenix reactors have, I believe, been instrumented, as part of the safety systems, for the acoustic determination of boiling in the core. Such instrumentation, however, probably cannot distinguish with certainty between such sub-cooled boiling and cavitation. I believe that cavitation has recently been detected by such instruments near the outer fuel elements of the Phenix core, and apparently the pumps do in fact operate ~~in the~~ with complete absense of cavitation. It may be recalled that cavitation also occurred in the seals at the bottom of the fuel elements in the Fermi reactor, and did produce considerable pitting after relatively short exposure. In this case (Fermi) the stainless steel inserts were then replaced by stellite, but no later observation of the stellite was ever possible.

As a result presumably of these acoustic instrumentation requirements, an acoustic group has been built up at Cadarache, and has worked on the development of instruments for the measurement acoustically of entrained gas in sodium (or other fluids) by measuring either velocity of sound or attenuation effects due to the gas as well as ~~They have~~ of course also being active in the development of high-temperature transducers for use in sodium. Similar developments have ~~of course~~ also been made at Argonne and at Risley (to be discussed later). The French instrumentation for entrained gas measurement does not seem equal to that developed at Risley, so that the Risley instruments have been used in cooperative programs in France, and I believe this cooperation is now continuing.

B Sodium Cavitation Research at Risley

1. General Background

The writer visited the group of Mr. C. Boorman at Risley in September, 1974 after the I. Mech. E. Conference on Cavitation at Herriot-Watt University in Edinburgh. I have been in fairly close contact with this group for about 5 years since the visit to U-M of Mr. Boorman, and hence have been exchanging pertinent reports with them since about that date, which is probably about the time of the commencement of a serious effort on cavitation pertinent to the FBR program at this location (Risley). Their effort at first was limited to cavitation in stationary components as venturis, orifices, etc., and involved very careful work in a water tunnel with highly sophisticated acoustic instrumentation for the counting of individual cavitation bubble collapse pulses, as well as the development of a system for measuring the entrained gas size and population densities. The initial work in water has later been compared with sodium cavitation results in the same components. This has lately been extended to pump tests. In general I believe they have done the most sophisticated and successful work in the field so far available. As a result, they are now able to "commercialize" their instruments, and use them in joint programs, e.g., with the French. I have in fact recently determined that they are willing to sell the instrumentation for entrained gas microbubble spectrum measurement to ourselv

2. Cavitation Tests in Water

Mr. Boorman's group at Risley (Engineering Technology) consists of at least Messrs: A. F. Taylor, C. Betts, and A. Collinson, and has developed a water-tunnel facility for the cavitation-inception testing of various stationary components. They work closely with the Acoustics group of Mr. Burton, which includes Messrs: B. Gray, McLeod, McKnight, and others. The cavitation inception measurements are now made both visually and acoustically. The acoustic apparatus at present involves the counting of individual bubble collapse events, as shown in Fig. 5 7 attached.* At constant velocity, for example, it is found that as NPSH is reduced from a very high value, the number of such counts per second increases at a fixed rate (from the initial "background" reading), as the conventional cavitation inception point is approached. When "visible inception" is reached, it is found that the slope of the counts vs. NPSH curve increase proximately as a step to a higher and constant value. Thus a very precise definition and measurement of cavitation inception is afforded. This same approach has been used at the University of Minnesota in water tunnel tests (13). To my knowledge this work at Risley has not yet been published in the open literature.

In addition, acoustic methods for measuring entrained gas microbubble content in liquids were developed by the Risley group using both changes in velocity of sound and sound scattering effects. Again nothin is apparently published in the open literature, and they are not willing to disclose the details of these instruments, since they are considered to have commercial potential and hence are proprietary. As already mentioned, these instruments can apparently be purchased for use in our own laboratories. As already mentioned, they are being (and will be) used in cooperative programs with the French at Cadarache and at Grenoble (CENG) for boiling and cavitation tests in sodium.

Total gas content is also measured in a conventional manner in the water cavitation tunnel at Risley. A very effective deaereator is used in conjunction with this loop, so that total air content is about 10^{-6} by volume (saturation is about 10^{-2}). Even so, there are apparently enough entrained particles that cavitation occurs with relatively conventional sigma values. Thus conventional deaereation, even down to very low values, will apparently not appreciably suppress cavitation in water (or perhaps in sodium). Of course no data to verify this is as yet published.

* Fig. 7 shows conventional results for nozzles.

3. PFR Pump Development and Sodium Cavitation

After development of the acoustic techniques for bubble pulse measurement and entrained microbubble spectrum measurement at Risley, the same techniques have been applied to sodium cavitation tests of some components such orifices, etc., and are being applied, according to my understanding, to tests of the PFR pumps (both in water and sodium). A description of the pump tests in general has been published (14), but no detailed results concerning bubble collapse counts and entrained gas content spectra as yet. I believe some of these ~~the~~ tests and data reduction are still in progress.

Data from these tests, and also those at Neratoom for the German-Dutch work on SNR-300 (to be described later), can be used, along with other data sources already available, to generate a normalized curve comparing acoustic, visible, and head fall-off cavitation inception points for centrifugal pumps (and perhaps other components if desired), to be used perhaps to specify vendor and laboratory pump tests and design for reactor sodium pumps. A crude form of such a curve was attached to my letter to Dr. Hoppenfeld of October 12, 1974. Hopefully it will be possible to produce a later document incorporating <u>all</u> available data ~~information~~ into such a curve, and from this specifying probable cavitation-free NPSH for given cases from the standard Head vs. NPSH curve.

Additional sophisticated cavitation pump work to support the group at Risley is being continued at National Engineering Laboratory (NEL). The group at NEL (Dr. I. S. Pearsall) has long experience with, and are world leaders in, cavitation pump research and design (15, 16, eg.). To quote Dr. Pearsall (17) concerning pump cavitation inception scale effects, i.e., variation of inception sigma with model size, speed, etc. in a most recent article (1974); "On cavitation inception there is so little information that no reliable conclusions can be drawn. There is some evidence that air content alters the trends of scale effects. Most of the tests on pump performance breakdown have shown an improvement with higher speeds and larger sizes (- - - i.e., higher suction specific speed). Some tests, however, show the reverse effects.".

It thus appears to the present writer that very careful model tests are necessary to achieve a given objective regarding cavitation performance, and that the possible differences between model and prototype due to speed and size changes, etc., are much greater than the uncertainties between water and sodium. In any case, acoustically instrumented prototype tests are clearly necessary to verify the cavitation performance of the reactor pumps. Damage testing, on the other hand, is much more difficult, in that model tests where velocity and/or size are modelled are almost meaningless, even over extremely ~~slow~~ long test periods. Of course if <u>zero</u> cavitation is ~~allowed~~ obtained, as is apparently the case in the Phenix and PFR designs, damage should <u>not</u> occur. If limited cavitation is allowed (very slight visible, e.g.) as in the SNR-300 design, to be discussed next, damage is certainly a good possibility. Presumably the present lack of damage in EBR pumps is due to the fact that the pump design was <u>very</u> conservative, so that in fact, <u>zero</u> cavitation was achieved.

C. Neratoom and SNR Pump Development and Test

1. General Background

After my visit to Risley described above, I visited (1-day) Neratoom at the Hague, and in company with some of the Neratoom pump group engineers, the Stork/~~company~~ Engineering Works, Hengelo, Holland, where the sodium pumps for SNR-300 have been manufactured and designed. The sodium tests were conducted in West Germany at Bensburg. This project is quite well documented in the published literature (18-24), and the Dutch group is quite willing to discuss the pump designs in detail. The leader of the group ~~is~~ was R. H. Fakkel, but it appears that he has been incapacitated by illness for some time, and it may be that he will be transferred to other work when he returns. C. J. Hoornweg seems to be prominent as a replacement at the moment.

This group is also using acoustic techniques for the detection of cavitation inception, as well as for an indication of gas content, both in water and sodium (21). I did not discuss this part of the work with anyone familiar with it, but have the general impression that it is much less advanced than that at Risley.

2. SNR-300 Pump Design

The SNR-300 pumps, designed primarily by the Stork Engineering Works, who have long experience in the design of large drainage pumps where suction heads are low and cavitation a problem, are designed to accept minimum visible cavitation (a plume of about 1 mm length on blade leading edges according to water model tests) during normal operation.* They are convinced by their experience with the drainage pumps that this will not create important cavitation erosion. A 6000 hour test of the sodium prototype pump for SNR-300 convinces them that this is the case. Apparently no cavitation pitting was observed in these tests, though there was some relatively smooth erosion in apparently non-cavitating regions, which they attribute to some sort of chemical effects. They state that this erosion (19) is a result of "washing out" of silicon particles originally embedded in the metallic skin of the impeller.

The SNR-300 pump development (18-21) was started with model tests in water in a 1/2 scale model, and using transparent windows such that cavitation could be observed and correlated with the acoustic detection The necessary detailed changes in impeller design were made in this model to attain the desired cavitation performance. A rather similar method was

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*This changed design philosophy from the French and British designs appears to indicate that SNR-300 does not expect to use acoustic boilin detection as a portion of the safety system.

employed in the design of the Risley pumps, and seems to me to be necessary in general, if the final product is to be reasonably suited to the conditions, i.e., neither too conservative, nor vice versa.

Once the impeller design had been settled, a full-scale model was built and tested in water using acoustic detection of cavitation, as well as the measurement of the normal flow parameters. The full-scale model was then tested in sodium, and ~~a~~ the 6000-hour endurance run already discussed was made. Acoustic instrumentation was used to verify the performance with regard to cavitation inception, and the full head vs. NPSH curves run. Thus a direct comparison in a prototype machine of cavitation performance in cold water and reactor temperature sodium is afforded (19). I believe that this is the only presently published comparison for reactor prototype-size pumps.

A slightly greater NPSH (about 10%) was required for the sodium test than for the water test. The authors believe that this was due primarily to detailed differences in the test loops and experimental error. To quote their second conclusion (19): "There is <u>no</u> deviation* in NPSH behavior between water at room temperature and liquid sodium at 580°C". However, this of course does <u>not</u> mean that there is no difference in cavitation damage potential between these fluid conditions. Present evidence in fact does indicate that the damage potential of cold water and reactor temperature sodium may be of the same order, ~~but~~ and that this is a great deal greater than the cavitation damage potential of PWR temperature water**

The above result, that there is no significant engineering difference in NPSH behavior between cold water and reactor temperature sodium, ~~xxxx~~ isthe same as that reached from previous tests in the U.S. for pumps at CANEL and at Oak Ridge. Thess results were reviewed in a previous report by the present author (22).

**To provide sodium closer in properties of ~~cold~~ PWR-temperature water with regard to cavitation damage, and thus reduce substantially cavitation damage potential, it is likely that the sodium pumps should be located in thehot leg of FBR reactors.

*My underlining

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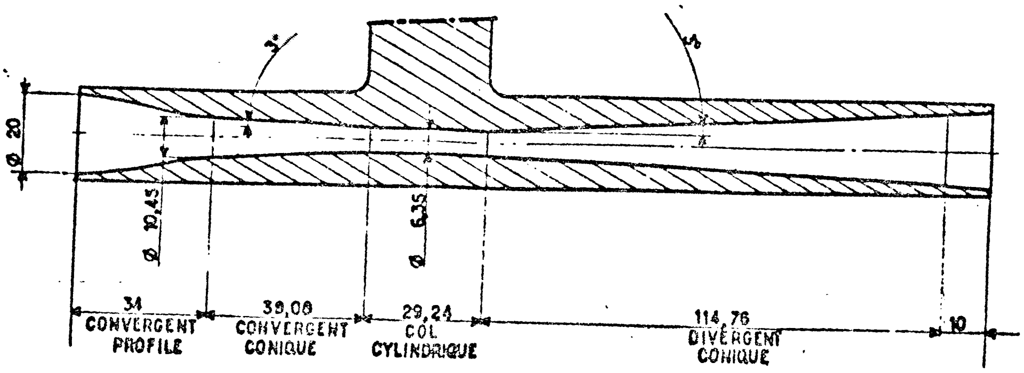

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Fig. 1 Schematic of Venturi Tube (Dimensions in min.)

Electricite de France Tests same internal flow path as U-M venturi

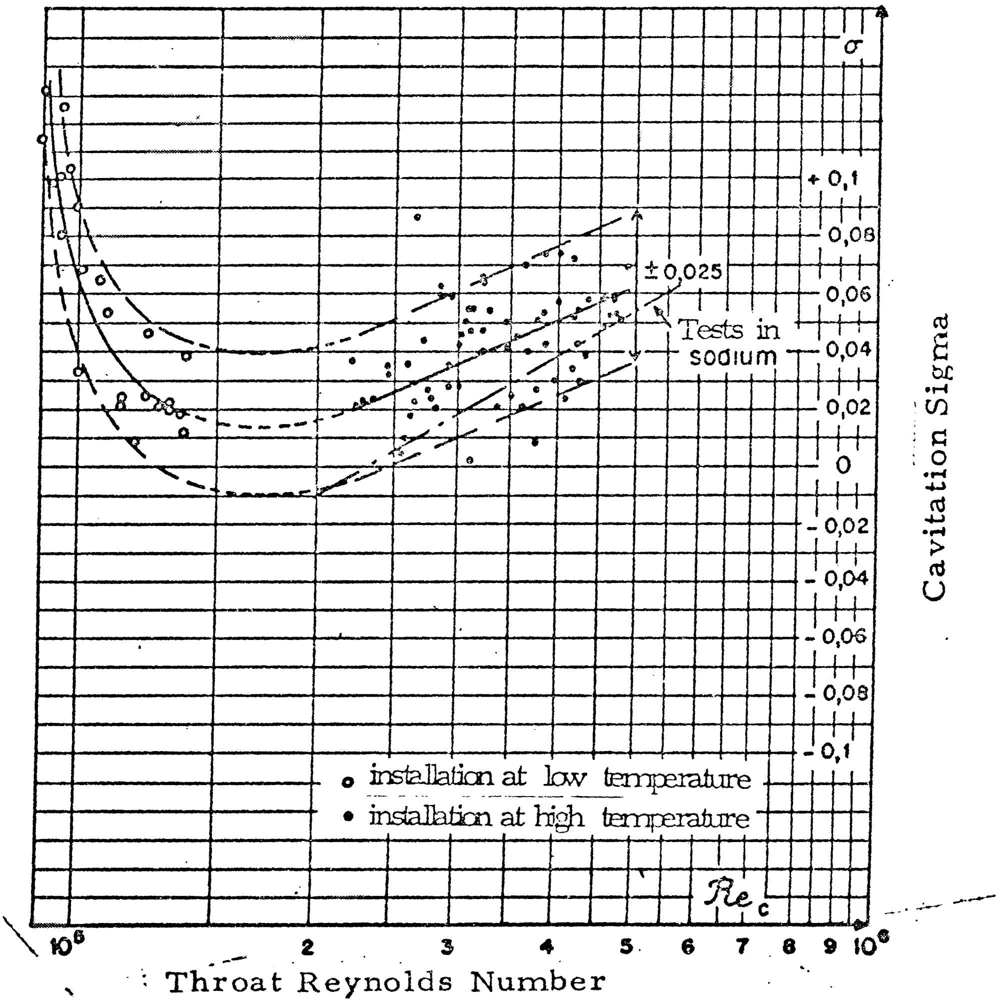

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Fig. 2 Water Cavitation Inception Tests

Electricite de France

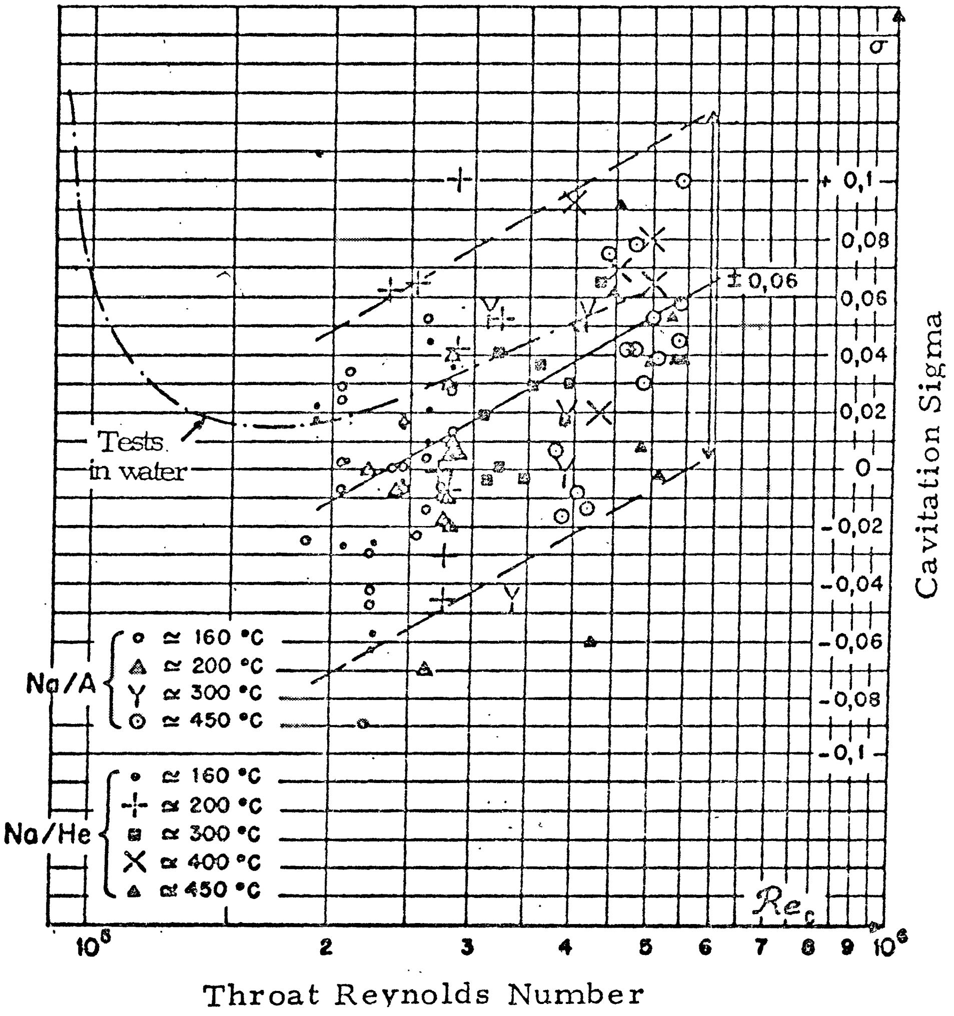

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Fig. 3 Sodium Cavitation Inception Tests

Electricite de France

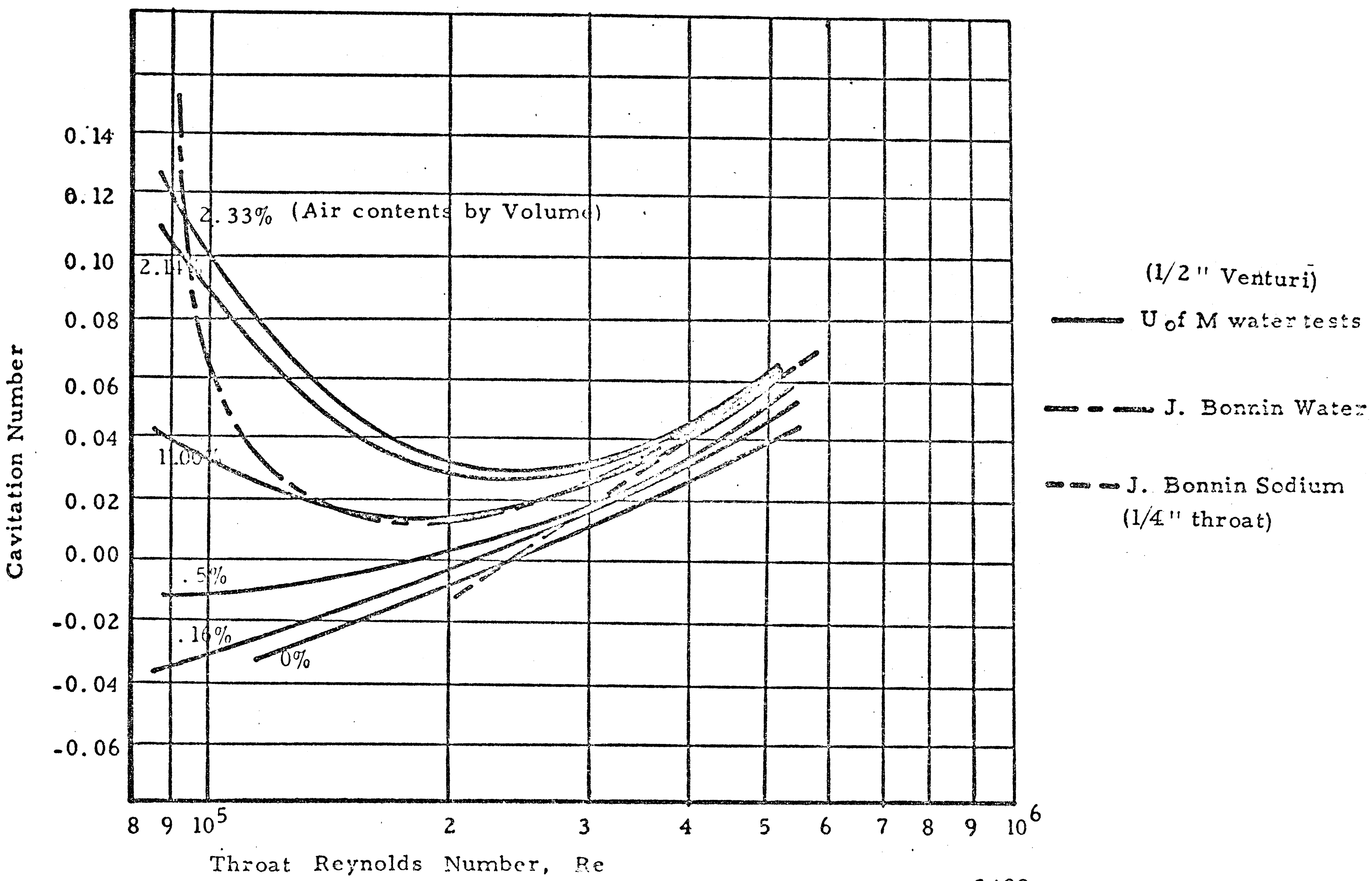

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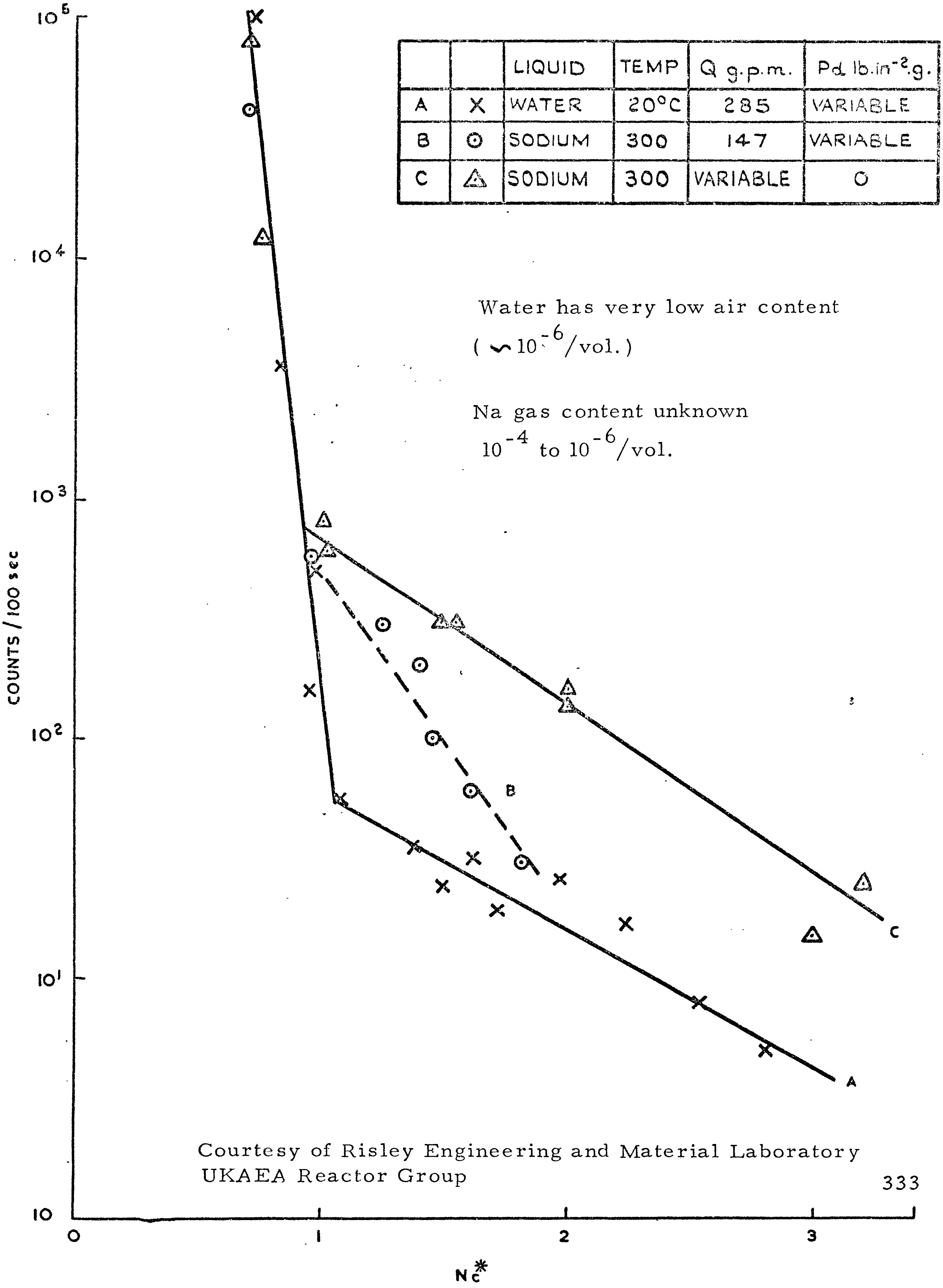
FIG. 4 CAVITATION SIGMA VS. REYNOLDS NUMBER IN VENTURI FOR WATER AND SODIUM CONTENTS
Electricite de France and University of Michigan



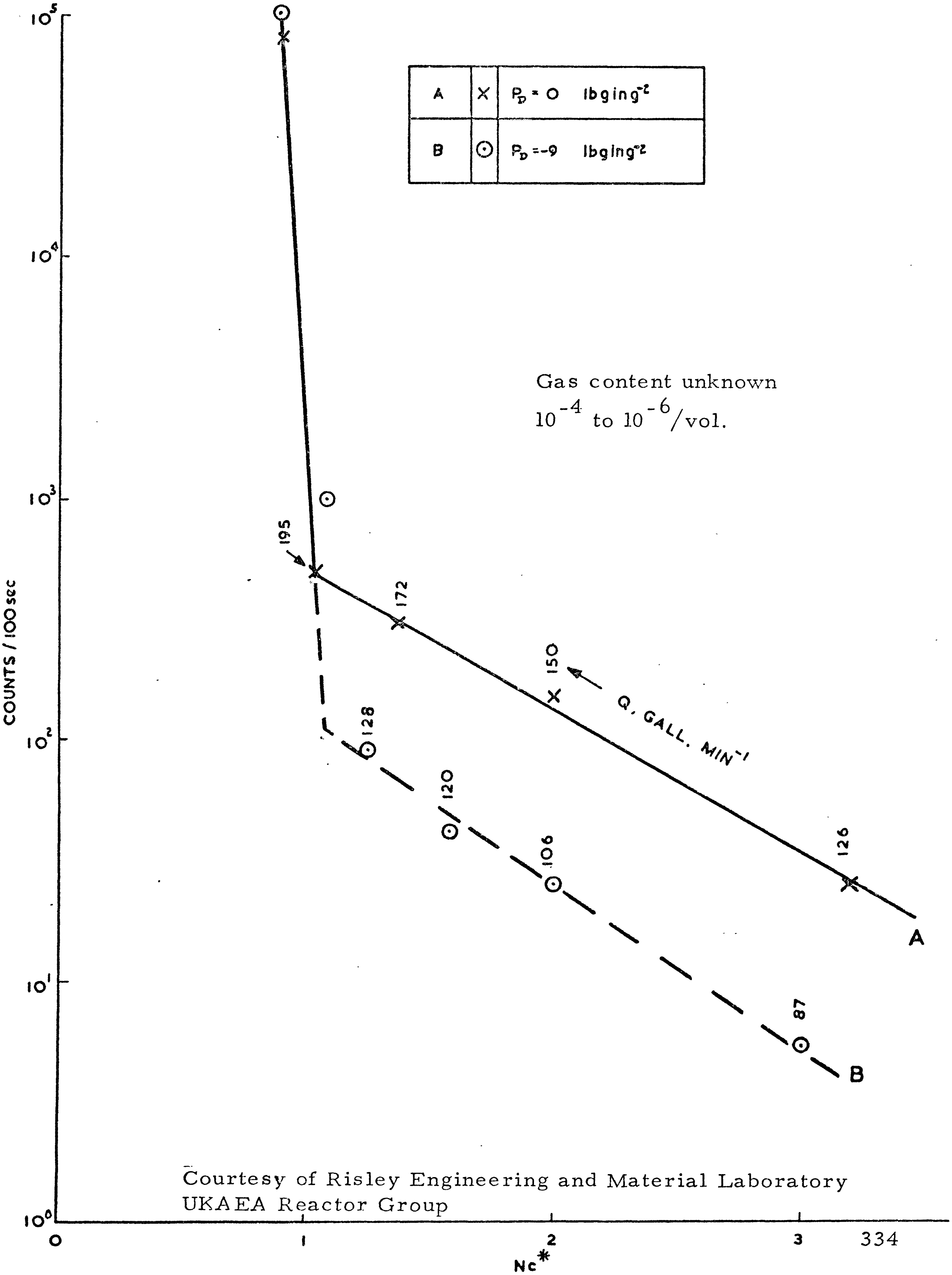
		LIQUID	TEMP	Q g.p.m.	Pd lb.in^{-2}g.
A	×	WATER	20°C	285	VARIABLE
B	⊙	SODIUM	300	147	VARIABLE
C	△	SODIUM	300	VARIABLE	0

Water has very low air content
(~ 10^{-6}/vol.)

Na gas content unknown
10^{-4} to 10^{-6}/vol.

Courtesy of Risley Engineering and Material Laboratory
UKAEA Reactor Group

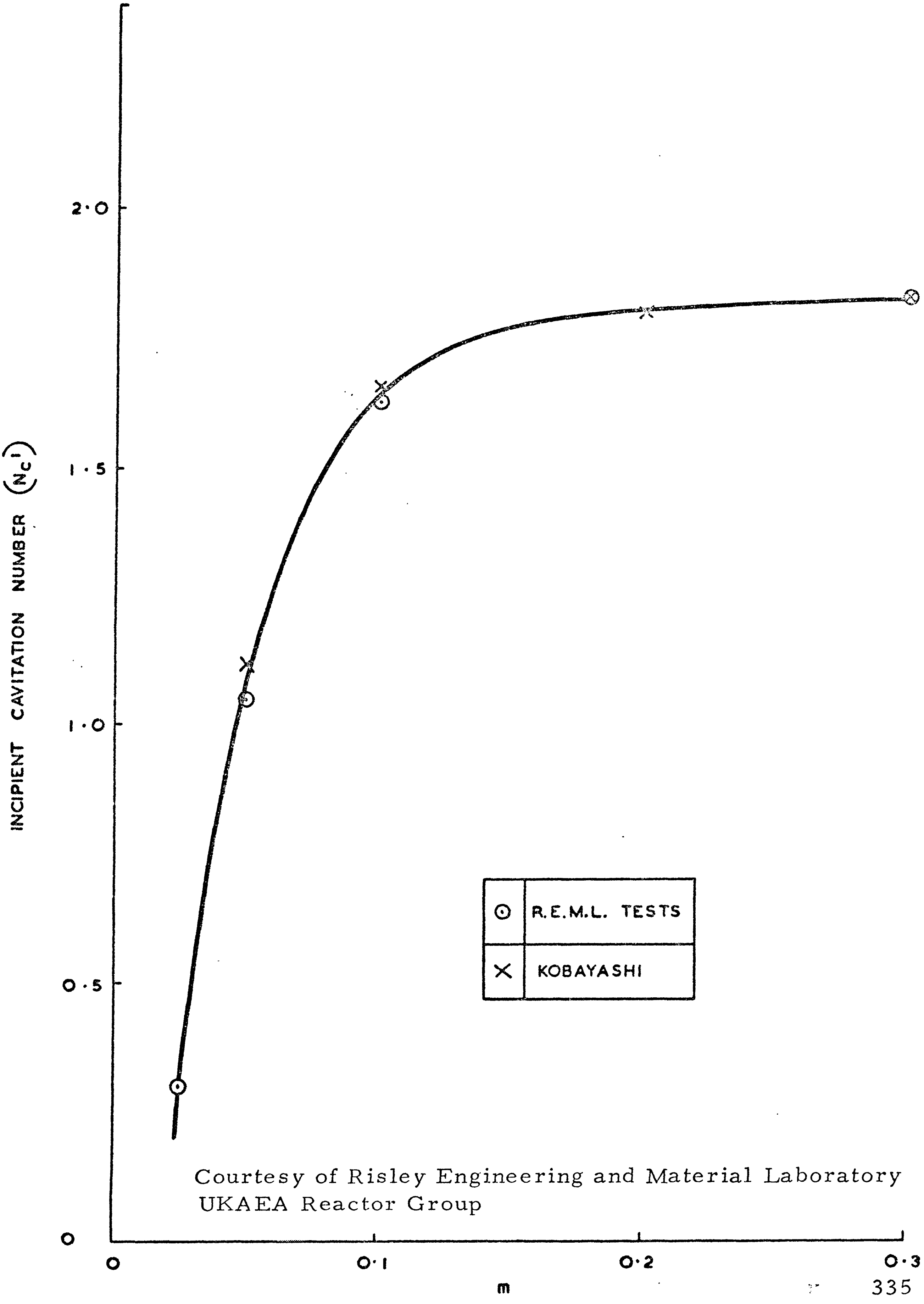
FIG. 5 CAVITATION CHARACTERISTIC OF I.S.A. NOZZLE IN SODIUM AND IN WATER (m = 0·05)



Gas content unknown
10^{-4} to 10^{-6}/vol.

Courtesy of Risley Engineering and Material Laboratory
UKAEA Reactor Group

FIG. 6, "VELOCITY EFFECT" FOR I. S. A. NOZZLE IN SODIUM AT 300 °C ($m = 0{\cdot}05$)



Courtesy of Risley Engineering and Material Laboratory
UKAEA Reactor Group

FIG. 7 INCIPIENT CAVITATION (N_c') NUMBER VS. m FOR I.S.A. NOZZLES