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Ice Nucleus Activity Measurements of Solid Rocket Motor Exhaust Particles

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TECHNICAL MEMORANDUM

ICE NUCLEUS ACTIVITY MEASUREMENTS OF SOLID ROCKET MOTOR EXHAUST PARTICLES

SECTION 1. EXECUTIVE SUMMARY

During the initial phase of launch, the Space Shuttle's two Solid Rocket Boosters exhaust approximately 3×10^6 g s^{-1} of aluminum oxide (Al_2O_3) into the atmosphere. Approximately 300 tons of this material ranging in size from the submicron to in excess of 20 micrometers diameter is emitted per launch. Although the material exhausted from the accelerating vehicle is primarily deposited in the lower troposphere, some is also dispersed along the vehicle path well into the stratosphere. In the days following launch it spreads over much of the hemisphere of injection before finally being removed by natural processes. Since aluminum oxide under some circumstances is known to act as a moderately efficient ice nucleating material and since copious amounts are exhausted into the atmosphere with each launch, the possibility of inadvertent weather modification via an ice phase process has been a matter of concern for some time [1]. The first concern is that inadvertent modification might occur via ice nuclei from the exhaust ground cloud seeding natural supercooled cumulus clouds resulting in localized severe weather. The second concern is that ice nuclei from the upper exhaust column cloud might on repeated launches accumulate in the upper troposphere and lower stratosphere and cause wide spread formation of cirrus clouds, thus eventually changing the terrestrial radiation balance and climate [2].

In conjunction with the third Space Shuttle launch (STS-3) a National Oceanic and Atmospheric Administration (NOAA) Orion P-3 hurricane research aircraft, contracted by NASA/MSFC and equipped with numerous cloud physics instrumentation, repeatedly penetrated the exhaust ground cloud. In this way the various microphysical properties of the cloud were characterized. Ice nucleus counts were obtained by the two methods compatible with aircraft operations. Membrane filters were utilized by Dr. Garland Lala of the State University of New York at Albany. Dr. Gerhard Langer, working under a Universities Space Research Association (USRA) agreement, used a National Center for Atmospheric Research (NCAR) portable continuous ice nucleus counter. Ice nucleus counts taken periodically in the ground cloud from four minutes to four hours after launch showed no statistically significant difference from out of cloud measurements during the same time period. These results have been previously documented [3-4].

The STS-3 ice nucleus measurement results were at variance with both earlier laboratory work and the interpretation of measurements by other investigators in the ground exhaust cloud of a similar solid rocket motor, e.g., Titan III. Published results suggested that solid rocket motor exhaust products had a moderately high ice nucleus activity [5-13]. Since there was a question about the suitability of using exhaust products from unpressurized combustion of Shuttle-type propellant for the earlier laboratory work and since there was also some question about the representativeness of ice nucleus measurements using portable counters or membrane filters, tests were initiated by NASA/MSFC's Systems Dynamics Laboratory to clarify these issues. The Shuttle Program Office directed Morton-Thiokol, Wasatch Division, to furnish, fire, and characterize scaled-down solid rocket motors for these tests. Tests using scaled-down motors with Shuttle propellant and with a similar but non-aluminized propellant were conducted during May 1985 at Colorado State University. The ice

nucleus effectivities of the resulting exhaust products were measured in the Colorado State University isothermal cloud chamber as well as with the same NCAR portable ice nucleus counter used to make measurements in the STS-3 exhaust ground cloud. The two papers in this document are the independent final reports of the principal investigators for these scaled-down solid rocket motor tests.

Both papers conclude that in the present launch configuration Shuttle propellant exhaust particles have a very low ice nucleus effectivity even at -20°C. The activity decays rapidly with time and is decreased further in the presence of moist air. These tests corroborate the low effectivity ice nucleus measurement results obtained in the STS-3 exhaust ground cloud. Such low ice nucleus activity implies that Space Shuttle induced inadvertent weather modification via an ice phase process is extremely unlikely.

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SECTION 2. ICE NUCLEUS ACTIVITY MEASUREMENTS

2.1 CSU Isothermal Cloud Chamber

(Final Report by W. G. Finnegan and L. O. Grant: "Ice Nucleus Aerosols from Combustion of Shuttle Propellant In Small Rocket Motors")

2.1.1 Introduction

Beginning in 1976 the question of possible environmental effects arising from release of particulate aerosols from large solid rocket motor combustion was addressed. Laboratory studies were conducted on the ice nucleating activities of aluminum oxide from combustion of unpressurized samples of cast-composite rocket propellant containing ammonium perchlorate and aluminum powder (Hindman, 1978, 1980). Ice nucleus effectivities of 5×10^{10} g^{-1} of aluminum oxide (Al_2O_3) produced were measured at -10°C in the Colorado State University cloud chamber. Portable ice nuclei counters such as the NCAR counter (Langer, 1973) and the Mee Industry counter were also used to measure the Al_2O_3 effectivities in preparation for monitoring ice nucleus concentrations in stable ground clouds produced by large solid propellant rocket launches (Hindman et al., 1981). The portable counters tended to undercount the ice nucleus concentrations by factors of 10^2 to 10^3, presumably due to instrument design, short residence times in the counters, and possible interference with nucleation and ice crystal growth due to the presence of gaseous hydrogen chloride (HCl) produced from the ammonium perchlorate on combustion.

Airborne measurements of ice nuclei in stable ground clouds produced by rocket launches proved difficult to interpret and generated much controversy. The portable counter data suggested that initial concentrations were less than those found in outside ambient air. Appreciable concentrations (200 liter^{-1}) of active nuclei then slowly developed over periods of several hours. The explanation advanced for this phenomenon was that the HCl interfered with the ice nucleus (IN) detection and time was required to dilute the HCl to values below some critical value (Hindman et al., 1981). Filter samples of aerosol were collected and developed for determination of IN concentrations in the stable ground cloud. Different values were obtained in different laboratories and the technique became suspect as a method of gaining information on ice nucleus aerosol in these rather complex clouds (Hindman and Lala, 1980; Parungo, 1983; Hindman et al., 1983).

2.1.2 Background for Current Work

One of the main criticisms of the laboratory studies and their comparison with field observations was that the laboratory ice nucleus studies were conducted on aerosols generated by unpressurized combustion of shuttle-type and actual shuttle propellants. The large solid rocket motors burn at internal motor pressures of $\approx$400 to 500 psi. Rocket motor combustion temperatures (internal) might be expected to be different from those of unpressurized propellant burns; the crystal structures of the Al_2O_3 produced might vary with temperature of combustion, thus possibly affecting IN effectivities. Rocket motors burn a particular weight of propellant in much shorter times than an equal weight of unpressurized propellant takes to burn, since the burning rate of the propellant increases with pressure. The possibility existed that increased concentration of potential ice nucleating species in the rocket exhaust, compared to unpressurized propellant burns, would lead to rapid coagulation of the submicron sized aerosol generated. Ice nuclei production by rocket motors would then be lower than that for unpressurized propellant burns of equal propellant weights.

To explore the possibility that the Al_2O_3 aerosol produced by rocket motor burns might differ in its IN effectivity from the aeorsol produced by unpressurized propellant burns, the Cloud Simulation and Aerosol Laboratory of the Atmospheric Science Department, Colorado State University, was tasked by the USRA to conduct these studies using its isothermal cloud chamber.

Discussions with NASA/MSFC, USRA, and Morton Thiokol Company, Wasatch, Utah, determined that small rocket motors containing 200 g of shuttle propellant were appropriate for use in the study of the effectivity of the Al_2O_3 exhaust. To investigate the possibility that exhaust products (non Al_2O_3) such as carbonaceous material from the propellant binder or the Fe_2O_3 (ferric oxide) used as a combustion catalyst might contribute to or be responsible for the previously measured IN effectivity, identical motors were also loaded with a non-aluminized propellant formulation for study. In the actual study, a heavy walled demountable test motor on a thrust stand was loaded for each firing with a prepared, inhibited propellant grain and the rocket nozzle throat diameter was adjusted to provide desired chamber pressures.

The participation of Dr. Gerhard Langer on the study was a USRA requirement. Comparison of the isothermal cloud chamber results with Dr. Langer's NCAR portable counter data would then permit more confident interpretation of portable counter measurements in shuttle launch clouds.

Considering the very short rocket motor burn times (approximately 0.5 sec) predicted, the motors could not be burned in the Cloud Simulation and Aerosol Laboratory's vertical wind tunnel for aerosol sampling. It was decided, therefore, that the motors would be burned adjacent to the laboratory's 1800 ft^3 aerosol storage tank and the motor exhaust would be directed into the tank. The storage tank was therefore equipped with a closeable shielded entry for aerosol admittance, a sealable door for cleanout, a blower system to exhaust aerosol on completion of each test, a sampling port and a fan to ensure uniform aerosol distributions in the tank.

The isothermal cloud chamber determinations for effectivities were to be conducted at -20°C. A holding tank of 770 liter volume was provided as an auxilliary holding tank and dilution system for aerosols for use in the NCAR portable IN counter.

The rocket motors, thrust stand and instrumentation for determining motor performance characteristics were furnished by the Morton Thiokol Company. Mr. Orson Wilson and Mr. Norman Lloyd of the Morton Thiokol Company conducted the rocket motor loadings, and firings and measured rocket motor performance characteristics (Table 2).

2.1.3 Experimental Procedures

The procedure used during this study consisted of loading the desired propellant grain into the test motor on the thrust stand. An appropriately sized nozzle was attached and the motor was fired after safety checks were made to ensure all personnel were clear of the firing area. The rocket motor exhaust was directed into the 1800 ft^3 holding tank. Immediately after the motor firing, the access port into the holding tank was closed, the circulation fan was started and a 4 liter syringe sample of the aerosol in the tank was taken and injected into the isothermal cloud chamber, either at initial tank concentration or after a single standard dilution with dry (or wet) dilution air.

A second 4 liter syringe sample of aerosol was taken as rapidly as possible after the motor firing and injected into the 770 liter small holding tank. This diluted aerosol constituted the supply for the NCAR portable IN counter. Initial attempts by Dr. Langer to sample the aerosol in the holding tank, directly, were unsuccessful. The aerosol concentration was too high for testing directly in the NCAR counter.

After a systems check on May 3, 1985, during which the isothermal cloud chamber was run at -13.5°C, the remainder of the isothermal cloud chamber experiments on aerosol effectivities were conducted at -20°C.

2.1.4 Calculation of Effectivities from Isothermal Cloud Chamber Determinations

The holding tank volume, including miscellaneous piping used for exhausting the aerosol after an experiment, was estimated to be 51,000 liter (1801 ft^3). It is assumed that all the propellant aerosol was kept within the tank on motor firing. A 4 liter syringe sample was taken for effectivity determinations and the propellant weight was 200 g. The effectivity per gram of propellant burned would be:

$$E = \frac{\text{syringe dilution (a) x ice crystal count (b) x chamber area x holding tank volume (liters)}}{\text{view area (microscope) x syringe volume (liters) x propellant weight (grams)}}$$

$$= \frac{\text{syringe dilution (a) x ice crystal count (b) x } 8.35 \times 10^3 \text{ cm}^2 \times 51{,}000 \text{ liters}}{2.01 \times 10^{-2} \text{ cm}^2 \times 4 \text{ liters} \times 200 \text{ grams}}$$

$$= \text{syringe dilution (a) x ice crystal count (b) x } 2.66 \times 10^7 \frac{\text{ice crystals}}{\text{grams propellant}}$$

(a) Syringe dilution value is 1 for undiluted sample, 8.64 for samples diluted once, and 74.7 for samples diluted twice with nuclei free air.

(b) Ice crystal count is the total number of crystals falling on an average viewing area of the microscope during the total sample time in the chamber.

The effectivity value (E) reported refers to ice crystals produced per gram of propellant burned. The effectivity value per gram of aluminum oxide produced may be calculated by multiplying the former value by 3.31 assuming a 16 percent Al content of the propellant.

2.1.5 Results and Discussion

The results obtained during this study are shown in Table 1. Table 2 shows the motor data obtained during the study by the Morton Thiokol representatives.

Several immediate conclusions can be drawn from initial inspection of the effectivity data from this study. The initial maximum effectivities measured at -20°C in the isothermal cloud chamber were $1.7 \times 10^9\ g^{-1}$ (Motor No. 1), and $1.6 \times 10^9\ g^{-1}$ (Motor No. 3). The majority of effectivity values ranged from 1.8 to $6.4 \times 10^8\ g^{-1}$

at -20°C. These results are from 1 to 2 orders of magnitude lower than those reported for effectivities measured on aerosols generated by unpressurized propellant combustion.

It can also be seen on inspection of the data that the effectivities of the aerosols in the holding tank decrease rapidly with time, in general.

Initial effectivities of aerosols injected into the holding tank, which had been wetted down with water to increase the humidity, were markedly lower than initial effectivities of those injected into a dry tank. Effectivities ranged from a low of 1.1×10^7 g^{-1} to a high of 9.2×10^7; values on holding then decreased to $\sim 10^6$ g^{-1}.

Propellants containing no aluminum powder gave aerosols with low effectivities of 2.1×10^7 g^{-1} to 9×10^7 g^{-1} (-20°C) and 5.3×10^6 g^{-1} (-13.5°C).

A single determination of effectivities at -13.5°C (motor No. 1A) gave values of 1.4×10^8 g^{-1} (initial) and 2.1 to 2.7×10^7 g^{-1} on holding in the tank. These values do not differ markedly from those determined at -20°C.

Two 21.6 g propellant grains ($\sim$1/10th scale) were prepared, loaded with the test motor and burned at essentially ambient pressure to determine whether a lower aerosol concentration in the holding tank might affect the effectivity values. A value of 5.9×10^7 g^{-1} at -20°C was attained on the initial aerosol; the values did not decrease significantly with time.

2.1.6 Summary and Conclusions

The ice nucleus effectivities of aluminum oxide aerosols generated by small scale rocket motor firings have been measured in the Colorado State University isothermal cloud chamber. Effectivities of these aerosols were also determined in an NCAR portable ice nucleus counter by Dr. Gerhard Langer.

The ice nucleus effectivity measured at -20°C chamber temperature were substantially lower than those determined on aerosols generated by combustion of unpressurized propellant samples in previous studies.

Aerosols injected and held at high relative humidities in the grain bin holding tank displayed lower effectivity values than those held in ambient humidity air.

Since non-aluminized propellants give substantially lower effectivity values for their combustion aerosols than do aluminized propellant, aluminum oxide (Al_2O_3) as generated in the presence of hydrogen chloride (HCl) is an ice nucleus, although of naturally low effectivity at -20°C.

Actual shuttle launches involve the generation of copious quantities of water vapor from the main shuttle engines, from after-burning of solid rocket booster exhaust, and from vaporization of launch pad water during the launch phase. The aerosols studied in this program demonstrate (1) initial low effectivity values at -20°C, (2) rapid decay of effectivity values on holding, and (3) decreased effectivities and rapid decay rates when held at high relative humidities.

It is difficult to conclude from these studies that the ice nucleus aerosol generated by shuttle solid propellant booster motors would induce a severe environmental supercooled cloud modification effect.

2.1.7 Acknowledgments

We wish to thank Dr. Vernon Keller for suggesting the experiments involving holding the combustion aerosol at high relative humidities.

The skilled and safety-conscious assistance of Mr. Orson Wilson and Mr. Norman Lloyd of the Morton Thiokol Company, Wasatch, Utah, is greatly acknowledged.

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TABLE 1

Motor No.	Date	Time of Run	Run No.	Temp (°C)	LWC	Count	Syringe Dilution	Wet or Dry Dil	Effectiveness (g^{-1})	Motor Pressure (psi)
1a	5/3/85	10:13:25 10:28:15	5-850189	-13.5	1.5	5.4	0X	—	$1.4x10^8$	600
1a	5/3/85	10:33:30 10:43:40	5-850190	-13.5	1.5	0.8	0X	—	$2.1x10^7$	600
1a	5/3/85	10:51:25 11:01:25	5-850191	-13.5	1.5	1.0	0X	—	$2.7x10^7$	600
2a	5/3/85	1:24:40 1:54:40	5-850192	-13.5	1.5	0.2	0X	—	$5.3x10^6$	1192 Non-alum
1	5/6/85	9:45:00 10:00:00	5-850193	-20.0	1.5	7.2	1X	Dry	$1.7x10^9$	1023
1	5/6/85	10:08:00 10:18:00	5-850194	-20.0	1.5	0.8	0X	—	$2.1x10^7$	1023
1	5/6/85	10:27:00 10:37:00	5-850195	-20.0	0.5	1.0	0X	—	$2.7x10^7$	1023
1	5/6/85	10:52:00 11:02:00	5-850196	-20.0	0.5	0.4	0X	—	$1.1x10^7$	1023
2	5/6/85	1:19:50 1:39:50	5-850197	-20.0	0.5	6.7	0X	—	$1.8x10^8$	750
2	5/6/85	1:45:20 2:05:20	5-850198	-20.0	0.5	3.4	1X	Dry	$7.8x10^8$	750
2	5/6/85	2:12:20 2:22:20	5-850199	-20.0	0.5	0.8	1X	Dry	$1.8x10^8$	750
3	5/6/85	2:56:40 3:06:40	5-850200	-20.0	0.5	0.8	2X	Dry	$1.6x10^9$	704
3	5/6/85	3:13:15 3:28:15	5-850201	-20.0	0.5	1.2	1X	Dry	$2.8x10^8$	704
3	5/6/85	3:35:40 3:50:40	5-850202	-20.0	0.5	0.0	0X	—	—	704
4	5/7/85	9:36:35 9:051:35	5-850203	-20.0	0.5	1.6	1X	Dry	$3.7x10^8$	708

TABLE 1 (Continued)

Motor No.	Date	Time of Run	Run No.	Temp °C	LWC	Count	Syringe Dilution	Wet or Dry Dil	Effect-iveness (g^{-1})	Motor Pressure (psi)
4	5/7/85	9:56:10 10:06:10	5-850204	-20.0	0.5	0.4	1X	Dry	9.2×10^7	708
4	5/7/85	10:10:40 10:20:40	5-850205	-20.0	0.5	0.8	1X	Dry	1.8×10^8	708
4	5/7/84	10:29:25 10/29/25	5-850206	-20.0	0.5	0.4	1X	Dry	9.2×10^7	708
5	5:7:85	11:22:50 11:27:50	5-850207	-20.0	0.5	0.8	1X	Wet	1.8×10^8	567
5	5/7/85	11:42:10 11:52:10	5-850208	-20.0	0.5	0.8	1X	Wet	1.8×10^8	567
5	5/7/85	11:58:10 12:08:10	5-850209	-20.0	0.5	0.2	1X	Wet	4.6×10^7	567
5	5/7/85	12:57:25 1:07:25	5-850210	-20.0	0.5	0.0	1X	Wet	1 hr hold	567
6	5/7/85	1:34:00 1:54:00	5-850211	-20.0	0.5	2.8	1X	Dry	6.4×10^8	578
6	5/7/85	1:57:30 2:12:30	5-850212	-20.0	0.5	0.8	1X	Dry	1.8×10^8	578
6	5/7/85	2:15:13 2:25:12	5-850213	-20.0	0.5	1.2	1X	Dry	2.8×10^8	578
6	5/7/85	2:28:50 2:38:50	5-850214	-20.0	0.5	0.8	1X	Dry	1.8×10^8	578
7	5/7/85	2:45:50 3:00:50	5-850215	-20.0	0.5	2.4	1X	Dry	5.5×10^8	578
7	5/7/85	3:03:40 3:23:40	5-850216	-20.0	0.5	2.4	1X	Dry	5.5×10^8	578
7	5/7/85	3:27:40 3:42:40	5-850217	-20.0	1.5	1.6	1X	Dry	3.7×10^8	578
7	5/7/85	3:46:25 3:56:25	5-850218	-20.0	0.5	0.6	1X	Dry	1.4×10^8	578

TABLE 1. (Continued)

Motor No.	Date	Time of Run	Run No.	Temp °C	LWC	Count	Syringe Dilution	Wet or Dry Dil	Effectiveness (g^{-1})	Motor Pressure (psi)
8	5/8/85	9:32:25 9:47:25	5-850219	-20.0	0.5	2.0	1X	Dry	$4.6x10^8$	1434
8	5/8/85	9:15:25 10:06:35	5-850220	-20.0	0.5	2.0	1X	Dry	$2.3x10^8$	1434
8	5/8/85	10:10:45 10:25:85	5-850221	-20.0	0.5	1.4	1X	Dry	$3.2x10^8$	1434
8	5/8/85	10:29:30 10:44:30	5-850222	-20.0	0.5	1.0	1X	Dry	$2.3x10^8$	1434
9	5/8/85	10:56:40 11:11:40	5-850223	-20.0	0.5	2.6	1X	Dry	$6.0x10^8$	1397
9	5/8/85	11:16:40 11:51:40	5-850224	-20.0	0.5	1.2	1X	Dry	$2.8x10^8$	1397
9	5/8/85	11:36:05 11:51:05	5-850225	-20.0	0.5	1.4	1X	Dry	$3.2x10^8$	1397
9	5/8/85	11:53:45 12:03:45	5-850226	-20.0	0.5	1.2	1X	Dry	$2.8x10^8$	1397
10	5/8/85	1:13:30 1:33:30	5-850227	-20.0	0.5	2.8	1X	Dry	$6.4x10^8$	361
10	5/8/85	1:36:20 1:51:20	5-850228	-20.0	0.5	2.8	1X	Dry	$6.4x10^8$	361
10	5/8/85	1:57:05 2:12:05	5-850229	-20.0	0.5	0.6	1X	Dry	$1.4x10^8$	361
11	5/8/85	2:29:55 2:39:55	5-850230	-20.0	0.5	0.4	1X	Dry*	$9.2x10^7$	353
11	5/8/85	2:45:15 3:05:15	5-850231	-20.0	0.5	1.2	0X	Dry*	$3.2x10^7$	353
11	5/8/85	3:07:50 3:27:50	5-850232	-20.0	0.5	1.2	0X	Dry*	$3.2x10^7$	353
11a	5/9/85	8:59:00 9:13:00	5-850233	-20.0	0.5	2.2	0X	—	$5.9x10^7$	21.6g Motor Amb. Press.

TABLE 1. (Continued)

Motor No.	Date	Time of Run	Run No.	Temp °C	LWC	Count	Syringe Dilution	Wet or Dry Dil	Effect-iveness (g^{-1})	Motor Pressure (psi)
11a	5/9/85	9:15:35 9:25:35	5-850234	-20.0	0.5	2.2	0X	—	$5.9x10^7$	21.6g Motor Amb. Press.
11a	5/9/85	9:29:05 9:44:05	5-850235	-20.0	0.5	1.6	0X	—	$4.3x10^7$	21.6g Motor Amb. Press.
11a	5/9/85	9:46:50 9:56:50	5-850236	-20.0	0.5		0.6	0X	$1.6x10^7$	21.6g Motor Amb.Press.
12	5/9/85	10:08:05 10:23:05	5-850237	-20.0	1.0	2.6	1X	Dry	$6.0x10^8$	753
12	5/9/85	10:28:10 10:42:10	5-850238	-20.0	1.0	2.6	1X	Dry	$5.0x10^8$	753
12	5/9/85	10:27:40 10:57:40	5-850239	-20.0	1.0	2.2	1x	Dry	$5.0x10^8$	753
12	5/9/85	11:04:30 11:14:30	5-850240	-20.0	1.0	1.0	1X	Dry	$2.3x10^8$	753
13	5/9/85	11:20:50 11:35:50	5-850241	-20.0	1.0	0.8	0X	—	$2.1x10^7$	589 Non-alum
13	5/9/85	11:38:40 11:45:40	5-850242	-20.0	1.0	0.2	0X	—	$5.3x10^6$	589 Non-alum
14	5/9/85	1:09:30 1:19:30	5-850243	-20.0	1.0	0.6	1X	Dry	$1.4x10^8$	567
14	5/9/85	11:22:30 1:32:30	5-850244	-20.0	1.0	0.2	0X	—	$5.3x10^6$	567
14	5/9/85	1:35:50 1:40:50	5-850245	-20.0	1.0	0.0	0X	—	—	567
15	5/9/85	1:52:45 2:07:45	5-850246	-20.0	1.0	1.0	1X	Dry	$2.3x10^8$	772
15	5/9/85	2:11:00 2:21:00	5-850247	-20.0	1.0	0.2	0X	—	$5.3x10^6$	772
15	5/9/85	2:23:10 2:28:10	5-85048	-20.0	1.0	0.0	0X	—	—	772

TABLE 1. (Concluded)

Motor No.	Date	Time of Run	Run No.	Temp °C	LWC	Count	Syringe Dilution	Wet or Dry Dil	Effectiveness (g^{-1})	Motor Pressure (psi)
16	5/9/85	2:41:55 2:55:55	5-850249	-20.0	1.0	0.4	0X	**	$1.1x10^7$	743
16	5/9/85	2:58:00 3:08:00	5-850250	-20.0	1.0	0.4	0X	**	$1.1x10^7$	743
16	5/9/85	3:10:10 3:15:10	5-850251	-20.0	0.5	0.2	0X	**	$5.3x10^6$	743
16a	5/10/85	--	--	--	--	--	--	--		Not Tested
17	5/10/85	9:49:20 10:04:30	5-850252	-20.0	0.5	3.4	0X	—	$9.0x10^7$	613 Non-alum
17	5/10/85	10:05:20 10:20:20	5-850253	-20.0	0.5	0.2	0X	—	$5.3x10^6$	613 Non-alum
18	5/10/85	10:32:40 10:47:40	5-850254	-20.0	0.5	2.2	1X	Dry	$5.1x10^8$	585
18	5/10/85	10:51:16 11:06:16	5-850255	-20.0	0.5	1.0	1X	Dry	$2.3x10^8$	585
19	5/10/85	11:20:05 11:30:05	5-850256	-20.0	0.5	1.6	1X	Dry	$3.7x10^8$	563
19	5/10/85	11:36:30 11:46:30	5-850257	-20.0	0.5	0.8	1X	Dry	$1.8x10^8$	563
20	5/10/85	1:28:10 1:38:10	5-8550258	-20.0	0.5	2.4	1X	Dry	$5.5x10^8$	599
20	5/10/85	1:40:50 1:50:50	5-850259	-20.0	0.5	1.2	1X	Dry	$2.8x10^8$	599
21	5/10/85	2:02:00 2:12:00	5-850260	-20.0	0.5	0.6	0X	*	$1.6x10^7$	577
21	5/10/85	2:15:10 2:25:10	5-850261	-20.0	0.5	0.4	0X	*	$1.1x10^7$	577

Note: Motor Nos. 1a and 2a were preliminary system check firings.

Motor Nos. 2a,13, and 17 contained non-aluminum analog propellant.

Motor Nos. 11a and 16a were 10th scale (21.6g) motors burned at ambient pressure.

LWC is liquid water content in g m^{-3}.

*Walls and floor of grain bin were wet with water.

**Floor of grain bin wet with water.

TABLE 2

TU-172 MOTOR DATA
FROM C. S. U. ICE NUCLEATION STUDY

Motor No.	Chart Speed (cm/sec.)	Trc. Lgth. (cm)	Trc. Area (cm^2)	Noz. Dia. (in.)	Web (in.)	P_c (psi)	R_b (ips)	K_n
1	12.75	12.9	67.0	0.281	0.490	1023.2	0.484	227.90
2	12.75	14.7	55.9	0.313	0.490	749.1	0.425	183.75
3	12.75	15.7	46.2	0.339	0.490	703.7	0.399	156.48
4	12.75	14.8	53.2	0.313	0.490	708.1	0.422	183.75
5	12.75	15.8	45.5	0.339	0.490	567.3	0.395	156.48
6	12.75	15.5	45.5	0.339	0.490	578.3	0.403	156.48
7	12.75	16.1	47.2	0.335	0.490	577.5	0.388	160.31
8	12.75	11.8	85.5	0.250	0.490	1433.5	0.532	287.78
9	12.75	11.8	83.7	0.250	0.490	1397.4	0.529	287.78
10	5.08	7.1	13.0	0.386	0.490	360.7	0.351	120.75
11	5.08	6.7	12.0	0.386	0.490	352.8	0.371	120.75
12	12.75	15.1	48.7	0.333	0.490	752.5	0.414	162.22
13	12.75	17.2	51.4	0.301	0.490	588.7	0.363	198.46*
14	12.75	15.6	44.9	0.336	0.490	567.0	0.400	159.30
15	12.75	14.5	56.8	0.312	0.490	771.7	0.430	184.71
16	12.75	13.9	52.4	0.312	0.490	742.7	0.449	184.71
17	12.75	16.7	52.0	0.301	0.490	613.4	0.374	198.57*
18	12.75	15.7	46.6	0.339	0.490	584.7	0.398	156.48
19	12.75	15.6	44.6	0.339	0.490	563.2	0.400	156.48
20	12.75	14.9	45.3	0.339	0.490	598.9	0.419	156.48
21	12.75	15.5	45.4	0.339	0.490	577.0	0.403	156.48
1a	12.75	15.2	44.6	0.339	0.490	579.5	0.411	156.48
2a	12.75	14.5	77.0	0.254	0.490	1192.0	0.431	278.78*

* Non-aluminum analog propellant.
Note: Numbers 1a and 2a were preliminary system check firings.

2.2 NCAR Portable Ice Nucleus Counter
(Final Report by G. Langer: "Ice Nucleus Activity of Shuttle Propellant Exhaust Particles from Scaled-Down Motors")

2.2.1 Introduction

This report covers NCAR Counter ice nucleus (IN) measurements made during tests conducted May 6-10, 1985, at the Colorado State University (CSU) Atmospheric Simulation Laboratory. Small (200 gm) shuttle propellant type rocket motors were specially prepared and fired by Thiokol personnel. The smoke was exhausted into a 51,000 liter grain bin to hold the smoke for testing. CSU measured IN activity with their one cubic meter isothermal chamber. This report only deals with the NCAR IN counter measurements made in parallel to the CSU IN tests. The same NCAR Counter was used that sampled the Space Transportation System (STS-3) launch ground-cloud March 22, 1982.

2.2.2 Experimental Procedures

The arrangements for firing the rocket motors and counting the IN in the CSU cloud chamber are reported by Dr. W. Finnegan of CSU. The NCAR IN counter operation is outlined in Figure 1. A 4 liter syringe sample of the smoke was collected from the bin right after firing and transferred to the 860 liter holding tank resulting in a dilution factor of 215X. Subsequently, additional samples were withdrawn from the bin to study the activity of the smoke versus time. At the end of a test series the 860 liter tank was purged by pulling room air through a filter attached to the tank. This reduced the IN count to near zero before the next test.

2.2.3 Results and Discussion

Table 1 summarizes the IN data. NCAR counter data were collected on two days during the 5-day test period, i.e., the first and last day. Test No. 1 was an attempt to sample directly from the bin. However, the counter was overwhelmed by the very high smoke concentration, that is, the ice crystal sensor capillary collected an interfering smoke particle deposit in 6 minutes. Only 26 IN were counted during this period. Ice crystal growth was presumably suppressed by the large number of cloud condensation nuclei, which pre-empted all the available water vapor in the cloud chamber of the NCAR counter.

Tests No. 2 and 3 will now be discussed. For test No. 2 and for all subsequent tests one or several syringe samples were transferred from the bin to the holding tank as discussed previously. Subsequent syringe samples were injected into the holding tank when activity had decayed by a factor of 5 or so. For Test No. 3 the syringe sample was diluted 8.6 times before injection into the holding tank, resulting in a total dilution factor of 1850X. This was done to learn if IN activity might increase for a more dilute aerosol. The increase in IN activity between Tests No. 2 and 3 for the initial sample was not significant, taking into account that the temperature was decreased 2°C to -20°C for this and the remaining tests. A decrease in 4°C usually causes a 10X increase in IN activity.

In Test No. 3 the aerosol in the holding tank was agitated with a syringe containing clean air. The object was to verify if the smoke was completely mixed in the tank during the injection process. Since there was an increase in count both times, indicating incomplete mixing, a small stirring fan was installed for subsequent tests.

A fan was also installed in the bin. Continuous stirring leads to increased wall losses. Also, the fan itself acts as an aerosol particle collector due to impaction on the leading edges of the fast moving blades. This was obvious from the appearance of the fans. Table 1 shows a reduction in activity after these changes were made. The undesirable impact of the fans, however, was more than off-set by the improved control over aerosol homogeneity which they provide.

The propellant in the motor for Test No. 4 weighed only 20 gm compared to the usual 200 gm. The activity was higher for the lighter motor, but not enough to be statistically significant for the number of tests involved.

Test No. 5 used a propellant charge that contained no aluminum (Al) and no IN activity was expected, because aluminum oxide (Al_2O_3) is thought to be the nucleating agent. The first sample was somewhat lower in activity than a comparable motor with Al. The subsequent sample gave no response. Thus, one test is inconclusive as to the role of Al in the nucleation process, but the Al free propellant has a small amount of IN activity. The source of activity may be in the binder or catalyst.

Tests No. 7 and 8 are repeat tests to establish how consistent the IN activity is for the same propellant charge. The results show that the experimental procedures are well controlled, that is, the variation in activity is small for the two runs.

Finally, Test No. 9 was an experiment in which the walls of the bin were wetted with water. This was to simulate IN activity in a moist environment. The first sample gave the usual response, but subsequent samples showed no activity. This points to the possibility of even less IN activity in humid environments, such as Cape Canaveral, and in the presence of the large amounts of deluge water introduced into the ground cloud.

2.2.4 Conclusions

The above tests confirm the results of the STS-3 flight. Namely, the shuttle propellant exhaust particles do not produce significant numbers of IN as measured with the NCAR IN counter. The tests with the CSU isothermal chamber will show whether or not this is also true for this sophisticated but non-portable IN detector. The above NCAR IN data were extrapolated to the amount of aerosol released in the troposphere by a full sized Shuttle solid rocket motor burn. This gives a total -20°C IN activity equivalent to only one gram of silver iodide (AgI)! Field tests on Project FACE (Florida Area Cumulus Experiment) indicate that it takes approximately 1 kg of AgI to modify the dynamics of a cumulo-nimbus cloud.

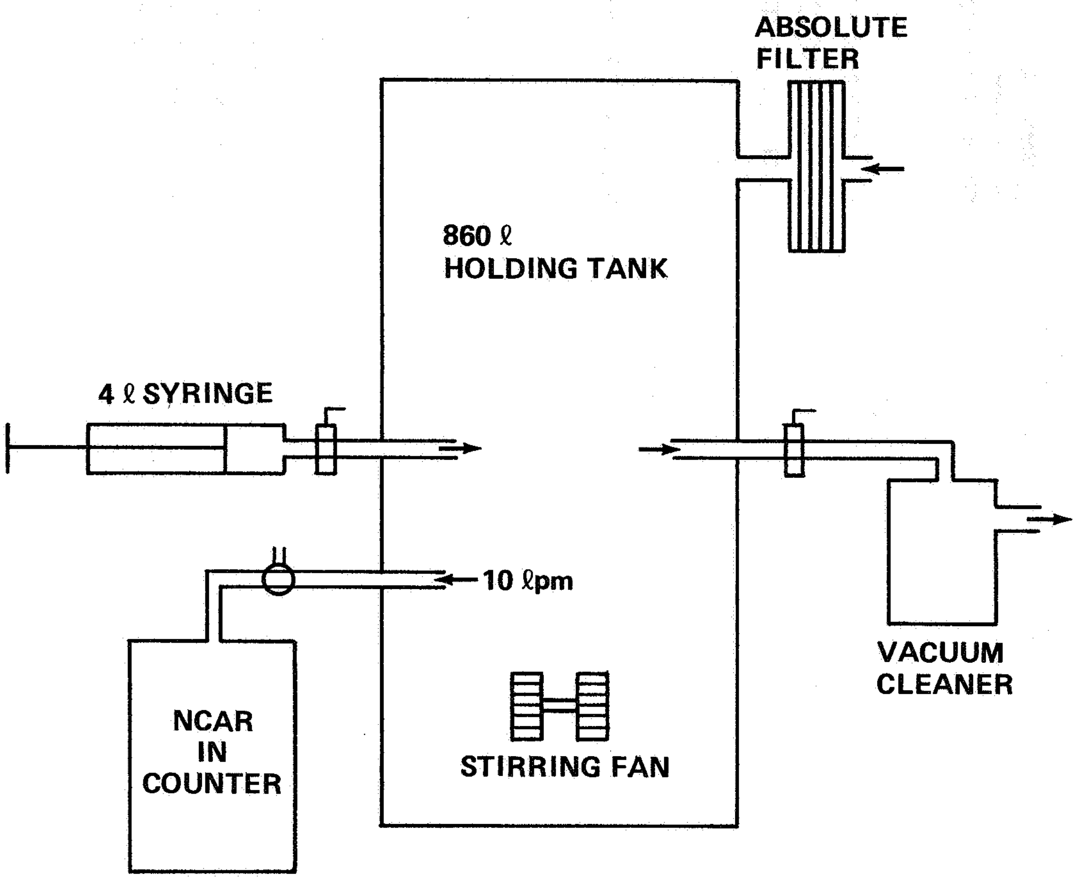

Figure 1. Experimental arrangement for determining ice nucleus activity of Shuttle propellant using NCAR ice nucleus counter.

TABLE 1. ICE NUCLEUS ACTIVITY OF PARTICLES FROM EXHAUST OF SCALED-DOWN SHUTTLE MOTORS

TEST NO.	DATE	TIME MOTOR (a) WAS FIRED	TIME THE SAMPLE (b) WAS INJECTED INTO HOLDING TANK	TEMP. OF CLOUD CHAMBER, °C	NUCLEI PER gm OF PRO-PELLANT	COMMENTS
1	5/6	0934	0934	−18	-- ---	COUNTER ON BIN
2	5/6	1308	1308	−18	6.9×10^6	
			1400	−18	1.5×10^6	
3	5/6	1448	1448	−20	1.4×10^7	DILUTED SAMPLE 8.6X
			1500	−20	2.0×10^7	AGITATED AEROSOL
			1541	−20	5.0×10^7	AGITATED AEROSOL
4	5/10	0855	0855	−20	3.3×10^6	20 gm MOTOR. (c)
			0986	−20	3.3×10^6	
			0916	−20	1.5×10^7	
5	5/10	0940	0940	−20	7.1×10^5	NO AL IN PROPELLANT
			0955	−20	0.0	
6	5/10	1022	1022	−20	1.6×10^6	
			1038	−20	1.9×10^5	
7	5/10	1110	1110	−20	1.4×10^6	
			1124	−20	4.7×10^6	
			1138	−20	0.0	
8	5/10	1318	1318	−20	1.8×10^6	
			1330	−20	1.5×10^6	
9	5/10	1352	1352	−20	1.5×10^6	WALLS OF BIN WET
			1403	−20	0.0	WALLS OF BIN WET
			1417	−20	0.0	WALLS OF BIN WET
			1424	−20	0.0	WALLS OF BIN WET

(a) PROPELLANT IN ALL MOTORS WEIGHTED 200 gm EXCEPT FOR TEST #4 (SEE COMMENTS).

(b) AN UNDILUTED 4 LITER SYRINGE SAMPLE, EXCEPT FOR TEST #1 AND 3 (SEE COMMENTS), WAS TAKEN FROM BIN AND INJECTED INTO HOLDING TANK OF IN COUNTER.

(c) FOR THE REMAINING TESTS A FAN WAS PLACED INTO THE HOLDING TANK TO STIR THE AEROSOL.

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16. ABSTRACT

The ice nucleus activity of exhaust particles generated from combustion of Space Shuttle propellant in small rocket motors has been measured. The activity at -20°C was substantially lower than that of aerosols generated by unpressurized combustion of propellant samples in previous studies. The activity decays rapidly with time and is decreased further in the presence of moist air. These tests corroborate the low effectivity ice nucleus measurement results obtained in the exhaust ground cloud of the Space Shuttle. Such low ice nucleus activity implies that Space Shuttle induced inadvertent weather modification via an ice phase process is extremely unlikely.

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