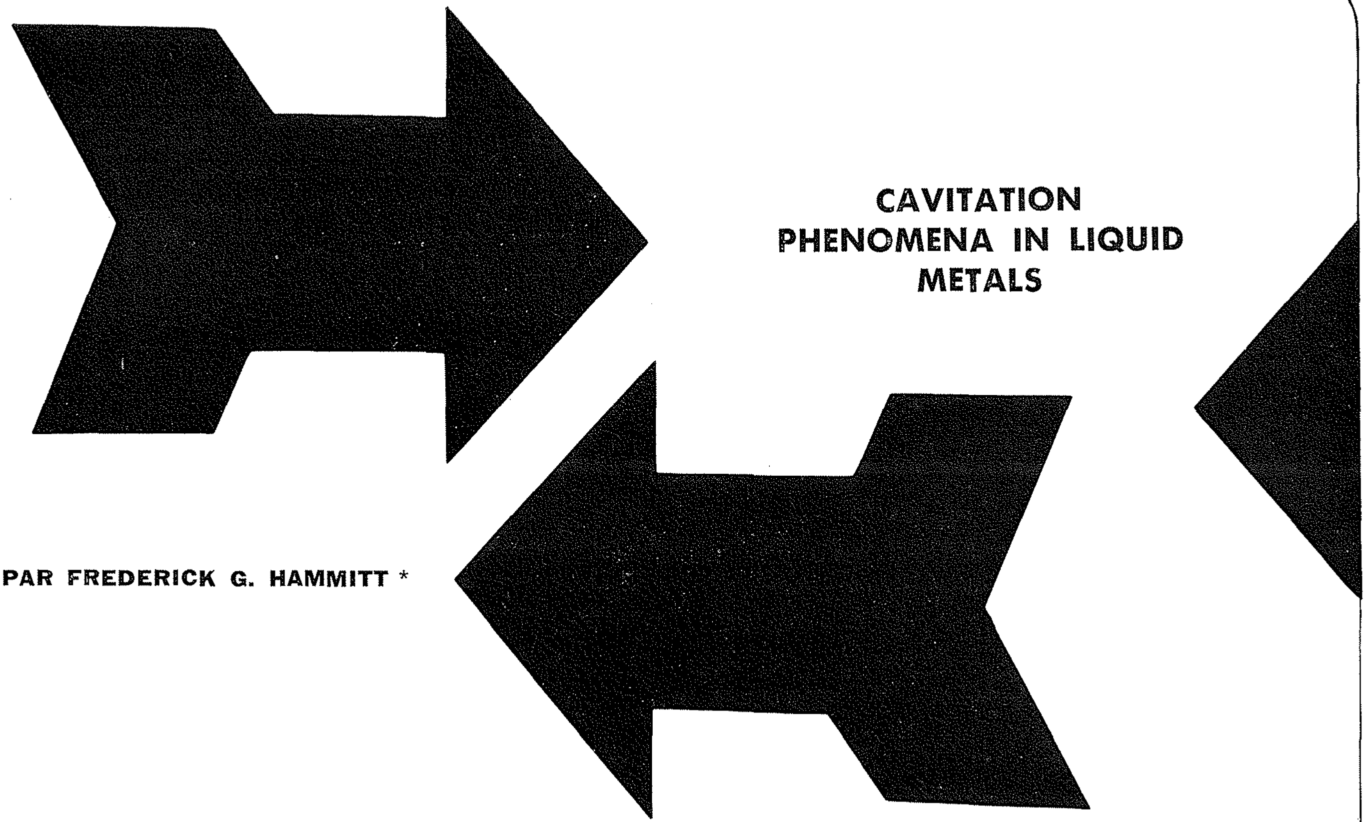

CAVITATION PHENOMENA IN LIQUID METALS

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Introduction

Problems of cavitation have been important in liquid metal fluids at least since the early 1950s when, to my personal knowledge, it was necessary to design high temperature centrifugal pumps for sodium and sodium-potassium alloy of minimum size and weight for the aircraft nuclear powerplant project then under development in the United States. It became quickly evident that cavitation would impose limits on the possible miniaturization of this equipment. It was also evident that it was not known whether or not cavitation could be expected under the same conditions under which it would occur in water, or, if it did occur, whether or not cavitation damage would be an important problem. This latter issue assumed particular importance since a relatively short life, as compared to ordinary industrial practice, was required of the equipment. Although research progress has been made in the intervening years, one must admit that the same questions remain largely unanswered today.

During the late 1950s and early 1960s liquid metal cavitation received renewed interest in the United States in connection with the development of several types of space nuclear powerplants (SNAP systems) for the production of electrical power aboard space vehicles. Some of these were to use liquid metal Rankine cycles to convert the heat energy from a nuclear reactor to mechanical energy. As for the aircraft nuclear powerplant, the miniaturization of the pumps associated with these Rankine cycles and with the reactor coolant circuits is limited by cavitation and the questions cited above in connection with the aircraft nuclear plant are still pertinent. The problem was aggravated in SNAP since long, unattended life was required. The liquid metals involved include mercury, sodium, potassium, and lithium.

Liquid metal cavitation research in the United States has been conducted at several government laboratories and industrial concerns, and also at the author's laboratory at the University of Michigan.

At the present time, new important interest have arisen with regard to liquid metal cavitation in connection with sodium-cooled fast neutron breeder reactors. These are discussed in the next section.

Cavitation and related phenomena problems with fast neutron breeder reactor

A. "Noise problem".

A present safety concept in many fast reactor designs is that "boiling noise" should be detected and used as a signal to activate safety circuits and

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shut down the reactor if necessary. In the ordinary operation of such a reactor boiling does not occur, and its occurrence would signal either the blockage of a sodium passage in the core with consequent over-heating of the fuel elements in that vicinity, or perhaps a power surge due to some perturbation of the nuclear reactivity. In either case, failure to promptly shut down the reactor after boiling had started could result in fuel melt-down and consequent release of fission products. If boiling did occur it would likely be of highly subcooled type.

It is well known that both subcooled boiling and cavitation bubble collapse present an essentially "white noise" over a considerable frequency spectrum, with substantial intensities out to very high frequencies. Hence the detection of either usually involves a filtering of low frequency to avoid masking by ordinary machine noise from the pump bearings, etc., so that the high frequency components alone are detected as the signal from bubble collapse. Since it may be very difficult to distinguish boiling noise from cavitation noise in the proposed reactor noise detection system, it may be necessary to eliminate cavitation completely from pumps and all other system components.

A requirement of absolutely no cavitation bubble nucleation or collapse in the centrifugal pumps of the sodium system may be difficult and expensive to achieve in that it may force a highly over-conservative design. In nearly all cases in the past a pump has been considered cavitation-free if there were no measurable effects on pump head and flow, and experience has usually shown that if this condition were met cavitation damage also would not be a problem. However, it has been shown in tests using a transparent casing that even that very carefully designed pumps and well-smoothed blades cavitation bubbles are visible at a much higher NPSH than that which corresponds to the initiation of head drop [1]. In fact it is in many cases possible to design a centrifugal pump to operate without prohibitive cavitation from the viewpoints of either head loss or damage at a suction specific speed of the order of twice that at which consideration of the probable pressure coefficients of the blades would indicate the formation of bubbles. For cases such as rocket pumps where cavitation damage is not usually a problem due to short life requirements, it is possible to operate with suction specific speeds several times higher than that common for industrial pumps (such as boiler feed pumps).

The question then arises with regard to the sodium pumps for fast breeder reactors whether or not it is in fact necessary to avoid all bubble collapses in order to achieve a reliable boiling noise detection system. The answer of course involves various presently imponderable items such as the attenuation of sound in sodium as a function of frequency, distance, geometry, void fraction etc., the precise details of the sound spectra from both boiling and cavitation as they will actually occur in the system, etc. Much research on these problems is apparently necessary.

In addition to pumps, there is the possibility of cavitation from such components as orifices and pressure-drop devices designed to adjust the flow in the various reactor passages in accordance with the heat flux distribution, from seals which may not be quite tight and which may allow some downstream pressure recovery so that vapor pressure may exist in the seal itself even though the downstream pressure is considerably greater, etc.

B. "Sodium superheat" problems.

In many boiling tests sodium and other liquid metals have sometimes exhibited considerable tensile strength in that they do not boil without the application of considerable superheat above the saturation temperature. In fact, in a recent test here at Chatou, relatively impure sodium exhibited a superheat requirement of about 40 °C when boiling under an imposed pressure of one bar of argon [2] and the observation of similar and even larger superheat requirements at other laboratories have become relatively common.

The sodium superheat problem itself has many important implications with regard to fast reactor safety and the assurance of prompt voiding of a region of the core in case of local overheating, so that the assumed negative void reactivity coefficient can come into play. However, the existence of the same phenomenon has important implications for sodium cavitation as well. If substantial "sodium superheat" can be relied upon under reactor conditions, it would perhaps not be possible to obtain cavitation in the circuit under ordinary operating conditions so that the previously discussed cavitation "noise problem" would not exist. This condition might obtain only if the sodium were extremely free of entrained microbubbles of gas since otherwise it is not possible that the fluid could exhibit substantial tensile strength. This fact has been recently demonstrated in recent tests with sodium in an electromagnetic pump at Oak Ridge in the United States [3, 4]. When an argon blanket was used in the loop pressurizer in the conventional way, it was found that the EM pump cavitated approximately as expected. When the argon blanket was replaced by sodium vapor, locally heated, as the pressurizing fluid, it was found that the pump could not be caused to cavitate within the operating limits of the equipment.

C. Related choking-flow problem.

Related to the bubble nucleation and sodium superheat problem areas is that of the choked flow condition which may result from the consequent two-phase medium. If boiling does occur in a fast reactor core due to local overheating it is anticipated that the void region will grow rapidly and that the "negative void coefficient" of the reactor will then cause a reduction of nuclear reactivity and hence heat flux, hopefully preventing more serious consequences. However, it is well known that the sonic velocity in a two-phase mixture of even small void fraction may be reduced by orders of magnitude from that of the pure liquid. If the sonic velocity is taken as the maximum velocity of flow in such a region, then the voiding of the affected region may not be able to occur with sufficient rapidity.

On the other hand in the event of rupture, the rate of outflow may be significantly restrained by the same mechanism. This can be perhaps more important with the water-cooled than with the sodium-cooled reactors. Thus another problem area requiring major research efforts closely related to those phenomena occurring in cavitation is defined.

D. Cavitation damage.

According to present concepts cavitation damage is not likely to be a major problem in sodium fast breeder reactors, since apparently the design of pumps and other components will have to be such, as already discussed, that even slight cavitation does not occur.

Detailed theoretical considerations

A. Liquid tensile strength.

As previously discussed, liquid tensile strength, or superheat requirement, is a most important parameter in determining whether or not cavitation or boiling will occur under given conditions. The usually accepted mechanism for the generally observed fact of liquid rupture at tensile strength values many orders of magnitude below theoretical expectations is the presence of multitudes of microbubbles either carried along with the fluid or entrapped in crevices in the walls. For water, where there is a high solubility for the gases in question, it is usually postulated that these "gas nuclei" exist in non-wetted acute angle crevices either in the walls or in solid impurity particles within the liquid. Under such conditions the action of surface tension will cause the gas pressure within the "nucleus" to be less than the surrounding liquid pressure. Thus such gas nuclei will not be dissolved even though the liquid is undersaturated with the gas in question, since the equilibrium pressure difference between gas and liquid will increase as the bubble radius is decreased.

In sodium the above solid particle host mechanism may not be required to explain the persistence of microbubbles since the solubility for the pertinent gases in sodium is so small as not to be of importance in this respect. As demonstrated by the previously discussed Oak Ridge experiments [3, 4] the effectiveness of microbubbles in reducing tensile requirements in the liquid, and hence presumably the number of microbubbles present, is very largely a function of the specific loop arrangement. Judging from the ease with which sufficient microbubbles to destroy the tensile capability of the sodium apparently penetrated the system from the argon free surface in this case, it seems unlikely that such adequate numbers of microbubbles will not also be present in systems using sump-type centrifugal pumps with the usual free surface, or where there is some other large free surface as in the reactor vessel.

In water systems there is difficulty in obtaining a measure of entrained gas content, as distinct from dissolved gas, since only the total gas content can be measured in a relatively feasible manner, and the entrained gas is generally only a very small portion of the total. This problem may not exist in sodium since the dissolved portion can probably be considered negligible in this case. However, there is still a difficulty in obtaining easily even total gas measurements in sodium, whereas this measurement is easily obtained in water.

Even if precise entrained gas measurements could be obtained for any fluid it would still be no simple problem to determine from this the effective tensile strength of the fluid when exposed to highly transient underpressures or superheats. Hence it may be necessary to "calibrate" the sodium (or other fluid) in situ. Such an approach is presently contemplated here [5] using a venturi in a bypass loop. The writer's laboratory at the University of Michigan has recently undertaken a program to obtain similar results with sodium and other fluids using a vibratory cavitation facility.

B. Thermodynamic parameters.

It has become generally accepted that cavitation bubble growth and collapse become increasingly subject to thermal restraints, as the fluid approaches its boiling point, i.e., as the "sub-cooling" is reduced from the viewpoint of the heat transfer engineer, so that under these conditions inertial restraints, which are entirely predominent for the fluid under "cold" conditions, become relatively less important. Under those conditions where thermal restraints are important, both growth and collapse are inhibited so that for a given NPSH both cavitation performance and damage effects may become less important. This situation was first emphasized by Stepanoff [6] who proposed a "thermodynamic parameter", B, which related the volume fractions of vapor and liquid in a cavitating regime, assuming thermal equilibrium conditions to apply. Partially because of the neglect or rate effects, the numbers derived from the Stepanoff parameter may not be quantitatively meaningful, although the trends predicted to apply. A much more rigorous derivation has more recently been used by Florschuetz and Chao [7] resulting in a somewhat modified parameter. In the writer's laboratory in the University of Michigan we have still further modified the parameter to include rate effects in such a way that a thermodynamic effect correction to cavitation damage data can be applied [8]. A large amount of data was obtained from our own laboratory and some from elsewhere [9] for vibratory cavitation tests on a variety of liquid metals (mercury, sodium, lithium and lead-bismuth alloy) in most cases at 500 and 1 500 °F. It was found that in many cases there was no thermodynamic damage effect, but in the cases of sodium and lithium at 1 500 °F there was a very large damage reduction due to this effect. For sodium at 500 °F there was no effect, so that the temperature at which thermodynamic restraints become important with sodium is probably about 1 000 °F. Hence it is probable that the damaging capability of sodium under fast reactor conditions will not be greatly reduced due to thermodynamic restraints.

C. Other fluid properties.

Generally the variation of other fluid properties between reactor temperature sodium and room temperature water does not appear great enough so that large differences in cavitation damage or performance reduction capabilities between the two fluids would be expected, assuming that the choice of materials is such that chemical effects do not become important. To summarize, some of the pertinent parameters are:

1. *Bulk modulus.* — This is probably the most important of the remaining parameters with respect to damage. It is the order of a factor of 3 greater for sodium than for water so that some additional damage might be expected from sodium on this account.

2. *Surface tension.* — About twice that of water. This would tend to inhibit nucleation and bubble growth with sodium, but detailed numerical calculations of bubble collapse indicate that it would probably not have much effect on collapse violence [10, 11] for a given size of bubble. It might retard nucleation in sodium so that the maximum bubble radius and number of bubbles would be reduced thus perhaps reducing damage.

3. *Viscosity and density.* — Both are about equivalent to warm water. Hence both kinematic and absolute viscosity of sodium are also about equivalent to these parameter for warm water.

D. Cavitation damage.

Present rough indications are that for materials of similar properties reactor temperature sodium and room temperature water would have relatively similar damaging capabilities [8, 9]. The change in material properties between room temperature and reactor temperature, however, may be of much greater importance than the difference between these two fluids, if ambient temperature water tests are to be used to predict damage in high temperature sodium. The previously mentioned University of Michigan damage study [8] using data from a vibratory facility showed that the statistically best correlation between damage and material properties was achieved in terms of "ultimate resilience", as first suggested by Hobbs [12]. Ultimate resilience is simply the area under a stress-strain curve if elastic strain continued until the breakings stress is reached, i.e., ductility apparently does not play a large part in cavitation-induced material failure. The regression analysis utilized with this data showed a best fit as follows:

$$\text{volume loss} = C_1 \, [C_2 + C_3 \, (\text{ultimate resilience})^{-1/2}]$$

where C_1 is the previously discussed correction for thermodynamic effects. Numerical values for C_1, C_2 and C_3 are given in the paper [8].

Engineering results with sodium cavitation

There are a few applicable engineering results on cavitation effects with liquid metals which have been published. Generally these lead to the conclusion that warm water tests provide at least a reasonable approximation of cavitation performance effects to be expected in the same component with reactor temperature sodium. If it occurs that sodium superheat is an important phenomenon in reactor loops, such water tests would be conservative, in that if the unit cavitated with water it might not cavitate with sodium.

There is still insufficient evidence, in the writer's opinion, to conclude that water damage tests can be considered meaningful with respect to sodium damage. However, there does not seem to be order of magnitude differences between the damaging capabilities of the two fluids. These and the above conclusions are somewhat verified by the reported engineering results mentioned below.

The experiences with an EM pump at Oak Ridge [3, 4] with respect to the possibility of sodium superheat applying to cavitation have already been discussed.

A cavitating test of a high-temperature potassium pump which had previously been tested very carefully in water under cavitating condition is reported from Pratt and Whitney Aircraft [13]. Cavitation occurred about as expected in potassium from the water tests. The noise level was similar and damage was observed in potassium after a test of several hundred hours (no extended damage test had been made in water).

The writer's laboratory at the University of Michigan has tested cavitating venturis in both water and mercury [14, 15]. In both cases it was found that the cavitation number for initiation was a strong function of Reynolds number and gas content, varying in similar fashion for the two fluids although the results did not fall on precisely the same curve.

Tests on cavitating liquid metal and also molten salt centrifugal pumps are reported in the literature [16, 17] from the Oak Ridge group. The cavitating behavior in the liquid metals and molten salts were normal and some damage was sustained after a prolonged test.

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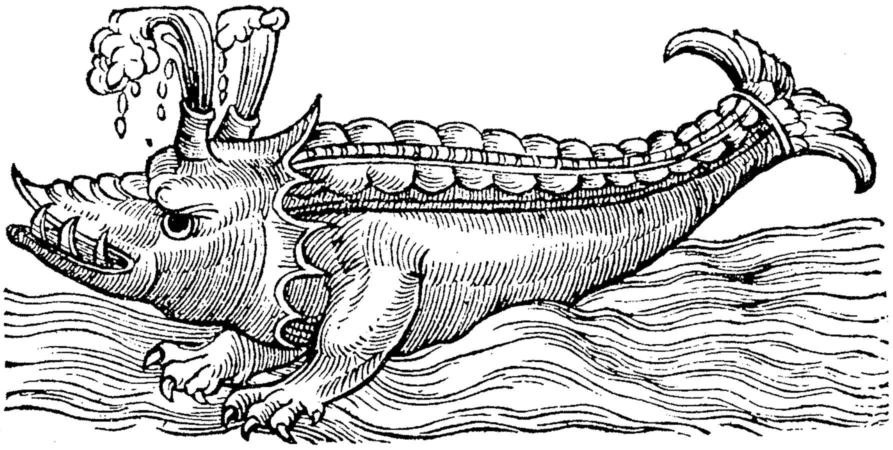

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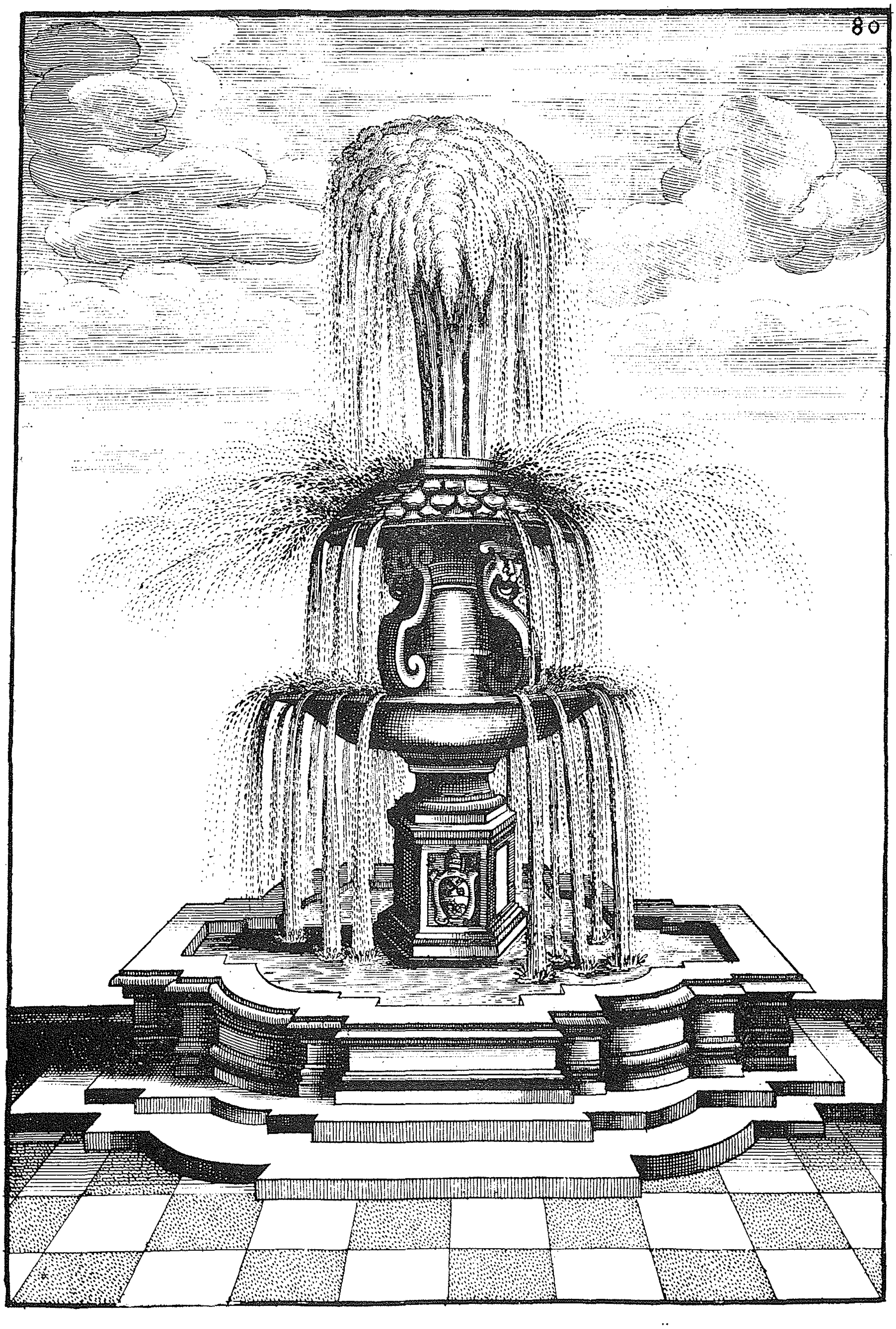

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