Performance Characteristics of Various Artificial Ice Nuclei Sources

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ABSTRACT

A variety of devices that produce artificial nuclei have been used in weather modification experiments. These fall into two broad classifications, i.e., pyrotechnics and steady-state flame-type generators.

The effectiveness-temperature relationships for these classes were measured and are presented in graphical form. In summary, the steady-state systems are in general one order of magnitude more effective than the pyrotechnics at temperatures below −12C. Above this temperature, the effectiveness of the pryotechnics approaches and in some cases exceeds that of the steady-state systems. These different characteristics can be explained by particle size effects.

Other performance parameters are examined. Air-fuel ratio is one of these since effectiveness varies markedly near the stoichiometric air-fuel ratio for steady-state systems. A system which employs isopropylamine as the AgI carrier is more sensitive to changes in air-fuel ratio than the NaI-acetone AgI carriers. Another important performance parameter is AgI burn rate. In general, the effectiveness of a pyrotechnic decreases rapidly and then levels off as the burn rate increases. This same effect has been observed in steady-state systems.

1. Introduction

The development of devices to produce artificial nuclei for weather modification research is an important activity since different types are needed to examine modification effects. These vary from low output steady-state ($\simeq$ 10 gm hr^{-1}) to high output pyrotechnic ($\simeq$60,000 gm hr^{-1}) devices, the performance of which must be known to the particular experimenter employing it. Many performance measurements have been made and it is well known that the number of effective nuclei per gram of AgI from a given source is strongly dependent on the temperature. It is also known that the number of effective nuclei per gram of AgI is strongly dependent on the source. Other important factors are the method of measurement, shelf life and nuclei source parameters.

Certain facilities are required to adequately evaluate all of the parameters outlined above. These include a cloud chamber controllable over the temperature spectrum, a dilution facility, aerosol sampling equipment and an electron microscope as well as a host of other auxiliary equipment (Steele and Krebs, 1967).

These facilities were available at Colorado State University and in 1965 it was decided to propose a National Test Facility for evaluation of ice nuclei sources. The National Science Foundation funded this in 1966 and since that time 80 devices have been tested for a number of private and federal agencies.

The purpose of this paper is then to compile the results of these evaluations as well as to explain the various performance characteristics of a number of ice nuclei sources. This will hopefully permit the user of these sources to select a device which will best suit his needs.

2. Devices evaluated

Both steady-state flame-type generators and pyrotechnics were evaluated. The former are listed in Table 1 as are the AgI complexes employed, the supporting fuels, and the AgI burn rates. Most of the pyrotechnic samples which were tested are listed in Table 2, along with the AgI concentrations and AgI burn rates.

3. Results

The test procedure used on all devices was that described by Steele and Grant (1966) in which an evaluation is made of the following performance parameters:

a. Effectiveness vs temperature
b. Effective nuclei min^{-1} vs temperature
c. Effectiveness vs air-fuel ratio
d. Effectiveness vs burn rate

These are discussed below.

a. Effectiveness vs temperature. The effectiveness-temperature curves for the steady-state flame type generators are shown in Fig. 1, while those for the pyrotechnics are given in Fig. 2. It can be seen that the CSU (Colorado State University) research generator using a solution of AgI in NH_3 produces the highest effectiveness measured at −8C. On the other hand, the Howell String generator produces the highest effectiveness measured at −20C.

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TABLE 1. AgI complex, supporting fuel and AgI burn rate for various steady-state systems.

Generator	Complex used	Supporting fuel	AgI burn rate (gm AgI min^{-1})	Reference
N.A.W.C.—Acetone[a]	2% AgI & $\frac{2}{3}$% NaI in acetone	Propane	0.10	—
Bollay Skyfire[b]	2% AgI & $\frac{2}{3}$% NaI in acetone	Propane	0.10	Fuquay and Wells (1957)
IAS—IPA[c]	3% AgI in isopropylamine	None	0.35	Steele (1966)
CSU Skyfire	3% AgI in isopropylamine	Propane	0.40	—
CSU—IPA (natural draft)	3% AgI in isopropylamine	None	0.40	Steele (1966)
Lohse-Airborne[d]	3% AgI & 1% NaI in acetone	None	4.50	—
Howell String[e]	—	Cord burned in propane flame	0.04	—
CSU Research	3% AgI in ammonia	#1 fuel oil	2.2	Steele and Sciacca (1966)
CSU Research	2% AgI & $\frac{2}{3}$% NaI in acetone	None	4.6	Steele and Sciacca (1966)
CSU Research	2% AgI in isopropylamine	None	4.3	Steele and Sciacca (1966)

[a] N.A.W.C.—North American Weather Consultants, Goleta, Calif.
[b] Bollay—E. Bollay Associates, Boulder, Colo.
[c] IAS—Institute of Atmospheric Sciences, Rapid City, So. Dakota.
[d] Lohse—Lohse, Valier, Montana.
[e] Howell—Wallace Howell, E. Bollay Associates, EG & G, Inc., Bedford, Mass.
Note: IPA has been used as an abbreviation for isopropylamine.

In general, at −20C, the effectiveness of the pyrotechnics has been found to be at least one order of magnitude less than that found for the steady-state systems. At temperatures of approximately −12C, the effectiveness of the pyrotechnics approaches and in some cases exceeds that of the steady-state systems.

This variation between pyrotechnics and steady-state systems can be explained in part by differences in the particle size distribution of the two systems. This discussion applies in particular to the Bollay Skyfire generator and the ARC (Atlantic Research Corporation) 5-67.5 pyrotechnic. However, with few exceptions the conclusions can probably be applied in general to the various nucleating devices that were tested. These are broken down as follows:

1. Bollay Skyfire. The Bollay Skyfire produces AgI particles which have an average size of 0.04 μ. The maximum AgI particle size observed was 0.2 μ and the minimum 0.01 μ. The theory of Fletcher (1959) and the experimental work of Sano *et al.* (1956), as reported by Fletcher, indicate that particles less than 0.05 μ do not become active until the supercooled cloud temperature is below −10C.

If the above statement is true, one would expect the effectiveness of this generator to be high at temperatures lower than −10C because about 90% of the AgI particles produced by the Bollay Skyfire generator are less than 0.05 μ in diameter and a large number of particles ($10^{15}-10^{16}$) are produced per gram of AgI. According to the above references, particles $<0.05\ \mu$ should not be active at temperatures >-10C and one would thus expect a sharp decrease in effectiveness at the warmer temperatures; that this is the case is shown in Fig. 1.

2. ARC-5.67.5 pyrotechnic. The particle size produced by this pyrotechnic is roughly 3.0 times the particle size found for the Bollay Skyfire generator, i.e., the average particle size produced by this pyrotechnic is 0.13 μ. The maximum size observed was 2 μ and the minimum 0.05 μ. Therefore, 1 gm of AgI burned in the Bollay Skyfire system can produce 30 times more particles than 1 gm of AgI burned in the ARC 5-67.5 pyrotechnic assuming spherical symmetry in both cases. At −20C, where nearly all of the AgI particles are active, the effectiveness of the Bollay Skyfire would be expected to be at least 30 times that of the ARC pyrotechnic. In Fig. 3 it can be seen that the difference is actually about a factor of 80 which is reasonably good agreement considering the errors involved in sampling and particle size measurement.

It should be noted that the average, maximum and minimum particle sizes quoted for the Bollay Skyfire generator and the ARC 5-67.5 pyrotechnic were obtained from electron photomicrographs. A thermal precipitator was used to collect the AgI particles on an electron microscope grid. This precipitator was designed by CSU personnel and is perhaps unique in that the particles are deposited symetrically about the center of the collection plate. This device also collects >99% of the effective AgI nuclei. It also collects particles as small as 0.005 μ.

TABLE 2. AgI composition and AgI burn rate for various pyrotechnics.

Pyrotechnic	AgI (%)	AgI burn rate (gm AgI min^{-1})
ARC 5-37.5[a]	37.5	2.5
ARC 1-20M-45A	37.3	4.5
ARC 5-67.5	67.5	10.0
ARC 15A	63.1	150.0
NAVY 10% AgI—1% LiI[b]	10	1.5
NAVY CY-49	12.5	1.7
NAVY LW-83	69.0	150.0
OLIN Group #3[c]	—	1.0
OLIN M2-B-1	—	15.0
OLIN HSI	20	10.0

[a] ARC—Atlantic Research Corporation, Alexandria, Va.
[b] NAVY—Naval Weapons Center, China Lake, Calif.
[c] OLIN—Associated Products Operations, East Alton, Ill.

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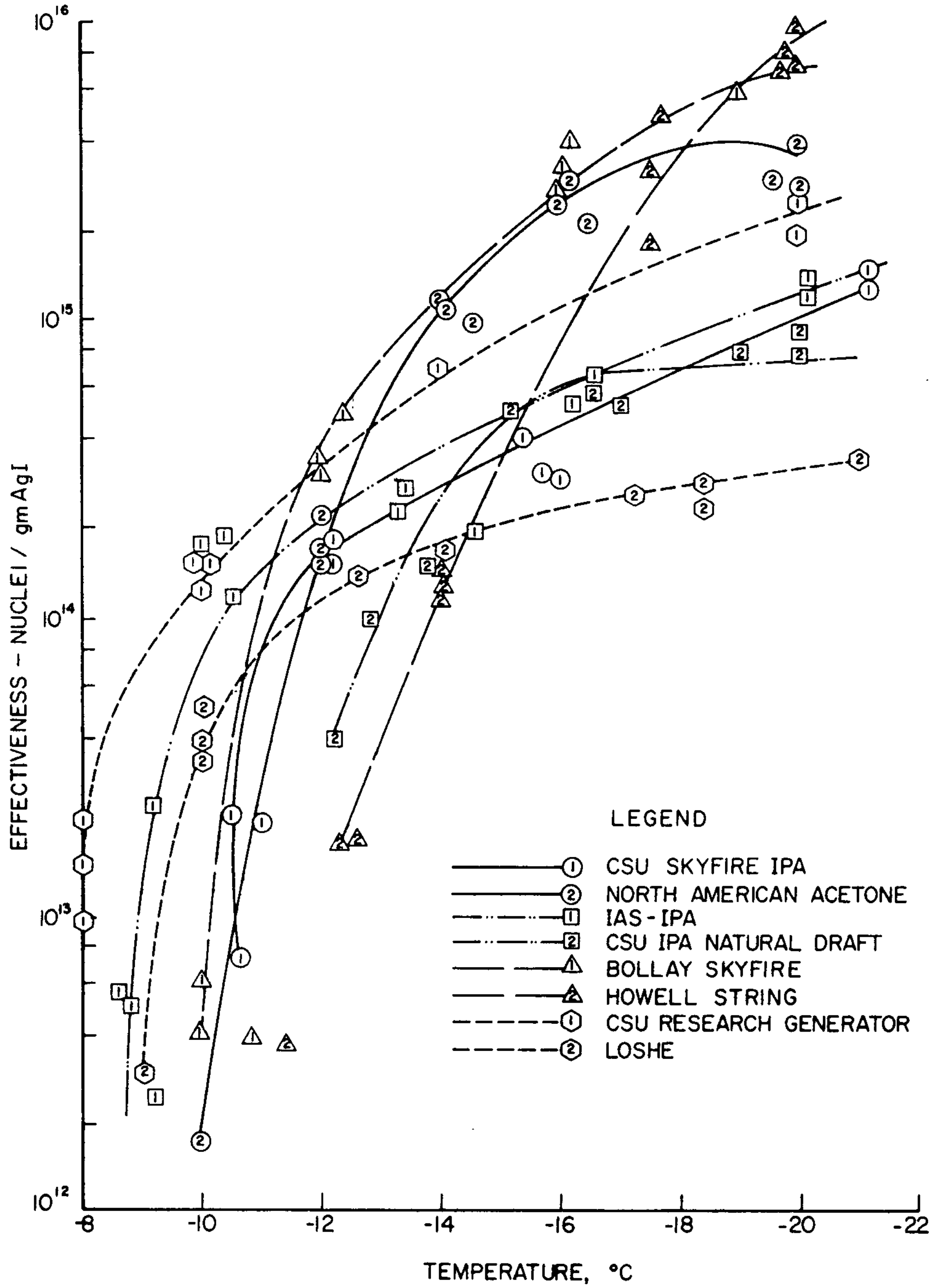

Fig. 1. The effectiveness-temperature relationships for various steady-state generators.

From Figs. 1 and 2 it appears that larger particles not only cause a lower effectiveness at the colder temperatures, but also cause the effectiveness to be less sensitive to temperature. From Fig. 1 it is seen that the effectiveness of the Bollay Skyfire varies three orders of magnitude from −20 to −10C. However, Fig. 2 shows that over the same temperature range the effectiveness of the ARC 5-67.5 pyrotechnic varies slightly more than one order of magnitude. This is to be expected if Fletcher's theory regarding the variation of nucleation temperature with AgI particle size is valid. For example, if a generator were to produce AgI particles which were spherical, 0.025 μ in diameter, and monodispersed, the theoretical effectiveness-temperature relationship for this generator would be constant at temperatures $\leqslant -15$C and while at temperatures > -15C the effectiveness would be zero. For 0.05 μ particles the effectiveness-temperature relationship would be constant for

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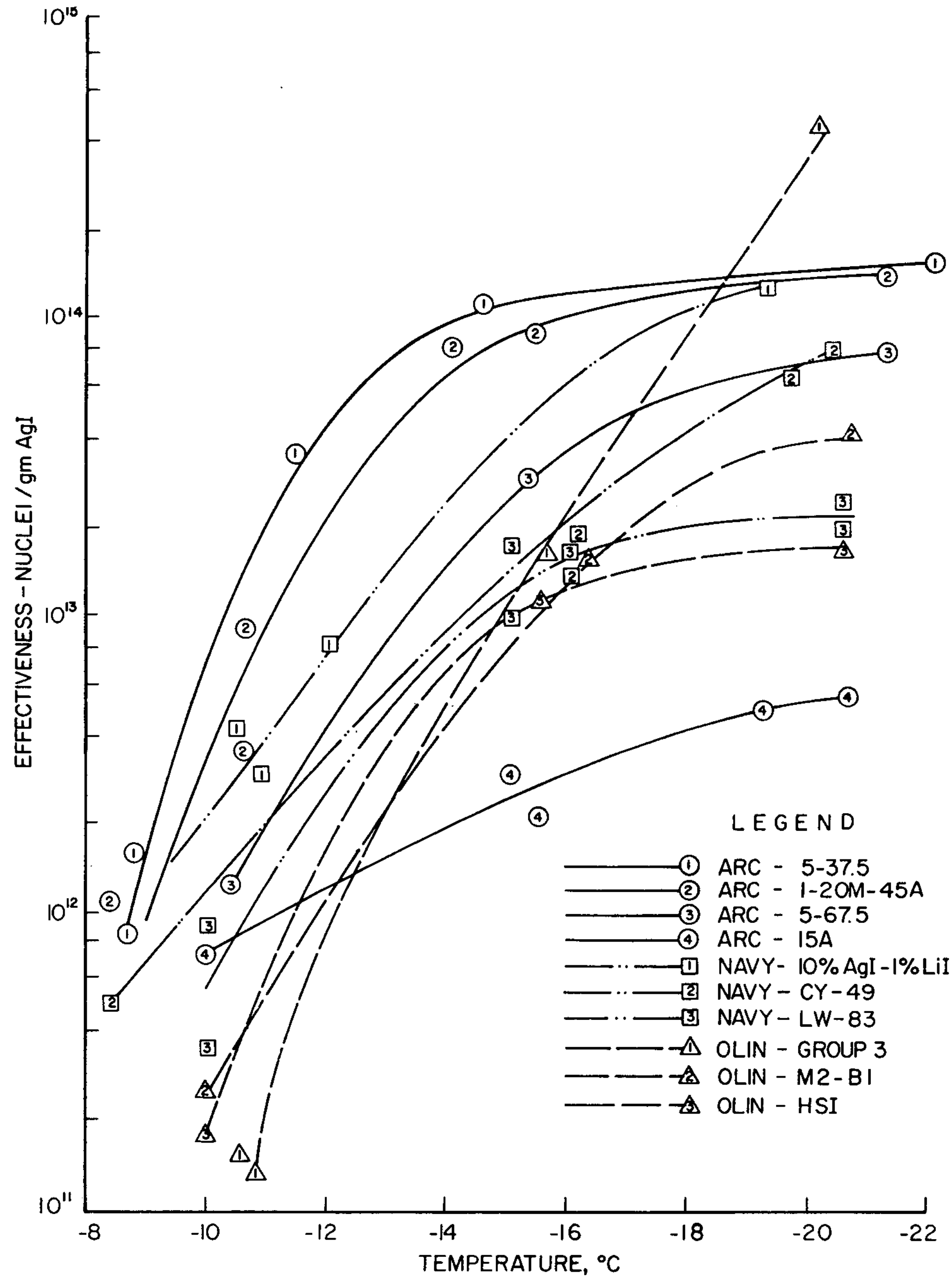

FIG. 2. The effectiveness-temperature relationships for various pyrotechnic type generators.

temperatures $\leqslant -10$C and would be zero at temperatures > -10C.

The above discussion is an abstraction. Obviously, the AgI particles produced by a generator are not all spherical nor are they of equal size. Consequently, variations of the curves shown in Figs. 1 and 2 are obtained. The above discussion does, however, give some insight as to why some generators are more sensitive to the temperature range than others. For instance, the Howell String generator produced the smallest particle size range of any nucleation device that was tested. This generator is also the most sensitive to the temperature range as is shown in Fig. 1. This is in good agreement with the above discussions.

For purposes of the above discussion, the writers attempted to choose a typical steady-state system and a typical pyrotechnic. It is known that particle size alone does not determine the effectiveness-temperature relation. However, with a knowledge of the particle size together with the work of Fletcher and Sano *et al.*, one

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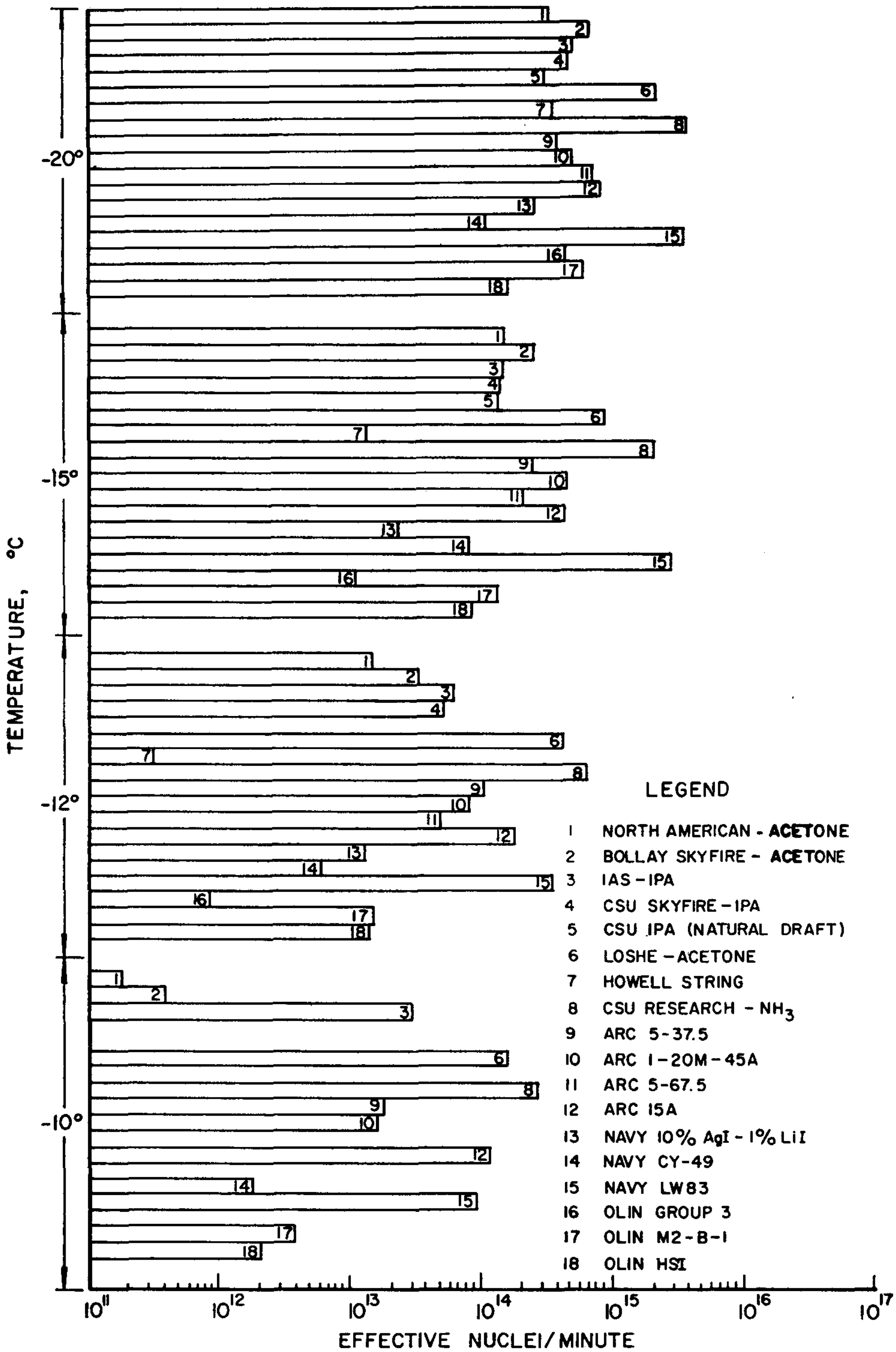

Fig. 3. Effective nuclei min^{-1} vs temperature for various steady-state and pyrotechnic generators.

can partially explain the variations in effectiveness-temperature relations from one generator to another.

b. Effective nuclei min^{-1} vs temperature. The effective nuclei min^{-1} parameter is important to those designing cloud modification experiments. The purpose of this section is to aid the designer of such an experiment in choosing the device that will optimize his needs. Fig. 3 shows the number of effective nuclei min^{-1} as a function of temperature for various steady-state systems and pyrotechnics.

At −20C both the Lohse generator and the Navy LW-83 pyrotechnic produce about 3×10^{15} effective nu-

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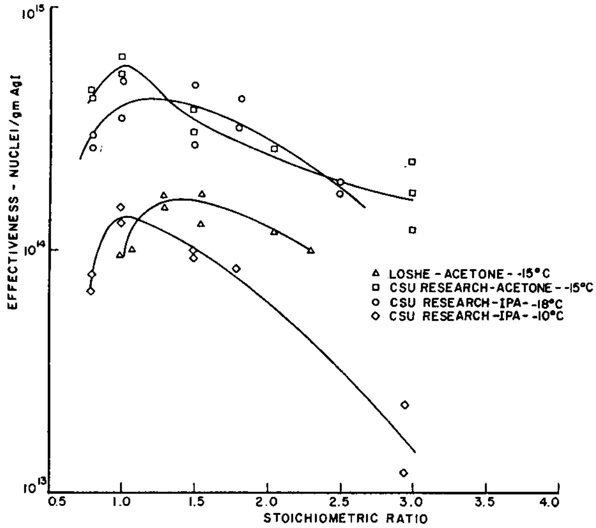

FIG. 4. Variation of generator effectiveness with stoichiometric ratio.

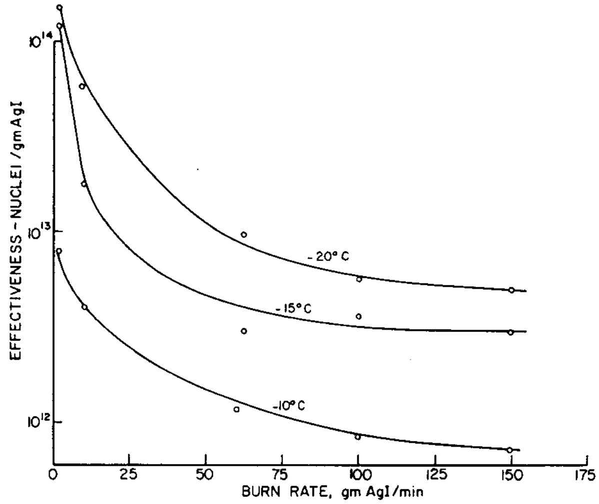

FIG. 5. Variation of effectiveness with AgI burn rate.

clei min^{-1}. However, the Lohse generator has a AgI burn rate of 4.5 gm min^{-1} while that of the LW-83 pyrotechnic is 150 gm min^{-1}. In other words, the LW-83 pyrotechnic must consume about 30 times as much AgI as the Lohse to produce the same number of effective nuclei min^{-1}.

At -10C the Bollay Skyfire produces 2×10^{11} effective nuclei min^{-1} while consuming 0.1 gm of AgI min^{-1}. The ARC 1-20M-45A pyrotechnic has a AgI burn rate of 4.5 gm min^{-1} and produces 2×10^{13} effective nuclei min^{-1}. In contrast to the first example, this shows that the device with the larger burn rate is the most efficient at -10C.

The above examples show that the device which is the most efficient at one temperature may not be the most efficient at another temperature. No general statements concerning efficiency in terms of effective nuclei min^{-1} can be made. The present state of the art is such that conclusions about optimization of given nuclei sources can only be reached after the particular source has been evaluated by experimental means. The above examples also show that the time rate of production of nuclei is just as important as the production per gram.

c. Effectiveness vs air-fuel ratio. The results illustrating the effect of air-fuel ratio on generator performance are shown on Fig. 4 for two types of generators using two different AgI complexes. These results show that the effectiveness is a maximum near the stoichiometric[1] air-fuel ratio. It decreases if the air-fuel ratio is markedly greater than or less than the stoichiometric ratio. This agrees with previous work at CSU (Steele and Sciacca, 1966) and with the work of Fuquay and Wells (1957). The hypothesis regarding some specifics concerning these effects are in order. It can be seen from Fig. 4 that the solution of AgI in isopropylamine (IPA) appears to be much more sensitive to air-fuel ratio than the solution of AgI and NaI in acetone. The hypothesis proposed for the explanation of this occurrence is as follows.

As stoichiometric ratios greater than or less than 1.0 the IPA is not completely burned. This results in the possible presence of IPA vapor in the air stream which inhibits the nucleation process.[2] The presence of this vapor may partly explain the fact that the IPA-AgI complex is much more sensitive to air-fuel ratio than is the solution of AgI and NaI in acetone.

It is also seen from Fig. 4 that the decrease in effecttiveness is not as sharp for stoichiometric ratios >1 as it is for ratios <1. This may be due to a decrease in the AgI particle density inside the combustion chamber. This decrease in particle density is caused by an increase in the rate of combustion air flow. A decrease in particle density reduces the losses due to coagulation. This in turn offsets some of the losses due to adverse air-fuel ratios. Consequently, the effectiveness-stoichiometric ratio curve would be much steeper for low stoichiometric ratios (<1) than for high stoichiometric ratios (>1).

The above discussion demonstrates the fact that the mechanism responsible for the variation of generator effectiveness with air-fuel ratio is not well established. This is a subject of further investigation.

d. Effectiveness vs AgI burn rate. The results showing the variation of effectiveness with AgI burn rate are shown on Fig. 5 for various pyrotechnic samples that were developed by a private concern. It is seen that the effectiveness decreases with increasing burn rate for test conditions of -10, -15 and -20C. As the burn rate increases, the effectiveness decreases at a slower rate. At burn rates of about 150 gm min^{-1} there appears to be very little variation in the effectiveness with a further increase in burn rate.

[1] The ratio of actual air required to the theoretical amount used for combustion of fuel.

[2] Preliminary experiments have shown that 30 ppm of IPA vapor will destroy the nucleating effectiveness at -20C.

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It has been suggested that the variation of effectiveness with burn rate is caused by increased coagulation losses resulting from increased AgI particle density. It should be noted, however, that the particle density of the smoke sample injected into the isothermal cloud chamber was controlled by dynamic dilution so that coagulation effects for these particular samples were minimized. On the other hand, coagulation and loss of particles to the walls of the dilution tunnel can occur before the sample is obtained. This may partially explain the variation of effectiveness with AgI burn rate.[3] (It is known that some of the AgI particles do collect on the walls of the dilution tunnel. However, the percentage of particles lost is not known.)

Vonnegut (1958) observed an effect similar to that described above for steady-state systems. He observed that as the concentration of AgI was increased in a particular complex, the effectiveness decreased. This effect has also been observed in another study of a steady-state device at CSU (Steele and Sciacca, 1966). An investigation of the variation in generator effectiveness with AgI burn rate (AgI concentration) for various AgI complexes is currently being pursued.

4. Conclusions

The following generalized conclusions may be drawn regarding the devices tested:

1) Steady-state generators are in general more effective than the pyrotechnics at the lower temperatures.

2) At temperatures > -12C, the effectiveness of the pyrotechnics approaches and in some cases exceeds that of the steady-state systems.

3) The AgI particle size plays an important role in generator effectiveness. Small AgI particles ($<0.05\ \mu$) are conducive to a high effectiveness at -20C. The effectiveness of a generator which produces small particles is more sensitive to the temperature range than a generator which produces rather uniform ($0.1\ \mu$) particles. The latter has a rather flat effectiveness curve while the former has a steep effectiveness curve. Both are in agreement with work of Fletcher and Sano *et al.*

4) Nuclei sources should be optimized in terms of effective nuclei min^{-1} as well as by effective nuclei gm^{-1}.

5) The effectiveness of the solution of AgI in IPA is very sensitive to air-fuel ratio. This may be due in part to the presence of unburned IPA vapor. The maximum effectiveness is seen to occur near stoichiometric conditions for both the AgI-IPA complex and the AgI-NAI-acetone complex.

6) The effectiveness of a pyrotechnic is dependent upon the AgI burn rate. As the burn rate is increased the effectiveness decreases. The mechanism which causes this effect is not known.

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[3] It should be noted that the pyrotechnic samples used to show the relationship between AgI burn rate and effectiveness were not identical in composition. Therefore, the possibility of composition affecting the results shown in Fig. 5 is present. It has been observed with very few exceptions, however, that the relationship between effectiveness and AgI burn rate tends to follow the pattern shown in Fig. 5, regardless of the pyrotechnic composition.

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