Mailing Address:
Water Resources Data System
University of Wyoming, Dept 3943
1000 E University Avenue
Laramie, WY 82071

Physical Address:
Wyoming Hall, Room 249
University of Wyoming
Laramie, WY 82071

Phone: (307) 766-6651
Fax: (307) 766-3785

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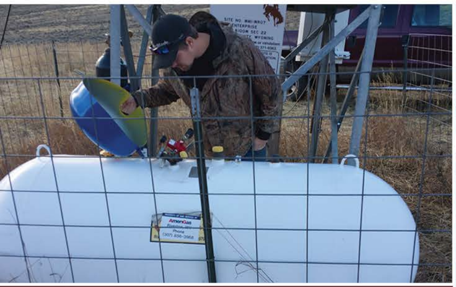
EXECUTIVE SUMMARY

WYOMING • WIND RIVER RANGE
WEATHER MODIFICATION PROGRAM



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Wind River

Mountain Range

WEATHER MODIFICATION INCORPORATED
3802 20th Street N.
Fargo, ND 58102

WYOMING WATER DEVELOPMENT COMMISSION
6920 Yellowtail Road
Cheyenne, WY 82002

Cloud Seeding Operations in the Wind River Range of Wyoming 2015-2016 Season

EXECUTIVE SUMMARY

prepared by

Weather Modification, Inc.
3802 20th Street North
Fargo, North Dakota 58102 USA

for the

Wyoming Water Development Office
6920 Yellowtail Road
Cheyenne, Wyoming 82002

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BACKGROUND AND OVERVIEW

Atmospheric water transformed to precipitation is one of the primary sources of fresh water in the world. However, a large amount of water present in clouds never is converted into precipitation that makes it to the ground. This has prompted scientists and engineers to explore the possibility of augmenting water supplies by means of cloud seeding.

From 2006 through the spring of 2014, cloud seeding operations in the Wind River Range were conducted within the context of the Wyoming Weather Modification Pilot Project (WWMPP). Though the WWMPP concluded in the spring of 2014, local and regional interest in continuing operations remained. The Wyoming Water Development Commission (WWDC) obtained legislative support and the funding for operational cloud seeding programs in the Wind River Range during the 2014-2015 winter, and again in 2015-2016. Funding provided by the 2015 Wyoming Legislature enabled the State of Wyoming, through the Wyoming Water Development Office (WWDO), to provide 25% of the operational cost. Additional funding came from other sources, detailed further, later in this executive summary.

Figure 1 (right). The ice nucleus generator sited at White Acorn Ranch on the southwest flank of the Wind River Range (Weather Modification Inc., photograph). For the locations of all the generators, see Figure 2.

The Science

Clouds in the lower troposphere form when, in cooling air, water vapor condenses upon cloud condensation nuclei (CCN), forming cloud droplets. The size of the droplets produced depends on the amount of water vapor present, and the character of the CCN. If the CCN are large or have properties that attract water (such as salt), the resulting droplets will be of increased size. All this happens on a very small scale. About one million (10^6) typical cloud droplets are required to produce a single, 1 millimeter (mm) raindrop.

Precipitation forms in two ways. The simpler process involves the collision and coalescence of cloud droplets until the droplet becomes large enough to fall as precipitation. Thus, the initially tiny cloud droplets grow in size, becoming drizzle, and with continued growth, rain. This process is known as the *collision-coalescence* or *warm rain* process.

The path to winter (cold cloud) precipitation development is through the formation of ice, and it is this process that plays a significant role in winter clouds in Wyoming. For ice to form the cloud must be colder than 0°C (32°F). However, ice does not form spontaneously at temperatures colder than 0°C (32°F). In the absence of ice nuclei, water can become "supercooled" (SLW); meaning the water in the cloud remains in liquid form at temperatures well below zero Celsius. To most persons this is surprising, as we are accustomed to seeing water (at the surface) freeze whenever temperatures fall "below freezing." Freezing happens at the surface because there are lots of substrates (substances or materials) present that encourage nucleation of the ice phase (freezing), and these substrates are largely absent in the free atmosphere. Nature's solution to the lack of substrates available to encourage the freezing process in clouds comes in the form of tiny particles called *ice nuclei.* Ice nuclei provide microscopic "templates" for supercooled liquid water (SLW) to follow, and become the hard crystalline form known as ice.

Once ice forms in a cloud, the crystals grow quickly. Initially, growth occurs through water vapor deposition directly on the nascent ice crystal, producing six-sided crystals. Within five minutes, these tiny ice crystals grow large enough to begin to fall. As they fall, growth by deposition continues, but because the ice crystals are heavier than the nearby SLW droplets they collect them as they fall. Upon contact with the ice crystals, the SLW droplets freeze. As they grow ever larger, the ice crystals may encounter each other and become tangled, forming aggregates known as snowflakes.

When clouds grow colder than about -5°C (23°F), but do not immediately form ice crystals, the introduction of silver iodide (AgI) ice nuclei will immediately initiate ice crystal formation, thus starting the ice-phase precipitation process. Ground-based seeding is commonly used in orographic applications, especially when the prevailing wind flow is roughly perpendicular to the mountain range, so that seeding agent is lofted immediately upward into the targeted clouds. This orographic seeding technique was the prime strategy used to seed winter clouds throughout the WWMPP, and continued to be the main approach utilized in the Wind River Range. The success of seeding operations depends upon three things:

- The clouds of interest must contain liquid water.
- The cloud temperature at the level where liquid water is present, typically in the neighborhood of 10,000 feet mean sea level (MSL), must be colder than -5°C (23°F). Natural ice nuclei, such as crystalline soil particles, do not act to form ice crystals until the cloud is much colder (at least as cold as -15°C (5°F)). The AgI seeding agent, by virtue of its crystalline shape being very close to that of ice, begins to form ice crystals much sooner, at about -5°C (23°F). As a result, precipitation formation within the cloud starts sooner, allowing more time for the ice crystals to grow and transform into snow.
- The wind direction and speed must be such that the seeding agent released from the ground-based generators will be transported up the mountain slope and into the target clouds.

In operational seeding, the temperature criterion can be met in slightly warmer conditions as long as some of the ice nuclei still produce ice crystals. This being said, it must be noted that the magnitude of the seeding effectiveness will diminish as temperatures warm. Seeding should not occur when temperatures aloft are warmer than -5°C (23°F). Widening the temperature window for seeding increases the number of seeding opportunities. Most operational (vs. research) seeding programs use this warmer temperature criterion.

2015-2016 Funding

Funding for cloud seeding operations in the Wind River Range for the winter of 2015-2016 was provided in part by the Wyoming State Legislature's "Omnibus Water Bill – Construction" approved by the 2015 Wyoming State Legislature. Per the legislation, the appropriate funds could only be expended once formal cost sharing agreements were in place with other Colorado River Basin water users, or other interested parties for 75% of actual project operational costs. Wyoming's cost share was capped at 25%. In addition to the funding provided by the State of Wyoming, funding was also provided by the following organizations/agencies.

Southern Nevada Water Authority. The Southern Nevada Water Authority (SNWA) is a cooperative agency formed in 1991 to address Southern Nevada's unique water needs on a regional basis. SNWA officials are charged with managing the region's water resources and providing for Las Vegas Valley residents' and businesses' present and future water needs. With Colorado River water currently representing 90% of SNWA's water supply, the SNWA partners with other Colorado River Basin states to optimize and enhance Colorado River water supplies.

The Central Arizona Project. The Central Arizona Project (CAP) delivers Colorado River water via a 335-aqueduct system to customers in Maricopa, Pinal, and Pima Counties in Arizona, home to 80% of Arizona's population. The CAP diverts more than 1.6 million acre-feet annually, providing water to cities, towns, irrigation districts, Native American communities, and stores water underground for future use during times of drought or shortage. The CAP manages its Colorado River resources for current and future residents in central Arizona, and continuously seeks collaborative approaches with partners in the Colorado River Basin to protect and augment the water supplies in the Colorado River System.

Colorado River Board of California - Six Agency Committee. The Six Agency Committee was created in 1950 through an agreement among Palo Verde Irrigation District, Coachella Valley Water District, San Diego County Water Authority, Imperial Irrigation District, the Metropolitan Water District of Southern California and the City of Los Angeles Department of Water and Power. The Six Agency Committee provides funding to support actions to safeguard the members' rights and interests in the Colorado River system and for the Colorado River Board of California.

The Arizona Department of Water Resources. The Arizona Department of Water Resources (ADWR) was created in 1980 to secure long-term, dependable water supplies for Arizona's communities. The ADWR also explores methods of augmenting water supplies to meet future demands, and develops policies that promote conservation and the equitable distribution of water.

STAFF AND FACILITIES

Personnel

The primary project personnel were the meteorologists and technicians. The project meteorologists were responsible for monitoring weather conditions, determining which generators would be used, and when each generator would be turned on and off. The project technicians supplied, maintained, and operated the generators in rugged, winter conditions.

Two meteorologists and four technicians participated in the 2015-2016 operational season. Meteorologist, Daniel Gilbert was located on site in Pinedale, WY throughout the project. The second meteorologist, Jason Goehring, worked off-site from his home using weather resources available via the Internet. Both Gilbert and Goehring are Weather Modification Association Certified Operators, and between the two of them, completed all the daily forecasting, weather monitoring, and implementation of seeding operations. Technical work was conducted by Michael Paul, Bill Hocker, Rich Keely, and Jeremy Silvey, with additional technical assistance provided by Ryan Richter.

Siting of Seeding Equipment

The Wind River Range operational program utilizes the same ten ground-based ice nucleus generators (ground generators) that were employed during the Wyoming Weather Modification Pilot Program (WWMPP) (Figure 2). Nine generators were sited on the west, southwest, and southern flanks of the range. The tenth was sited on the southeastern flank, southwest of Lander. All sites were on State-owned or private lands. Permissions were established through the Wyoming Office of State Lands and Investments or private memoranda of understanding, accordingly.

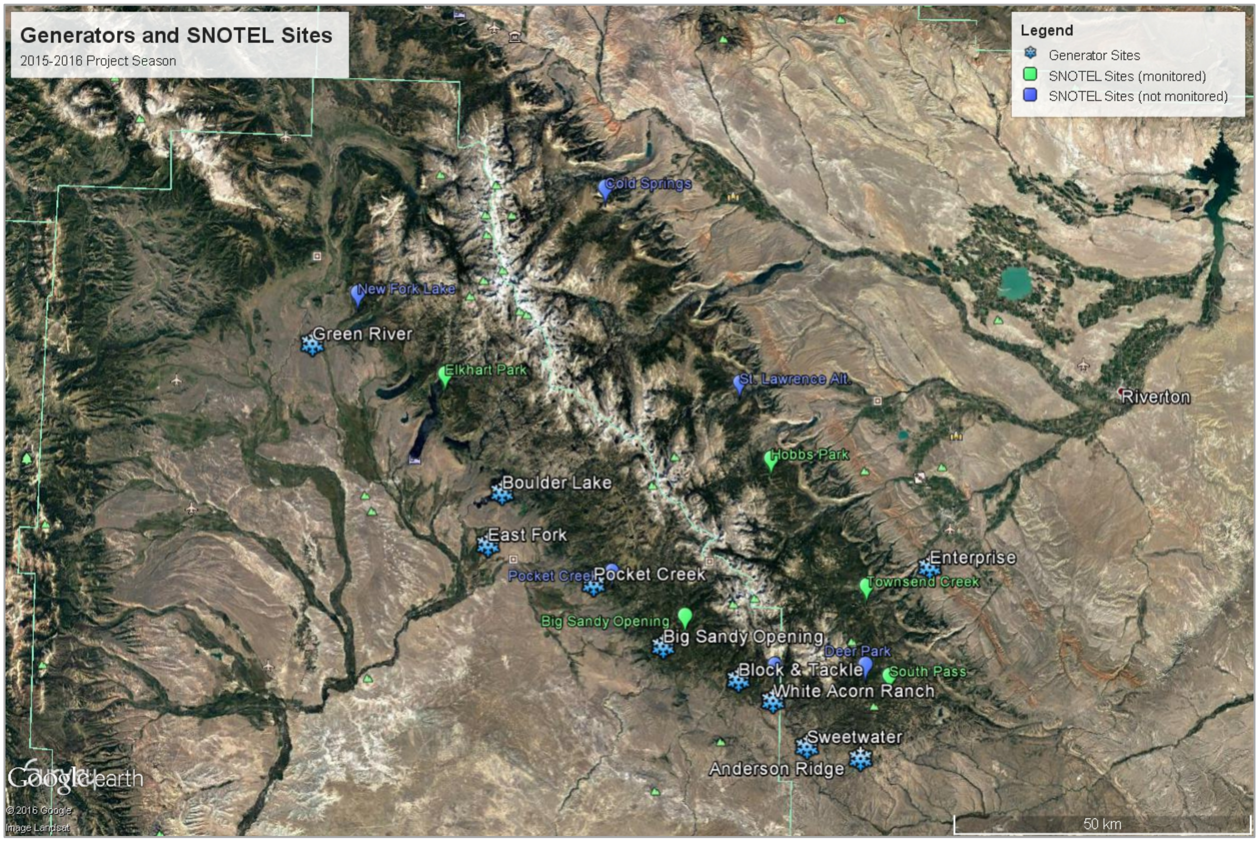

Figure 2. The locations of the ground-based ice nucleus generators are indicated by the snow crystal symbols. The green "balloons" indicate the locations of Natural Resources and Conservation Service (NRCS) snow telemetry (SNOTEL) sites used in monitoring snowpack during the 2015-2016 season. The blue balloons show the locations of additional SNOTELs that were not used because of proximity to sites that were used, or a short period of record.

The generator placement was such that individual generators could be activated according to wind direction, and as storms passed and conditions changed. The majority of seeding was conducted when winds were from the west or southwest. A number of seeding events also occurred when winds were easterly, supporting the activation of the single ground generator near Lander. During the season, operations were conducted twenty-four hours a day, seven days a week. There were a total of 27 seeding events during the season.

Ice Nucleus Generators

The ice nucleus generators were designed and fabricated by Weather Modification, Incorporated (WMI). The primary components are shown in Figure 3. The Wind River Range generators are fully independent, controlled via satellite, and powered by batteries charged by solar power. This provides the ability to site generators at higher elevations, significantly improving delivery of seeding agent to the clouds. Being remotely-controlled means that the generators can be activated and deactivated as weather conditions warrant. This results in less seeding agent being dispersed unnecessarily, as can occur with manually operated generators. All of the generator lines and fittings are made of corrosion-resistant stainless steel, necessary when high-performance seeding solutions, which contain oxidizers, are used. The generators are robust; designed to function in extreme temperatures, winds and precipitation.

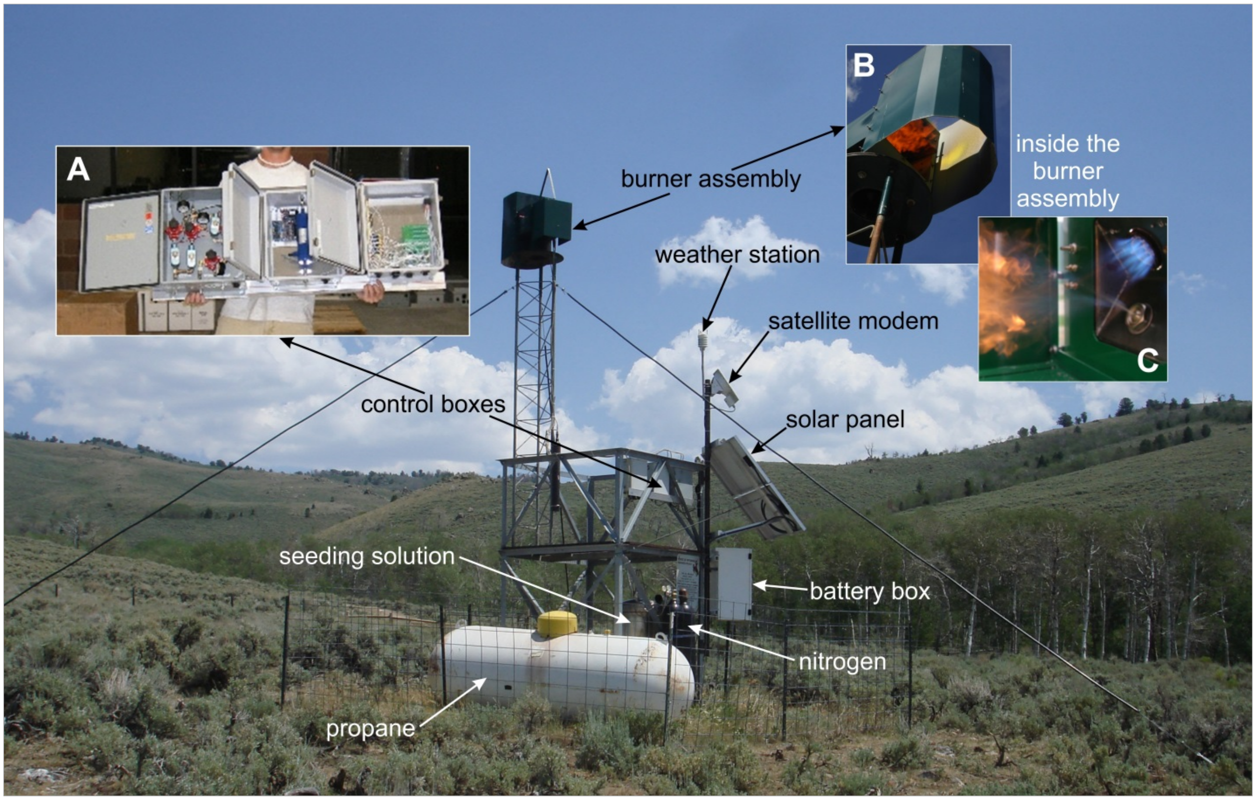

Figure 3. The primary components of the WMI remotely controlled ground-based ice nucleus generator are illustrated. Inset A, shows the contents of the control boxes. From left to right, these are: relays (electronic valves) to turn flows on and off, seeding solution flow rate regulation and measurement, and computer interface with the satellite modem. Inset B, provides a view up and into an ignited generator, and Inset C, shows how the seeding solution is atomized through a nozzle (silver disk, lower right) and into the burning propane (blue flame) and ignited (bright orange flame).

Seeding Solution

The high performance seeding solution was tested at the Colorado State University Cloud Simulation and Aerosol Laboratory by DeMott (1997). The results of those tests determined that colder cloud temperatures produce a bigger yield of active ice nuclei per gram of AgI burned. At -6°C (21.2°F), 3×10^{11} (300 trillion!) nuclei are active per gram. The yield increases markedly from -6°C (21.2°F) to -8°C (17.6°F), and even more at -10°C (14°F). However, operational programs in the western United States commonly commence seeding operations at -5 or -6°C (23 to 21.2°F). In the 2014-2015 Wind River Range operations, -6°C (21.2°F) at 700 hectoPascals (hPa) was the threshold cloud temperature used. The seeding rate was about 25 grams of silver iodide per generator, per hour. The number of generators used varied from event-to-event due to situations when the wind direction was such that only some of the generators would seed effectively.

Atmospheric Soundings (Weather Balloons/Rawinsondes)

Weather balloons were released from the WMI shop, in Pinedale, WY to help determine whether or not weather conditions (*e.g.,* temperature, humidity, & pressure) were suitable for seeding. The atmospheric sounding data were recorded and compared to the operating criteria to verify that observed weather conditions were sufficient to initiate cloud seeding procedures. Upon completion, the sounding data were immediately shared via e-mail with the National Weather Service Offices in Riverton and Cheyenne, and the State of Wyoming's Water Resources Data System (WRDS). All of the soundings were archived, and are available for any post-analysis efforts that might be undertaken.

Weather Stations

Five of the ten generator sites were equipped with Vaisala WXT-510 weather stations. These compact, tower-mounted instruments measured temperature, humidity, pressure, and wind speed and direction.

Shop and Site Servicing

Throughout the season WMI maintained a shop in Pinedale that provided project vehicle and equipment storage and served as a staging area for generator service and the preparation and release of weather balloons.

FORECASTING AND OPERATIONAL DECISION-MAKING

Meteorological Data Sources

The bulk of the weather information used for forecasting and weather monitoring was obtained from the Internet. Among these sites were those of RAP Real-Time Weather, the National Center for Environmental Prediction (NCEP), the College of DuPage, European Community satellite imagery, Northern Illinois University, and Unisys. While many of the web-based weather products (*i.e.,* National Weather Service (NWS) products) were publicly available, some data sources were project-specific.

Radiometer. A radiometer was deployed at the meteorologist's residence near Cora, WY (Figure 4). Since the presence of liquid water in the clouds over the target area is essential for successful seeding, this measurement was most helpful.

Figure 4 (right). The radiometer sited near Cora, WY. The instrument does not transmit, but passively measures the atmospheric liquid water and water vapor. (WMI photograph by Daniel Gilbert)

Atmospheric Soundings. The atmospheric soundings (weather balloons/rawinsondes) were discussed previously. Data from the soundings were immediately shared with the NWS and WRDS.

Timetables and Routines

If seeding was not underway at dawn, the following daily routine ensued.

WMI furnished a daily "first glance" update that provided an outlook into the probability of seeding operations taking place that day. This very simple form, sent to all project personnel, provided an early look at the weather expected each day Four time periods were specified, from issuance until noon, from noon until sunset, from sunset until midnight, and from midnight until dawn the next day. The probability of seeding operations occurring in each of these time periods was rated by the forecaster as *no chance*, *unlikely*, *possible*, or *probable*. Technicians used this outlook to help inform equipment operation and maintenance decisions. In instances when seeding operations were already active in the morning, the "first glance" outlook would still be issued, reflecting the status of current operations.

The early update was followed by a much more detailed forecast and weather briefing, typically disseminated to the WWDO and all funding partners by late morning via email. These daily briefings included a summary of the preceding day's weather and seeding activities, a summary of the current synoptic-scale weather pattern, and conditions likely to exist for the next 24 hours in the Wind River Range. Oftentimes weather conditions would vary sufficiently during the day that evening forecast updates were warranted and provided. The Daily Wyoming Wintertime Scale (DWWS), shown in TABLE 1. The Daily Wyoming Wintertime Scale numerically categorized the probability of seeding operations occurring.

TABLE 1. The Daily Wyoming Wintertime Scale

DWWS	SEEDING	METEOROLOGICAL DESCRIPTION
-3	*No*	Clear skies, or clear with isolated upper-level cloudiness.
-2	*No*	Occasionally clear, with cirrus, cirrostratus; or altostratus with bases above mountains.
-1	*No*	Limited coverage or short-lived orographic clouds, not enough temporal or spatial extent to warrant seeding activities.
0	*Possible*	Some orographic clouds or stratiform cloud deck(s) over mountain tops. SLW likely insufficient for seeding operations or winds clearly unfavorable.
+1	*Yes*	Orographic clouds and/or stratiform cloud deck(s) enshrouding mountain tops, winds favorable and SLW likely sufficient for seeding operations.
+2	*Yes*	Persistent orographic clouds and/or stratiform cloud deck(s) enshrouding mountain tops, SLW probable, winds favorable. Lengthy operations possible.

When all three conditions were satisfied, seeding was initiated by the meteorologist and the generator technician. The meteorologist communicated to the technician which generators would be activated, when, and for how long. The length of time a generator was activated depended upon how long weather conditions were expected to remain favorable.

Once seeding was initiated, the meteorologist tracked the real-time weather conditions. If wind direction changed, some generators could be deactivated while others would be turned on. When favorable weather conditions ended, the technician was directed to shut down all remaining active generators.

OPERATIONS

Seeding was conducted on twenty-seven occasions (TABLE 2). The most active month was December, when favorable conditions developed seven times, and the most seeding agent was released (10.2 kg). Only one of the seven events occurred in easterly flow, when the Enterprise generator operated solo. January was the second most active month with five events, all of which were quality opportunities in which at least seven generators were operated. Four seeding events occurred in February, half of which were Enterprise-only, east-slope opportunities. There were six seeding events in March, and like February, half of the events were Enterprise-only, east slope opportunities. The cloud seeding season ended with easterly upslope events dominating the scene. East slope events persisted through the end of March, and the only two events that occurred in April were short-lived opportunities, utilizing only the Enterprise generator.

In total, 31.6 kg of seeding agent were released. Generators were operated for 1,173 hours.

TABLE 2. Wyoming Weather Modification Wind River Mountains 2015-2016 Seeding Summary

Date	*Number of Generators Utilized*	*Length of Seeding (hours)*	*AgI Released This Date (kg)*	*AgI Monthly Total (kg)*	*AgI Season Total (kg)*
19-Nov-15	7	9.6	1.507		0.000
25-Nov-15	1*	24.8	0.708		0.000
28-Nov-15	1*	7.1	0.195	2.409	2.409
11-Dec-16	7	4.5	0.670		3.079
14-Dec-16	1*	18.5	0.517		3.596
17-Dec-16	9	4.2	0.883		4.479
20-Dec-16	7	10.3	1.915		6.395
21-Dec-16	9	20.2	4.251		10.646
23-Dec-16	9	5.6	1.250		11.896
24-Dec-16	9	2.6	0.700	10.187	12.596
14-Jan-16	7	7.5	1.392		13.988
17-Jan-16	6	3.1	0.497		14.485
20-Jan-16	8	12.6	1.994		16.479
23-Jan-16	9	8.1	1.658		18.137
30-Jan-16	9	18.5	3.221	8.762	21.358
1-Feb-16	1*	25.9	0.677		22.035
19-Feb-16	6	15.4	2.524		24.559
20-Feb-16	7	7.3	1.324		25.883
22-Feb-16	1*	11.9	0.283	4.808	26.166
14-Mar-16	7	3.9	0.712		26.878
15-Mar-16	7	7.8	1.450		28.328
18-Mar-16	1*	6.0	0.160		28.488
24-Mar-16	7	10.4	1.947		30.436
29-Mar-16	1*	22.9	0.572		31.007
31-Mar-16	1*	11.1	0.290	5.131	31.297
16-Apr-16	1*	3.5	0.092		31.389
18-Apr-16	1*	6.4	0.164	0.256	31.553

*seeding event with easterly flow, utilizing only the Enterprise generator

OUTREACH

WMI finds value in providing community outreach and educational presentations regarding aspects of the weather modification activities taking place in the field. During the 2015-2016 season, WMI collaborated with the Sublette County Conservation District (SCCD), which arranged for local students to visit the shop and learn about upper air soundings, and even to participate in the release of a weather balloon.

Additional outreach was achieved through the presentation of project activities at Wyoming weather modification Technical Advisory Team (TAT) meetings. The technical advisory team, initially organized by the WWDO for the WWMPP, is comprised of representatives of interested State and Federal agencies. Wyoming agencies include the State Engineer's Office, the Department of Environmental Quality, the Department of Transportation, the University Office of Water Programs, and the Game and Fish Department. Federal agency representation includes several different forests (Bridger-Teton, Shoshone, and Medicine Bow), the U.S. Geological Service, the NWS Riverton and Cheyenne offices, the Bureau of Land Management, and the NRCS. The TAT met in Cheyenne on 27 January 2016. At this meeting, WMI presented an update on the current 2015-2016 Wind River operational seeding efforts.

Figure 5 (right). Pinedale home schooled students and parents learn how to release weather balloons at the WMI shop during a 2016 public outreach event. Meteorologist Dan Gilbert (right) inflates the balloon with helium while the students guess when the balloon is large enough. (WMI photograph by Bruce Boe)

SUMMARY

The 2015-2016 cloud seeding effort in the Wind River Range began on 19 November 2015, and concluded on 30 April 2016, a duration of nearly 5.5 months. The season started four days later than normal (15 November) due to a delay in finalizing the collaborative weather modification agreements.

Twenty-seven seeding events were conducted. Seventeen events involved four or more generators, seeding in westerly or southwesterly flow. The other ten were solo events using the Enterprise generator, in easterly upslope flow. A total of 31.55 Kg of silver iodide was released in the course of 1,173 hours of generator operations.

The ice nucleus generators operated reliably, seeding as intended over 93% of the time. Generator failures occurred infrequently, in fact, only one generator, Pocket Creek, experienced two operational issues during the course of the season. In terms of seeding opportunities, the winter was 25% more active than the 2014-2015 season. Flow from the northwest is parallel to the Wind River Range axis rather than across it, so seeding isn't possible, even though snow may be falling over the range. As temperatures increased in April, seeding opportunities decreased. The final seeding event occurred on 18 April in easterly flow, and utilized only the Enterprise generator.