THE OPTIMUM PERFORMANCE OF SILVER-IODIDE SMOKE GENERATORS

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ABSTRACT

The ice-forming ability of silver-iodide smoke depends upon the size of the smoke particles in a way which can be calculated. From this relation, it is possible to find the maximum number of nuclei produced, per gram of silver iodide, which are active at a given temperature. Comparison of the performance of such an ideal generator with that of experimental burners shows that optimum performance is being approached in some cases.

1. Introduction

Because of the wide use being made of silver-iodide smoke as a cloud-seeding agent and the constant efforts being made to improve the performance of the smoke generators used, it seems helpful to have a theoretical estimate of the optimum performance which can be expected. It is the purpose of this paper to make such an estimate and to compare the results reported for various experimental burners with that for an ideal burner.

The most convenient criterion of burner performance is the number of nuclei produced, per gram of silver iodide burnt, which are active at a given temperature. When this quantity is specified at all points of the temperature range of interest, then the burner output is characterized. Additional considerations are decay of the nuclei in the atmosphere, output of nuclei per unit time, rate of consumption of other materials, and general operating ease and efficiency. Of these, only the decay effect will be mentioned further.

2. Silver iodide as an ice-crystal nucleus

We must first come to some conclusions about the way in which silver iodide acts as an ice-crystal nucleus. This has been treated in some detail in another paper [1] in which it is shown that silver iodide has a finite contact angle for water and is thus a poor condensation nucleus. Under ordinary conditions, it can therefore only act as a sublimation nucleus.

The action of small, approximately spherical particles with arbitrary surface properties as sublimation nuclei has been treated thermodynamically [2] and, from this treatment, curves for nucleation temperature as a function of size and surface properties can be derived. When these results are applied to idealized silver-iodide particles, the activity curve shown in fig. 1 is obtained. Experimental results verifying this curve have been obtained by Sano *et al* [3].

It may well be objected that though these results may apply to smokes of pure AgI, the output of a burner consuming a mixture of AgI and NaI is unlikely to behave in the same way. Indeed, Mason and Hallett [4] report finding no trace of hexagonal AgI in the output of such a burner. On the other hand, pure and "mixed" smokes are generally found to show the same threshold and general performance and the same order of size effect. We might make the assumption that mixed smokes consist of AgI-NaI mixed crystals which act as condensation nuclei, hydrolyze to give AgI suspensions, and then freeze. The experimental results, however, are adequately and much more simply explained by the alternate assumption that mixed smokes behave in exactly the same way as do pure smokes, and we shall adopt this as a basis for our calculation. This implies that either the surfaces of the smoke particles are essentially pure AgI or that any mixed crystals have essentially the same properties as pure AgI from the nucleation point of view.

3. Behavior of an ideal smoke

As the first type of ideal smoke, we shall consider one consisting of identical spherical particles. Once the particle diameter is specified, the number of

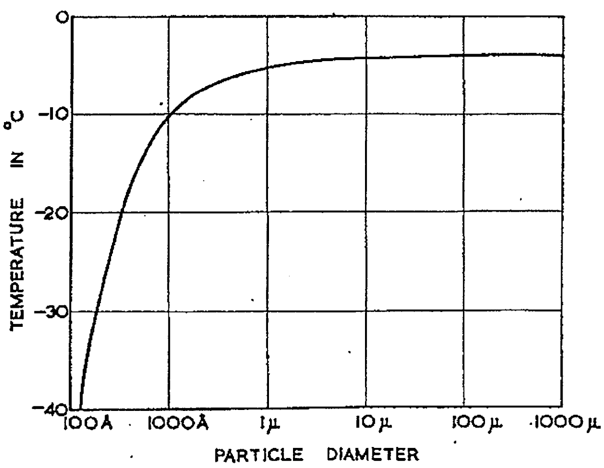

FIG. 1. The temperature at which a spherical AgI particle of given diameter will nucleate an ice crystal from a supercooled fog in 1 sec.

particles per gram of AgI is easily determined, and the temperature at which they act as ice-crystal nuclei in a supercooled fog can be found from fig. 1. The activity curve of such a smoke is given by the full line in fig. 2. In this case, the particle diameter was 1200 Å, giving a nucleation temperature of −10C.

The broken curve in fig. 2 gives the envelope of such activity curves. A homogeneous smoke from a perfect generator will give a right-angled distribution just touching some part of this curve. If the smoke is non-homogeneous or if the generator is imperfect, the activity curve must lie below this line.

In theory, it is possible to construct size distributions to reproduce any curve lying sufficiently below this theoretical maximum curve. We say "sufficiently below" since, if the activity curve comes very near the theoretical maximum at any one point, it must lie well below it at other points.

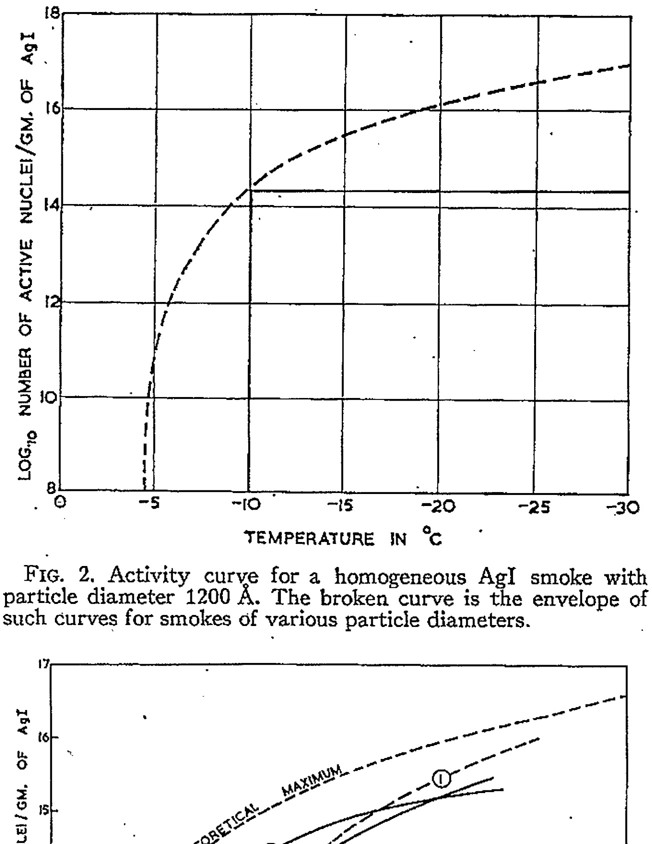

FIG. 2. Activity curve for a homogeneous AgI smoke with particle diameter 1200 Å. The broken curve is the envelope of such curves for smokes of various particle diameters.

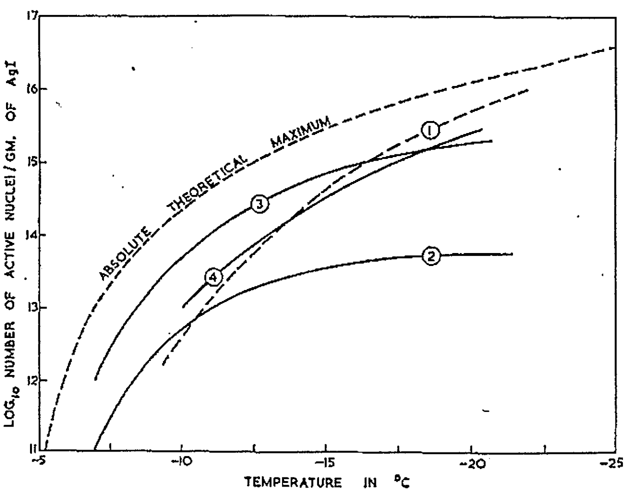

FIG. 3. Activity curves for experimental burners. 1. Vonnegut—hydrogen burner. 2. Smith and Heffernan—kerosene burner. 3. Smith and Heffernan—hydrogen burner. 4. Soulage—impregnated charcoal.

In practice, smoke-size distributions are usually such that the number of particles having a given diameter is distributed approximately normally when plotted against the logarithm of the particle diameter. This distribution restricts the number of both very large and very small particles, so that most smokes will show a saturation effect towards low temperatures, while at warmer temperatures they should roughly follow below the theoretical maximum curve.

4. Output of experimental generators

In comparing the output of real generators with our calculated maximum output, several things must be borne in mind. In the first place, measurements of output are often not of high accuracy because of fluctuations in the output and sampling technique. Secondly, the evaluation of the number of ice crystals counted depends upon the cold-box technique used and may not be of high accuracy. Systematic as well as random errors are often involved. The third point, which introduces a systematic error in the observations, is as follows. The theoretical activity curve is based on production of ice crystals after 1 sec, and most cold boxes sample for a longer time than this. The effect of this difference in technique and definition has been considered elsewhere [5] and has been shown to lead to an increase of a factor 2 to 5 in the number of ice crystals counted under typical circumstances. No correction has been made for this effect in the experimental data to be presented, but it should be borne in mind that the experimental numbers probably exceed their values on our definition by about this amount.

In fig. 3, we have plotted various published measurements on different types of burners. All these burners use a solution of AgI and either NaI or NH_4I in acetone, since simple evaporation of AgI usually produces rather large particles which are uneconomical. Vonnegut [6] burnt his solution in a hydrogen flame, and the data plotted are for a very fine smoke, shown by electron photomicrographs to contain few particles greater than 1000 Å in diam. This accords well with its nucleating behavior. The early kerosene burner of Smith and Heffernan [7] is seen from the figure to be rather inefficient, and the photomicrograph of its output suggests that this may be due to the formation of particle aggregates caused by incomplete burning. Their hydrogen burner, on the other hand, has a high output over the range −7C to −20C, and an approximate calculation suggests that it approaches ideal efficiency for a smoke distributed uniformly in volume over the size range defined by these temperatures. Soulage [8] has examined the output of several generators burning impregnated charcoal, and the best of these is shown in the figure. Its output tends to be weighted towards small diameters, as was Vonnegut's smoke.

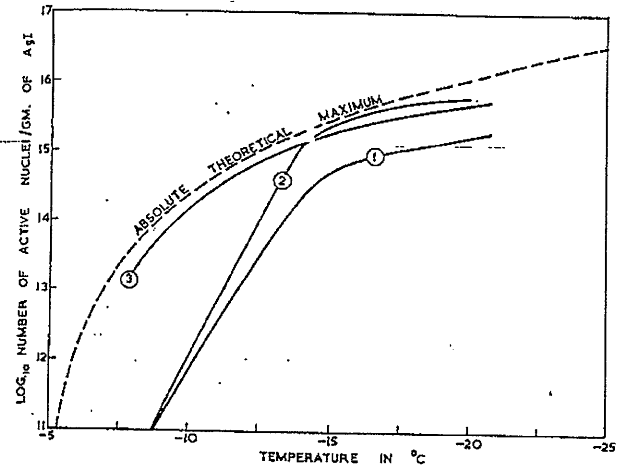

FIG. 4. Activity curves for experimental burners (Fuquay). 1. MRI propane flame. 2. MRI oxy-propane flame. 3. "Skyfire" burner.

Turning now to fig. 4, we show curves for three burners recently discussed by Fuquay [9]. Two of these burn AgI impregnated string, the first in propane and the second in an oxygen-propane flame. Both of these distributions are very sharply angled, indicating very homogeneous smokes, and the second reaches a very high efficiency, approaching the theoretical value. Both of these distributions have slightly too small particle size, however, if cloud seeding in the range −10C to −15C is contemplated. The "Skyfire" burner which burns solution in a chamber at about 1100C has a remarkably efficient output over the range −8C to −20C. The integrated output actually exceeds the theoretical value by about a factor 2, which can be accounted for by the measurement effect discussed above, if the results are accepted as otherwise accurate.

5. Photo de-activation of silver iodide

An important characteristic of silver-iodide smoke is that its efficiency as a nucleating agent is decreased by prolonged exposure to ultraviolet light. Since the actual nucleation act may not take place for as much as an hour after release of the smoke into the atmosphere in some cases, the rate of decay under such conditions is very important.

There is absolutely no general agreement on the magnitude of this decay rate, and the evidence seems to show that it is strongly dependent on the exact means used to generate the smoke. For example, Smith, Heffernan, and Seely [10] found that while the number of active nuclei in the smoke of their kerosene burner fell by a factor of 10 after one hour's exposure to sunlight, the number of active nuclei in the smoke from the hydrogen burner fell by a factor of 10^3 in half an hour. This led to preferred use of the kerosene burner despite its lower initial output.

Measurements [11] under free-air conditions on the "Skyfire" burner described by Fuquay [9] show that the decay rate for this particular burner is probably less than a factor of 10 per hour. This burner is thus apparently very efficient on all counts.

The mechanism of this photo de-activation has been discussed in another publication [12]. The de-activation rate depends in a rather complex way upon the chemical composition and size distribution of the smoke and may be considerably influenced by details of burner design and operation.

6. Conclusion

We have derived a curve for maximum possible burner output and compared it with the output of several types of experimental burners. This comparison shows that some modern burners are close to ideal in efficiency.

Efficiency is not, however, the only consideration. It is desirable to concentrate as much as possible of the burner's output into the temperature range most useful for cloud seeding under the existing circumstances. Comparison of the output of a burner with the ideal curve shows to what extent its output can be improved in the range of interest.

Other factors, particularly the rate of decay of the smoke in the free atmosphere, are also of great importance and must be considered when the performance of a burner is being assessed.

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