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ARM Aerosol Measurement Science Group Strategic Planning Workshop 2017

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Executive Summary

The Aerosol Measurement Science Group (AMSG) was tasked with evaluating the status of the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Climate Research Facility's existing aerosol instrumentation, measurement strategies, and data products in the context of ARM and Atmospheric System Research (ASR) science directions and the current and future needs of ARM data users. A workshop comprising the AMSG members and external experts in aerosol measurements was convened in February 2017 to delineate specific measurements and efforts in data product development that would align the ARM aerosol program investments well with the needs of the scientific community. Topics of discussion in the workshop included priority measurements and instrumentation to be deployed at the range of ARM sites, physical system configurations that impact the character of observables and quality of observations, calibration strategies, overarching deployment strategies for aerosol observing systems (AOS), and communication about and accessibility of data. This report provides an account of workshop discussions and prioritized recommendations for ARM supported activities that will bring measurements to quality and science-ready data products relevant to the ASR and larger science community.

Acronyms and Abbreviations

AA	absorbing aerosols
AAMS	Aerosol Aging and Mixing State
ACSM	aerosol chemical speciation monitor
AETH	aethalometer
AICE	Aerosol Inlet Characterization Experiment
ALWG	Aerosol Lifecycle Working Group
AMF	ARM Mobile Facility
AMIP	Atmospheric Model Intercomparison Project
AMSG	Aerosol Measurement Science Group
AOS	aerosol observing system
APS	aerodynamic particle sizer
ARI	aerosol-radiation interactions
ARM	Atmospheric Radiation Measurement
ARRA	American Reinvestment and Recovery Act
ASR	Atmospheric System Research
BC	black carbon
BrC	brown carbon
CAPS	cavity-attenuated phase shift monitor
CCN	cloud condensation nuclei
CESD	Climate and Environmental Science Division
CPC	condensation particle counter
CPCf	fine condensation particle counter
CPCu	ultrafine condensation particle counter
DOE	U.S. Department of Energy
DRE	Direct Radiative Effects
ENA	Eastern North Atlantic
EPA	Environmental Protection Agency
f(RH)	aerosol hygroscopic growth faction (function of relative humidity)
g(RH)	hygroscopic growth factor (quantified relative humidity)
HDTMA	humidified tandem differential mobility analyzer
HSRL	high-spectral-resolution lidar
IMPROVE	Interagency Monitoring of Protected Visual Environments
IOP	intensive operational period
IRE	Indirect Radiative Effects
MAOS	mobile aerosol observing system

NAI	Natural versus Anthropogenic Influence
NEPH	nephelometer
NOAA	National Oceanic and Atmospheric Administration
NOX	nitrogen oxides monitor
NPF	New Particle Formation
PI	principal investigator
PILS	particle into liquid sampler
PSAP	particle soot absorption photometer
PTR-MS	proton transfer reaction mass spectrometer
RH	relative humidity
SBIR	Small Business Innovation Research
SGP	Southern Great Plains
SMPS	scanning mobility particle sizer
SOA	secondary organic aerosol
SOAF	Secondary Organic Aerosol Formation
SP2	single-particle soot photometer
TAP	tricolor absorption photometer
TBS	tethered balloon system(s)
UAS	unmanned aerial system
uCPC	ultrafine condensation particle counter
UHSAS	ultra-high-sensitivity aerosol spectrometer
UV	ultraviolet
VAP	value-added product
WMO-GAW	World Meteorological Organization-Global Atmosphere Watch
WRF	Weather Research and Forecasting model
WRF-Chem	Weather Research and Forecasting model with Chemistry

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1.0 Introduction

1.1 Background

The U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Climate Research Facility has chartered the Aerosol Measurement Science Group (AMSG) to provide enhanced coordination of ARM Facility observations of aerosols and atmospheric trace gases with the needs of its users. The main objective of the AMSG is to ensure advanced, well-characterized measurements and data products for improving climate science and models as guided by the objectives of the DOE Atmospheric System Research (ASR) program and the ARM Facility's observational capabilities.

The AMSG is responsible for working with the ASR and ARM user communities to identify the required aerosol properties that can be provided by the ARM Facility that will improve the understanding of the impact of aerosols and gases on processes affecting climate and related model simulations and forecasts. The role of the AMSG is to provide expertise on the measurements and processes required to meet the aerosol science objectives of the ARM Facility and ASR programs, not to set scientific priorities or objectives in aerosol research.

ARM aerosol measurements have expanded appreciably since 2009 when investments from the American Reinvestment and Recovery Act (ARRA) were made. These investments created scientific, logistical, and financial challenges for managing measurements. Since the expansion in measurement hardware and infrastructure, the instrument operations investment by ARM has expanded, but the associated ARM software developer and translator efforts have remained largely constant, creating an imbalance in the end-to-end process of creating data products and distributing quality-controlled, science-ready data sets for the user community. ARM aerosol mentor resources continue to be strained in the ability to maintain high-quality continuous measurements due to the addition of new infrastructure and complex instrumentation.

ARM has asked the AMSG to focus on priorities to enable moving this end-to-end process forward for the most important set of measurements and to provide guidance on how measurements can be organized and managed more efficiently. Key considerations are whether there is a standard core set of instruments at all sites, where and how specialty instruments are deployed, and how personnel time and tasks are distributed to maintain high-quality measurements while simultaneously meeting science objectives. For this exercise, science direction for guiding aerosol measurements within ARM is primarily taken from the ASR community, although the AMSG has a breadth of scientific expertise to provide context for measurement decisions.

A strategic planning workshop for the AMSG, sponsored by ARM, was held February 14-16, 2017 at Argonne National Laboratory in Chicago, Illinois, to evaluate the status of ARM's existing aerosol instrumentation, measurement strategies, and data products in the contexts of ARM and ASR science directions, the current and future needs of ARM data users, and budget. The agenda for the workshop is provided in Appendix A and workshop participants, who included both AMSG members and external experts, are listed in Appendix B. The participants comprised experts in aerosol science, measurements, and deployment logistics from universities, national laboratories, and private industry. The outcomes of the workshop described in this report will aid in decision making among various options to efficiently build on current ARM capabilities to address these science needs of the ASR and ARM communities within scope and budget.

1.2 Constituent Groups

The ARM Facility has established several constituent groups to guide ARM activities in a direction that will best meet the science goals of the facility and the general atmospheric science community (Information on ARM Constituent Groups can be found at https://www.arm.gov/about/constituent-groups/). The AMSG is one of these groups, and acts on behalf of the aerosol and greenhouse gas measurement constituents.

2.0 AMSG Strategic Planning Workshop Overview and Drivers

2.1 Brief History of the ARM Aerosol Measurement Program

The first systematic measurements of aerosol properties made by ARM were at the Southern Great Plains (SGP) site in 1996, four years after ARM began measuring atmospheric radiation and cloud properties. The complexity and importance of anthropogenic aerosols to climate was being fully realized in the larger community at this time (Charlson et al., 1992), and within ARM the substantial effort and resources required for characterizing aerosol were also being realized (Penner et al., 1992.) At this time, the first Aerosol Observing System (AOS) was established and comprised measurements of aerosol number concentration and size distribution, light scattering, and light absorption. Later, size distribution measurements were discontinued due to operational challenges, but aerosol humidification and cloud condensation nuclei measurements were added. A system similar to the SGP AOS was built and first deployed in 2005 as part of the first ARM Mobile Facility (AMF1), which has since traveled extensively, collecting data from many parts of the globe.

ARM aerosol measurements remained static with these two relatively simple systems operating until the ARRA of 2009 injected funds into ARM for expanding infrastructure. Since that time the program has added an AOS to the fixed site in the Eastern Northern Atlantic (ENA), two more AOS mobile facilities (AMF2 and AMF3), and a specialty mobile AOS (MAOS) that contains more complex instruments for observing detailed aerosol composition, size, and optical properties. The original SGP system is currently being replaced with an expanded and updated system. See Chapter 21 of *The Atmospheric Radiation Measurement Program: First 20 Years* (McComiskey and Ferrare 2016) for a more detailed history of the aerosol program.

While the ARM aerosol infrastructure, number of instruments, and mentor efforts have greatly expanded with these new AOS, translator and developer investments have not expanded in step, and mentors are overtaxed in the operation of instruments that have grown in number and complexity through time. This has resulted in a lag of high-quality, science-ready data products available at the ARM Data Archive. The goals and objectives of this workshop were intended to address how available, yet limited, resources can be used to move forward the highest-priority needs of the ARM aerosol user community from production of the most valued set of measurements in the field to easily accessible, high-level, and high-quality data products in the ARM Data Archive.

2.2 Workshop Structure and Objectives

The general goal of the AMSG Strategic Planning Workshop 2017 was to identify an aerosol measurement and data product development strategy to align current ARM instrumentation and observational capabilities with aerosol science questions. More specific goals were to:

- Assess how well ARM is currently supporting pressing aerosol science questions,
- Identify gaps where ARM could be addressing these questions better, and
- Put forth strategies in each of several measurement areas to better address key questions.

To achieve these goals, the workshop was structured to evaluate the status of ARM's existing aerosol instrumentation, measurement strategies, and data products in the context of ARM and ASR science directions, the recent expansion of the AOS capabilities and resources, and the current and future needs of ARM data users.

The desired outcomes of the workshop were concrete and actionable options for efficiently building on current ARM capabilities that also address priority science needs. The following questions guided development of the outcomes:

- Is the current distribution of effort across the measurement areas and locations optimum for the science questions?
- Is the current distribution of effort across the following measurement strategies optimum?
  - Continuous ground-based facility measurements
  - Episodic ground-based facility measurements
  - Aerial Facility measurements
  - PI-supported measurements (ground or air).

Workshop participants were asked to consider the following constraints when answering guiding questions and developing outcomes:

- **Budget**: working within current and potential future funding constraints and making the best use of existing resources
- **Siting**: working within ARM's existing infrastructure versus developing strategies based on potentially ideal locations for priority science
- **Prioritization**: considering whether the outcomes allow for trade-offs between number and quality of measurements and/or data products – the charge to participants included a recommendation for a strong prioritization of efforts that would allow the program to invest in the level of measurements appropriate for addressing science priorities.

The two-and-one-half-day workshop convened with an introductory session that included a welcome, the charge to participants, an overview of the deliverables and outcomes, and participant introductions. This was followed by overviews of current measurements in the AOS, aerosol data products, and the status of the AOS Harmonization effort.

While distinct from the AMSG, the AOS Harmonization is highly relevant to the group and the goals of this workshop. This effort was initiated in 2013 to harmonize ARM aerosol data products made from old and new AOS that were operating simultaneously across the ARM Facility at that time. Given differences in AOS physical configurations, data ingest, Quality Assurance/Quality Control approaches, and general data processing (including corrections and calibrations), AOS Harmonization would assure a consistent final data product structure across all systems for the end data user. Since its inception, AOS Harmonization has had to address several unexpected issues related to data management, and has grown to encompass critical issues such as unifying and evaluating corrections to filter aerosol absorption measurements, among others.

This workshop structure followed established AOS Harmonization measurement areas (Table 1), that were devised to represent categories of measurement recommendations made to ARM by the AMSG for an AOS core configuration that could exist at all sites (see Appendix C, Section III: AMSG Recommended Core Configuration of Aerosol Observing System [AOS] Capabilities). An additional area found in Table 1 is the AOS System Configuration and Operation. This is a critical aspect of in situ aerosol measurements that dictates the air sample characteristics and whether that sample is consistent or distinct for each measurement (making those measurements comparable or not). Thus, the system configuration is arguably as relevant to the science drivers as the instruments and measurements themselves, and it is an area that has differed widely between the older and newer AOS systems within ARM.

Table 1. AOS measurement areas, associated instruments, measurements, data products, and some examples of issues to be addressed for each area during workshop discussions.

AOS Measurement Areas	Instruments	Measurement	Product	Issues
Number Density	CPC, CPCf, CPCu	N_{CN}	Number concentrations	
Size Distribution	SMPS-nano, SMPS UHSAS APS	Electrostatic mobility diam. Optical scattering diam.	dN/dlogDp 2-150 nm, 10-500 nm dN/dlogDp 60-1000 nm	Can different measures of size be combined across the full size range?
Optical Properties	Neph PSAP, CLAP, TAP, Aethalometer, PASS CAPS	Scattering/Backscattering Absorption Extinction	AOSAOP: σe, σs, σa, ω, g	Absorption corrections? No aeth absorption or AAE Automated closure? AE for all quantities?
Gas Phase Aerosol Chemistry	NOx Box O3 Analyzer SO2 Analyzer PILS	NO, NO_2, NOx, NOy, O3 SO2		Operational/sampling protocol? (where & when)
Aerosol Composition	Aethalometer SP2 ACSM	BC rBC SO_4, NH_4, Cl, NO_3	Mass conc & size distr OA-COMP	Effort intensive Not operational?
Hygroscopic Activity and Cloud Droplet Activation	Neph + humidograph HTDMA CCN, SFTG-CCN	f(RH) g(RH) N_{CCN}	Scatter/backscatter spectrum, 40-80% Size distribution spectrum, Number conc spectrum, 0.2-1.2 %SS	(dev) 0.05-1.5 %SS/150 sec
Greenhouse Gases	AOS stack Flasks LiCor CO2 Flux Precision Gas System	CO_2, CH_4 CO2, CO_2, CH_4, CO_2-C^{12}, CO_2-C^{13}, CO, N_2O		
System Configuration and Operation			T, RH, Impactor function, humidograph function, flows	Heating or drying control? Size cut utility?

Given the above objectives for the workshop, sessions were organized to address:

1. Science Drivers and Priorities Identification

2. Measurement Area I: HTDMA, Size Distributions, and *f*(RH)
3. Measurement Area II: Optical Property Consistency and Aerosol Composition
4. Measurement Area III: System Configuration and Operation
5. Integrating Strategies and Resolution of Option Conflicts.

Measurement areas that are highly related to each other were grouped into three different categories for the sake of simplifying discussions. Two measurement areas were omitted for this workshop: number density (because the AMSG had recent discussions leading to solutions in this area) and greenhouse gases. While the AMSG has the responsibility of managing recommendations for greenhouse gases, discussions of this topic would have required a distinct set of experts, and time did not permit for additional sessions to cover this area.

The first and last sessions were held in plenary, while the three measurement areas were structured into three breakout groups, each addressing all three measurement areas. Figure 1, which shows the structure of the measurement areas for breakout discussions and their relation to existing Science Drivers and ARM Siting infrastructure, was presented and distributed to the group at the start of the workshop. Figure 1 also has a set of questions addressing: i) Observations and Data Products, ii) Measurement Strategy, and iii) Measurement Issues that all groups were asked to answer in their breakout discussions. After the breakout groups developed recommendations and solutions for each area, all groups came together to share their different perspectives and to integrate solutions. The following discussion summarizes the sessions on Science Drivers and Priorities Identification and the three measurement areas.

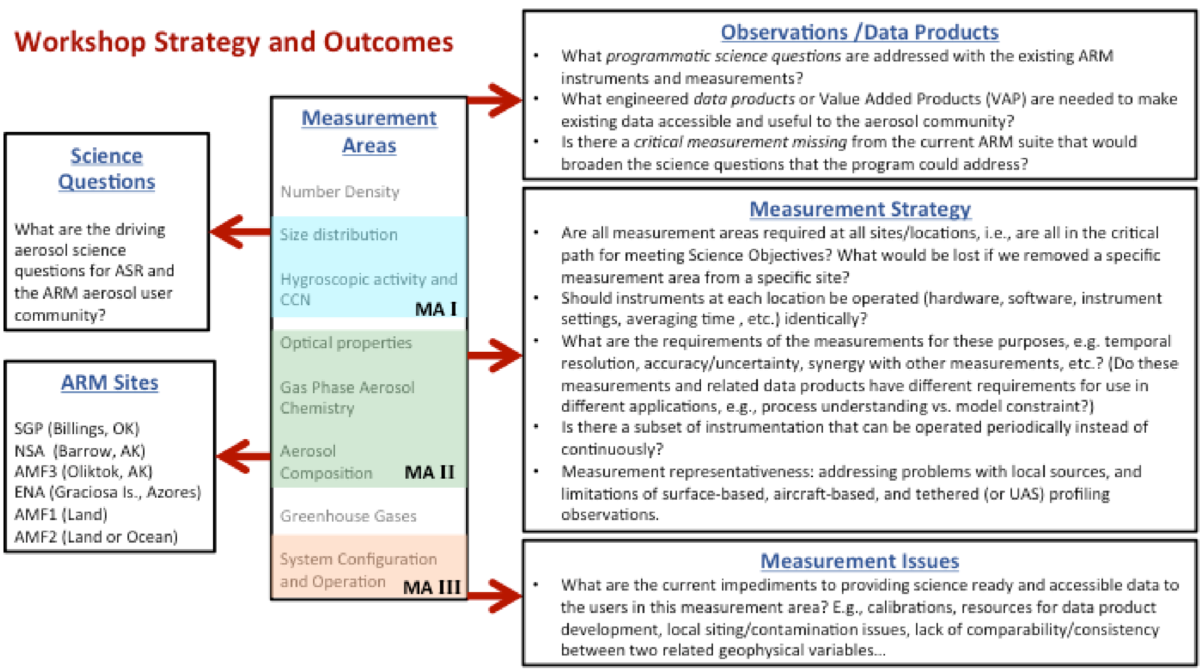

Figure 1. Schematic of the workshop strategy and guiding questions for the desired outcomes used to design and execute activities and discussions.

Questions from Figure 1 that all breakout groups were asked to consider are listed below for readability. These questions were designed before the workshop to address existing needs and issues known within the ARM aerosol measurement program. These questions guided breakout discussions within the separate groups, accounting for similarities in the discussions among the different groups. The intent of this framework for the breakout groups was to understand whether there were appreciably differing solutions to these issues or whether a strong concurrence or consensus could be met within the broad set of expertise present.

Observations/Data Products

- What *programmatic science questions* are addressed with the existing ARM instruments and measurements?
- What engineered *data products* or value-added products (VAP) are needed to make existing data accessible and useful to the aerosol community?
- Is there a *critical measurement missing* from the current ARM suite that would broaden the science questions that the program could address?

Measurement Strategy

- Are all measurement areas required at all sites/locations; i.e., are all of them in the critical path for meeting Science Objectives? What would be lost if we removed a specific measurement area from a specific site?
- Should instruments at each location be operated identically (hardware, software, instrument settings, averaging time, etc.)?
- What are the requirements of the measurements for these purposes, e.g., temporal resolution, accuracy/uncertainty, synergy with other measurements? (Do these measurements and related data products have different requirements for use in different applications, e.g., process understanding versus model constraint)?
- Is there a subset of instrumentation that can be operated periodically instead of continuously?
- Measurement representativeness: addressing problems with local sources, and limitations of surface-based, aircraft-based, and tethered (or UAS) profiling observations.

Measurement Issues

- What are the current impediments to providing science-ready and accessible data to the users in this measurement area? (e.g., calibrations, resources for data product development, local siting/contamination issues, lack of comparability/consistency between two related geophysical variables).

3.0 Workshop Discussion

3.1 Science Drivers

As previously discussed, the scope of the AMSG does not include establishing science questions or drivers for guiding ARM aerosol measurements; rather, the drivers are taken from the ASR Science Team and larger ARM data user community. For the purpose of scientific context for this workshop, high-level science questions were drawn from a range of sources including the ASR Science Plan, CESD workshops, ASR Aerosol Life Cycle Working Group meetings, and other relevant ASR and ARM breakout meeting reports. Before arriving at the workshop, participants were asked to review several of these documents and to prepare a white paper that addressed several questions pertaining to the adequacy of measurements and the impediments to providing the ideal set of data for ARM Archive users of aerosol products. The white paper assignment and list of background reading can be found in Appendix C.

Several themes emerged from the participant white papers. The most common was perspectives on overarching measurement strategy, where two approaches were repeatedly contrasted for their different benefits: deploying a uniform, core set of measurements versus deploying conditional and intensive measurements. The first lends itself to climatological applications, context for process studies, and model constraints, among others, while the latter is based in addressing specific science objectives for process understanding and model parameterization development. The need for better absorption measurements was an almost ubiquitous comment across white papers, while other suggestions for new instruments, measurements, or data products were also common, although the specifics were application-dependent. Many of the white paper authors expressed concern for improved data quality and several specific suggestions were repeated throughout the papers: i) implementation of calibration standards and process (e.g., following existing protocols or creating an ARM standard), ii) reduced down-time statistics through better field technician training, operations paradigm, or instrument spares, iii) better communication of data quality through web site development, and iv) resources for lab characterization of complex (or all) instruments. Finally, the desire for redundancy and closure in observations using fundamentally different approaches to providing measurements of the same geophysical quantities was called for in many of the white papers, and closure, perhaps automated and implemented by the Data Quality Office, among measurements of different aerosol properties was recommended, which could serve both as an instrument health check and to improve assumptions used to relate aerosol properties. This last point is critical for improving understanding of aerosol measurements and reducing uncertainties.

After the workshop introductory session, an interactive exercise was conducted to gain an early view of what participants felt were the most relevant science questions driving needed improvements to the ARM AOS measurements and data sets. Participants were asked to identify and prioritize the science questions that are most relevant to each of the measurement areas outlined in Section 2.2 and that would form the foundation for discussions throughout the rest of the workshop. Six science areas were self-specified by participants during the exercise (i.e., not provided in advance) and were assigned to the measurement areas as summarized in Table 2: 1) Direct Radiative Effects (DRE), 2) Secondary Organic Aerosol Formation (SOAF), 3) Aerosol Aging and Mixing State (AAMS), 4) New Particle Formation (NPF), 5) Natural versus Anthropogenic Influence (NAI) on Aerosol Properties, and 6) Indirect Radiative Effects (IRE).

In some instances, participants provided very specific and descriptive responses that were science oriented but could not be uniquely identified with one of the above science areas, including processes that control aerosol composition and morphology, understanding water uptake by aerosol composition, linking detailed aerosol and optical properties to remote-sensing observables, heating rate profiles dictated by aerosol, vertical distribution of aerosols, contribution of black and brown carbon to aerosol absorption, etc. Many of these science drivers could apply to any or all of the six science questions identified above. To preserve the accuracy of responses but not interpret the attribution of responses to the six question(s), the authors have identified such responses as “cross-cutting”.

Participants were provided 6 “ballots” – 2 green (highest priority), 2 yellow (higher priority), and 2 red (high priority) – to characterize the overall importance of a particular measurement strategy by science questions. The measurement strategy choices were constrained to the six categories listed in Table 1 as discussed above: size distribution, hygroscopic activity and cloud condensation nuclei, optical properties, gas-phase aerosol chemistry, aerosol composition, and system configuration and operation.

Table 2 summarizes the results of balloting that took place at the beginning of the meeting. Because the ballots were placed on large posters, all participants were able to visualize the results, with the range of value of different measurement categories to various science areas indicated by density of ballot color (see photos in Appendix D). This helped set the stage for much of the discussions and breakouts that followed over the next two days of the meeting. Although budget constraints were known to be a factor at the beginning of the workshop, it became clear as the workshop proceeded that more restrictive choices might have to be made than were initially being considered.

Table 2. Results from the initial interactive prioritization activity to relate the established aerosol measurement areas with priority science drivers. Red: high priority; yellow: higher priority; green: highest priority. For more detailed results see Appendix D.

	Size Distribution	**Hygroscopic Activity and CCN**	**Optical Properties**	**Gas Phase Aerosol Chemistry**	**Aerosol Composition**	**System Configuration and Operation**	**Totals**
Direct Radiative Effects	1 2 0	0 3 2	15 4 1	0 0 1	5 0 1	4 1 2	24 9 9
Secondary Organic Aerosol Formation	0 2 0	0 0 0	0 0 1	2 2 2	4 0 1	0 0 1	6 4 5
Aerosol Aging and Mixing State	0 1 0	0 1 1	1 0 0	2 0 2	4 1 0	1 0 0	8 3 3
New Particle Formation	1 2 1	0 0 0	0 0 0	1 1 0	2 2 0	0 0 1	4 5 2
Natural versus Anthropogenic Influence	1 1 0	0 0 1	1 0 0	0 1 0	4 0 1	0 1 1	6 3 3

	Size Distribution	Hygroscopic Activity and CCN	Optical Properties	Gas Phase Aerosol Chemistry	Aerosol Composition	System Configuration and Operation	Totals
Indirect Radiative Effects	1 2 0	0 4 2	0 0 0	0 0 0	1 0 1	0 0 2	2 6 5
Cross-cutting	0 2 1	0 1 2	0 0 0	0 0 2	0 1 1	0 4 2	0 8 8
Total by priority	4 12 2	0 9 8	17 4 2	5 4 7	20 4 5	5 6 9	50 38 35
Total	18	17	23	16	29	20	123

These results provide some perspective on the mindset of participants at the beginning of workshop on the importance of each measurement area for answering the priority science drivers in the breakout sessions. Aerosol composition measurements were highly valued and a strong need for addressing issues with optical properties measurements and system configuration and operation was indicated. Size distribution measurements were also given some value, with less given to gas-phase chemistry and hygroscopicity. A full accounting of the exercise can be found in Appendix D. A modified version of this exercise was conducted later in the workshop after the breakout discussions; those results are presented in Section 4.0.

3.2 Measurement Area I: HTDMA, Size Distributions, and *f*(RH)

3.2.1 Aerosol Size Distributions

Aerosol size distribution is arguably the most fundamental property of an aerosol population. It can be used to calculate optical properties (more accurately in conjunction with aerosol composition information) and is a critical piece of information in models for linking the emissions of aerosol and aerosol precursors to their radiative (and other) properties. This fact was clearly recognized in each of the breakout discussions and a clear consensus emerged that measurements of the full size range of particle size distribution should be prioritized as a measurement in ARM AOS. This may appear to conflict with the results from the poster exercise shown in Table 2, but these discussions brought forward the recognition that size distribution is critical for understanding aerosol source, optical properties, and cloud droplet activation – in addition to the obvious applications to new particle formation – and is thus applicable to the majority of science questions addressed in that exercise. The point was also made that operational size distribution measurements at all sites could and should be used to characterize the performance of the 1 and 10 μm impactors that dictate the sample for the optical property measurements. Discussion previous to the workshop had revolved around the crucial nature of knowing the impactor cutoff and relative humidity of the air sample, both of which will crucially impact measurements of optical properties.

Given the fundamental importance of the aerosol size distribution in determining aerosol life cycle and radiative effects, it was recommended that the full size range be measured using a combination of scanning mobility particle sizer (SMPS), ultra-high-sensitivity aerosol spectrometer (UHSAS), and aerodynamic particle sizer (APS) at every AOS location. The nano-SMPS provides a size distribution at smaller particle sizes and is especially useful for new particle formation (NPF) studies, but this measurement adds complexity and expense and was not recommended for deployment with every AOS. Rather, the SMPS could be used to indicate when and where there are likely NPF events, and the difference in number concentrations determined by the condensation particle counter (CPC) and ultrafine condensation particle counter (uCPC) could be used for a bulk quantification of the magnitude of the event. The nano-SMPS could be deployed at a particular site to obtain more detailed information about processes in such a useful location, for example, the current nano-SMPS deployment at SGP where a past field campaign detected NPF. There was a recommendation that the APS be run on a separate (dried) inlet to minimize losses of large particles and complications resulting from uncertain characterization of inlet efficiency at large particle sizes.

A subject of previous discussions within the ARM and ASR aerosol communities has been the production of a *value-added product (VAP) for the ARM Data Archive that merges all sources of aerosol size distribution information across different size ranges into a single product. While there were some arguments against such an effort, most participants felt that this was an effort that should be a high priority for data product development.* Size distribution is such a fundamental property that it is widely used and in high demand. However, different instruments with different measurement approaches measure in different size ranges; thus, production of a merged product would be an intensive task and would require development by individuals with expertise in both aerosol measurement and theory.

A comment noted that such a VAP would allow better accessibility to the data and might also enhance usage by making it ‘easy’ to use size distribution information in process studies and closure experiments and to ingest it into model analyses. Further, it would be preferable that ARM provide the product rather than leaving it to the general community to create a range of products for individual applications that may not be consistent or as accurate as they could be. Concerns for developing such a product were that differences in calibrations and the underlying physics of the measurement approaches to size determination (e.g., aerodynamic versus electro-mobility versus optical diameters) leave some ambiguity as to what "size" is the best to use, and require some assumptions regarding shape, density, etc. to reconcile the measurements, regardless of which "size" is selected. However, it was noted that this concern softened through ensuing discussion with regard to the utility of this VAP as an important part of quality assurance and instrument characterization. It was suggested that the process of creating the VAP could actually help to overcome these concerns through better understanding of the relationship among the measurements and perhaps make for their more extensive use. Finally, the Data Quality Office, mentors, and other research groups have already performed a first cut of this exercise, so pooling existing expertise for the effort would be relatively straightforward.

3.2.2 Aerosol Hygroscopicity

While discussion related to size distributions resulted in conclusions that were in general agreement, those related to particle growth factors (Humidified Tandem Differential Mobility Analyzer [HTDMA; $g\{RH\}$] and to scattering enhancement [wet nephelometer + humidification system; $f\{RH\}$]) with relative humidity (RH) proved much more difficult to resolve. Several points were considered in the course of the discussion: 1) the utility of g(RH) and f(RH) measurements (i.e., how they are actually used and how important is that utility to the priority science directives), 2) the complexity and effort involved in running these instruments to useful accuracy, and 3) whether the complicated data output could be presented to the user community in a more accessible and useful manner.

In theory, the utility of measures of aerosol humidity-related properties is obvious. While air samples and their aerosols are dried prior to measurement of aerosol properties for good reason (discussed in Section 3.4), they are then not representative of the aerosol under ambient conditions. Information on particle growth and scattering enhancement factors allows for the determination of optical properties and physical processes as they would occur in that ambient environment. It also provides a comparable measure of aerosol extinction to that determined through remote sensing – albeit only near the surface – which inherently measures ambient (i.e., humidified) aerosol in the full atmospheric column. Whereas measurements of both dried and ambient aerosol optical properties are important, in practice achieving these are exceedingly difficult in two particular aspects: first, to get an accurate measure of aerosol hygroscopicity representative of the ambient aerosol, and second, to achieve closure with remote-sensing measures of extinction due to other confounding factors such as sample efficiencies in the in situ systems (i.e., significant particle loss) and irregular vertical distributions of aerosols that an in situ system at the surface cannot capture. However, aerosol hygroscopicity is a critical aerosol property to understand for radiative forcing impacts of aerosol with different compositions, Additionally, it is essential information for developing reliable aerosol models that must calculate optical properties from composition and size information, and for understanding how trends in changing aerosol composition due to changes in anthropogenic behaviors (e.g., shifts in primary energy modalities) impact aerosol radiative forcing trends. It is critically important that a definitive objective for the use of aerosol hygroscopicity data be defined to determine whether it is worthwhile to make these measurements, and if so, how they should be made.

A consensus was not reached on whether the scientific impacts of these measurements, made at their current level of accuracy, justify the difficulty and cost of operating the HTDMA and/or *f*(RH) systems. ARM has invested in the improvement of the *f*(RH) system and, as discussed in Section 4.0, *there was a strong call at this workshop for better characterization for complex instruments such as the HTDMA, including a comparison of the new commercially available HTDMA procured by ARM with the previous research-grade instrument run at SGP for several years. Thus, it was suggested that a full suite of instruments deployed at a single testbed, likely SGP, might be the best path forward to develop useful measurements of these critical properties and understanding their utility for addressing the priority science questions.* This subject is also discussed in more detail in Section 4.0.

Aside from the difficulties in making measurements of aerosol hygroscopic properties, some recommendations were made for data products that would improve their usability for scientists who do not have the expertise (or resources) to process the raw data themselves. Simplified descriptions such as average kappa (a single-parameter quantity that characterizes aerosol hygroscopicity) by particle size bin could be provided. Additionally, the data could be collapsed into a set of scalars that retain some characteristic of the details of the modes observed in most growth factor distributions. Finally, there were comprehensive discussions of adding size-resolved CCN measurements to provide a kappa measure that could be achieved by reconfiguring instruments that ARM currently deploys. Doing so would require a two-column CCN, with one used for the conventional scanning of supersaturations for activation statistics and the other receiving flow from the SMPS. A relationship between kappa and particle diameter for supersaturated conditions could then be compared with HTDMA-derived kappa under sub-saturated conditions. This approach might involve trade-offs such as reduced temporal resolution in either the SMPS or CCN scans, and the methodology would have to be further explored for feasibility and desirability.

A common question is whether *f*(RH) or *g*(RH) is preferable (if a choice between them must be made)? The answer typically depends on the application. Ultimately, the goal of the measurements is to determine humidified optical properties (scattering), which would imply that the choice should be *f*(RH). However, *g*(RH) provides more direct information on the composition-dependent hygroscopic properties of the aerosol. If the size-resolved CCN and HTDMA measurements were made in tandem, the accuracy of the calculated ambient aerosol scattering could be evaluated; that is, the measured *f*(RH) value could be compared with that computed from *g*(RH) measurements. While closure studies are currently being pursued, this comparison would be difficult given the uncertainties in the measured *f*(RH) quantity and in the absence of an ambient scattering or extinction measure from the same sample volume as the in situ measurements. The potential for this latter measurement exists in an open-path extinction cell developed by the National Oceanic and Atmospheric Administration (NOAA) that is recently commercially available. Closure efforts that would make use of such an approach will be discussed in more detail in Section 4.0.

3.3 Measurement Area II: Optical Property Consistency and Aerosol Composition

Common themes that ran through the optical property measurements discussions were improved absorption measurements and exploring approaches to obtain aerosol composition information. Closure experiments among optical property measurements (scattering, absorption, and extinction) were deemed important, as were efforts to explore the relationships between those properties measured in situ and from ground-based remote sensing. The latter is typically used as a model constraint but does not yield as much information as in situ measurements, and uncertainties are of concern, especially for absorption. This was an important topic of discussion at the DOE CESD-sponsored Absorbing Aerosol Workshop in January 2016. Our follow-on discussions addressed the instrumental and deployment logistics issues that would need to be addressed for exploring the science questions put forth in the Absorbing Aerosol Workshop Report.

3.3.1 Aerosol Absorption

Significant time was spent discussing the capabilities, limitations, and historical and logistical considerations surrounding the use of the PSAP for absorption measurements. The PSAP does not provide a direct measurement of absorption, but rather provides a measurement of optical transmission, from which absorption is determined using one of several correction schemes. Filter interactions with the aerosol material has been addressed in the literature and various correction schemes have been put forth. However, these correction schemes have not been reconciled into a process and set of products that represent best practices for reporting absorption measurements. Several related needs were identified. A reconciliation of PSAP correction approaches is a priority, and ARM is well equipped to handle this exercise. As a note, since the workshop, ARM mentors and translators have begun to tackle this problem and have made substantial progress.

An alternative to the PSAP is the aethalometer, with a new model (AE-33) recently available. This instrument also uses a transmission measurement through a filter medium to infer aerosol absorption, but differs from the PSAP in several ways. It has a wider wavelength distribution and additional channels that can provide enhanced information on the wavelength dependence of absorption and thus some proxy information on aerosol composition. This information is directly applicable to better identifying absorption from black carbon versus organic substances, a current and important gap in knowledge. Because the PSAP and the historically used filters are no longer manufactured, a transition from the use of the PSAP measurement is inevitable. *The AMSG recommends investment in a comprehensive understanding of corrections for both the PSAP and aethelometer (AE-33), including past and future filter media, and rigorous intercomparisons between the two at this stage to prepare for this transition.* Such an effort will provide the information upon which to base a decision on whether or not to replace all PSAPs with AE-33s in the near term.

A direct, in situ measurement of absorption from a robust and sensitive instrument that can be run continuously and operationally, in keeping with the needs of ARM, is lacking and sorely needed by the research community. *Research-grade instruments exist, but development efforts (at the time of this report) have not progressed far enough to produce a robust, field-ready instrument that can be run in the continuous mode that ARM requires. The Small Business Innovation Research grant (SBIR) program from DOE was identified as one viable vehicle to push these development efforts forward and a recommendation that DOE consider this as an SBIR topic was made.* The lack of a direct absorption measurement is a critical limitation to the global aerosol community and to our ability to understand the radiative impacts of different types of aerosol on climate with the required measurement certainty. This is another area that has seen progress since the workshop, with ASR program managers being informed of and processing the need for such an SBIR.

3.3.2 Aerosol Composition

Composition is critical for understanding aerosol source and lifecycle processes, as well as developing aerosol parameterizations for climate models. The ACSM is the only instrument in the AOS suite that provides a direct measurement of composition, and its continued use in all AOS was recommended. ARM has been the first to attempt running this instrument operationally (continuously) in various aerosol environments around the world, including persistently clean environments, but ACSM operation has encountered some challenges. Specific issues were discussed at the workshop and a two-day meeting of the ARM ACSM mentor and translator with experts at Aerodyne, Inc., the instrument manufacturer, was scheduled after the workshop. Since the workshop, *this meeting has resulted in confidence that the ARM ACSM operation is robust and the resulting data is of high quality and very useful for the science questions prioritized here. Continuing such close collaborations with instrument manufacturers is recommended to provide benefits in measurement quality to ARM and larger communities.*

A critical gap that was ubiquitous in discussions during this breakout was the lack of observations on refractory aerosol composition: primarily sea salt and dust species. While the presence of these aerosols might be inferred through size distribution and optical property measurements, this approach is inconclusive and unsatisfying in the context of the above priority science questions. Filter measurements would provide the most efficient path toward providing this information, but they suffer from reduced temporal resolution and are still labor intensive and costly. *A consensus suggestion was that ARM partner with existing networks, such as the Interagency Monitoring of Protected Visual Environments (IMPROVE) Network, that have a bulk process that is more cost efficient.*

Gas-phase chemistry is important for determining particle-formation processes and for providing context regarding the conditions under which aerosol particles grow and evolve. However, measurements of gas composition tend to be complex and difficult to make continuously in the field in harsh environments.

The MAOS has housed a suite of instruments including the proton transfer reaction mass spectrometer (PTR-MS) and nitrogen oxides monitor (NOx) detector that have not been run regularly at fixed sites. Other useful measurements are those of O_3, made more routinely in most of the AOS, and SO_2, slated to be measured at SGP because of its contribution to new-particle formation studies. *Given the complexity of these measurements, several proposals were put forth including the prioritization of having them at SGP to fully characterize the aerosol formation environment there, given the full suite of measurements available at the site and ARM's interest in high-resolution modeling. The possibility of moving this suite among sites for year-long deployments to gain a characterization of the annual cycle at all ARM sites, or using shorter Intensive Operations Periods (IOPs) at a site prioritized as scientific needs dictated, was also proposed.* Some locations such as the Arctic may have instrument sensitivity issues due to low concentrations that would need to be considered before deployment. Another option that was discussed is to enter into partnerships with other agencies or groups such as the Environmental Protection Agency (EPA), or at least adopting their protocols that maintain rigorous standards for calibration systems and for data quality and assurance.

3.3.3 Optical Consistency and Closure

The need for optical closure exercises was agreed upon by the group, and these exercises are relatively straightforward if all of the appropriate inputs are available. With the recent addition of CAPS instruments, a consistency check on whether the sum of the measured scattering and absorption coefficients equals the measured extinction coefficient is possible. Currently ARM has the capability to perform this closure at one wavelength, but extending this ability to three wavelengths with the spectral cavity-attenuated phase shift monitor (CAPS) instrument would be highly advantageous and would address questions on the accuracy of the wavelength-dependent absorption measurements from the PSAP. Without a direct measurement of absorption, and given the uncertainties inherent in the filter-based measurements, a better understanding of all approaches to determining aerosol absorption (i.e., the difference of extinction and scattering) is needed. *Analysis of long-term, continuous closure in a range of conditions among these different approaches has the potential to yield new and valuable information about historical measurements.*

The use of the open-path extinction-cell measurements, introduced above for evaluating closure with humidified measurements, of dry aerosol properties to infer information about the aerosol hygroscopicity was discussed during this breakout. Also, the need for extending consistency checks and attempting closure to physical (size) and chemical information was stressed. Finally, a topic of much discussion was the need to relate information gained from detailed measurements on aerosol properties at the surface to those in the full column. Two primary questions arise: 1) how representative are the surface measurements of the column-integrated properties, and 2) what are the non-uniform vertical distribution of aerosol properties and how do they impact radiative effects? Aerosol aloft can be measured either in situ by manned or unmanned aircraft or tethered platforms or by making retrievals from passive (column) or active (profile) remote sensing. *There was a very strong conclusion that ARM is uniquely situated to answer these questions, and there was a strong recommendation that exploring the relationship between surface and column-integrated or column profile aerosol properties should be a high priority for the ARM and ASR aerosol community.* These cross-cutting activities will be discussed more in Section 4.0.

3.4 Measurement Area III: System Configuration and Operation

As mentioned above, the AOS configuration dictates the air sample characteristics and is thus a critical aspect of the measurements. Specific features of the physical system that are highly relevant to the science priorities indicated here are the sampling efficiency (i.e., the extent to which particle losses occur in the inlet system), the sample humidity (which controls the size distribution and optical properties), and whether measurements of different types of aerosol properties – physical, chemical, and optical – are inter-comparable (in that they are represented by the same air sample and suitable for the closure studies described above). Each of these issues has been discussed within the AMSG and/or ASR and ARM aerosol communities before this workshop. These discussions were intended to bring previous questions regarding these topics to consensus.

3.4.1 System Heating/Drying and Humidity Control

One consensus during the workshop was that the aerosol sample should be dried prior to making size cuts, measuring optical properties, and measuring some chemical and physical properties. This has been a topic of considerable discussion before the workshop as different-generation AOS have employed different approaches to sample heating, drying, or humidity control. Changes in the sample humidity can dramatically shift the size distribution of the aerosol, and typically effects are large near the peak of the mode where 1 μm-diameter size cuts are made by the impactor in both AOS designs. These changes strongly affect scattering and extinction measurements in the two size regimes (i.e., less than and greater than the cut), as well as the interpretation of such measurements and the implications for using them to infer information on composition and source. The World Meteorological Organization-Global Atmosphere Watch (WMO GAW) guidelines for aerosol optical property measurements recommend heating (or drying) the sample to a given RH for consistency in observations through time and space for the sake of comparability. Making all measurements at a specific (typically low) RH allows for consistent studies of aerosol processes and lifecycle (when combined with physical and chemical properties); however, as described above, such an approach does not provide information on the ambient aerosol properties or radiative effects. A collective statement at the workshop was that control of humidity of the aerosol sample is of utmost importance for understanding the effects of the size cut and the relations among optical, physical, and chemical measures of the aerosol.

There are two approaches to bring an aerosol sample to low RH (ideally considered to be ~30% by the participants, recognizing the two older AOS units heated the inlet and thus dried the incoming air to ~40-45% RH): heating of the air, or physically drying the air. Sample heating is the much simpler approach and widely used by the aerosol community; however, it may cause volatilization of aerosol material and thus loss of aerosol mass, impacting measured size distributions and optical properties. The extent to which this occurs depends on aerosol composition, making determination of the magnitude and importance of these artifacts difficult if not impossible, especially on an operational basis. Drying is the preferred approach, but for the sample volume that the ARM AOS draws, it is an engineering task that will require considerable resources for development. Even so, the group felt very strongly that this was a priority area for resources to be spent. Using heat sparingly after the sample is initially dried could be used to fine-tune humidity control potentially without appreciable losses. *Because of the importance of accurate and known size cut characterizations, and the impact of relative humidity on size cut, it was recommended that the impactors be characterized and that the RH at the impactors be monitored during routine operation.*

3.4.2 Inlet Sampling Efficiency

Characterizing the size-dependent particle loss in the inlet (stack) is critical for understanding the relationship of the measured aerosol properties to their lifecycle processes and to radiative impacts in the ambient atmosphere. ARM has invested in this exercise in the Aerosol Inlet Characterization Experiment (AICE) currently being undertaken at Brookhaven National Lab. *It was stressed at the workshop that this characterization be done, where practical, for the full size range of particle measurements made by the AOS (diameters ~3 nm to ~30 μm). Further, the characterization should include the drying elements and impactors used in the AOS.*

3.4.3 Temporal Resolution and Consistency

Currently, aerosol optical properties are measured circa one-second resolution and reported in high-level data products as one-minute averages. It was agreed that this temporal resolution is adequate to address the priority science questions and should not be changed. Some instruments require longer integration times and may be reported at resolutions up to 30 minutes. Additionally, some scanning instruments have schemes that are based on sensitivity to aerosol concentration whereas others are set for symmetry within an hour for ease of averaging and using with other data sets. This produces data sets with a range of temporal frameworks that users ultimately would like to integrate for consistency and closure studies. *Although no consensus was met on this issue, it was suggested that each of these instruments be left to run at the resolution that best complements the particular measurement and that data users determine the best averaging and/or integration schemes for their particular applications.* Closure experiments do require integrating these disparate data sets and thus a solution for temporal matching is necessary, but for now it is left to the data user to develop that solution according to the particular needs of his/her exercise.

3.5 Deployment Strategies

Several configurations were discussed during the workshop for operating the range of basic and specialty instruments in the AOS. Since 2014, ARM has asked for a ‘core configuration’ of instruments that would address the scientific needs of the community. First developed under an idealistic framework that would meet all the scientific needs of the ASR Aerosol Lifecycle Working Group (ALWG) and be deployed at all sites, this suite of instrumentation was costly and complex to operate and would require significant new purchases beyond what ARM already had. The strategies below embody a more efficient framework that considers both the priority science discussed above and resource efficiency, working mostly with what is already owned and supported by ARM, and considering different priorities based on particular site location and science drivers.

3.5.1 The Comprehensive Measurement Site

There was strong support for a single comprehensive aerosol measurement site within the Facility, entailing instrument co-location for the majority of the in situ aerosol measurements that ARM operates. The first advantage to this approach is the ability to better understand many aspects of the full aerosol lifecycle, maximizing scientific impact in a resource-limited scenario. The SGP site has been heavily instrumented for more than 20 years now and is considered the best location for the most comprehensive aerosol measurement suite in the ARM Facility. With a large investment in the development of high-resolution modeling tools and a process designed for use of comprehensive data sets with model output, the SGP is a natural place to concentrate aerosol measurements. This approach also provides a testbed for conducting consistency and closure experiments and developing new data products. With all measurements co-located, a host of closure experiments could be developed for instrument health, data quality, and scientific purposes. Available ancillary data would provide a better understanding of why closure was achieved or not.

3.5.2 Vertical Profiles and Column Aerosol Characterization

For improving estimates of aerosol radiative forcing, one question is whether surface aerosol measurements are adequate. While the detail and coherency provided by in situ systems are necessary for developing process understanding and relationships among aerosol properties for model development, this information is insufficient for calculation of aerosol radiative forcing at any time and place. Characterizing aerosol vertical distributions is critical for determining aerosol radiative effects and at the least the column extinction should be monitored. The co-location of various aerosol in situ measurements should be extended to co-location with remote sensors that provide information on aerosol properties in the atmospheric column above the surface. *ARM is uniquely situated to pursue a better integration of high-detail surface in situ data with remote-sensing capabilities.* The latter provide information with higher spatial resolution globally, can be used to link to information gained from satellite-based remote sensing, and are critical for climate model constraint. The use of airborne in situ measurements to aid in building relationships between these two types of measurement would be very useful on an episodic basis. *The use of unmanned aerial systems is highly desirable for this purpose and their implementation at SGP would be an advantage in this effort.*

3.5.3 Episodic Deployment of Complex Instrumentation

While the prospect of operating all complex aerosol instrumentation continuously at many or all ARM sites all the time is daunting, conversations regarding different strategies for episodic or rotational deployment of intensive measurements occurred throughout the topical discussions. While its final configuration is not established, the ARM Facility currently maintains a Mobile AOS (MAOS) – a single shelter that houses a single suite of instruments that make more complex composition measurements. These measurements are critical to understanding aerosol source and formation processes, but cannot be made continuously with current resources. Options for operating MAOS or a modified suite of instruments in addition to a ‘core configuration’ that were suggested were a year-long deployment rotating among sites (to characterize the annual cycle at each site) and scientifically driven IOP modes at a given site. *Developing a structure in which ARM could maintain instruments it already owns in an episodically deployable manner was favored. Housing the instruments with experts within the DOE laboratories, rather than with mentors supported by programs, could save on costs while providing expertise when needed.*

3.5.4 North Slope of Alaska: Specific Considerations

While not explicitly on the agenda for the workshop, discussions of the distribution of aerosol measurements across the North Slope of Alaska occurred extemporaneously. The advantages of the longer deployment of the ARM AMF3 at Oliktok Point for supporting UAS and tethered balloon system (TBS) activities and for developing measurement methods and sampling protocols were appreciated. However, from the perspective of aerosol process and lifecycle science, long-term measurements in close proximity to oil extraction activities were not considered a priority. There is little time when the boundary layer at Oliktok Point is not strongly influenced by extraction activities, making these measurements less relevant to regional Arctic science questions. *While having at least one year of comprehensive measurements was deemed essential for context and for better understanding the impacts of this industry on local- to regional-scale aerosol properties, it was suggested that the suite of measurements in the AMF3 could be better applied at a more regionally representative site such as Utqiaġvik (Barrow).* Maintaining a smaller set of measurements at the surface for context around UAS/TBS flight capabilities at Oliktok should be considered.

Advantages to having the AOS suite of measurements at Barrow were discussed and, in addition to the more representative environment, included the continuous vertical profiling of aerosol properties with the high-spectral-resolution lidar (HSRL) that occurs at that site. Given the strong stratification of the atmosphere at this site, determining whether the surface measurements can be meaningfully related to column measurements is critical. The additional information of how the surface and aloft layers evolve over the seasonal cycle would contribute greatly to understanding aerosol forcing in the region. If the AMF3 were to be moved to Utqiagvik, it would need to be determined whether the sensitivity of the instruments is adequate to provide useful background Arctic measurements.

4.0 Integrating Strategies and Operational Scenarios

4.1 Post-Discussion Prioritization Exercise

Following the conclusion of the three breakout discussions, a version of the exercise performed at the beginning of the workshop to connect measurement needs with priority science questions was again conducted, and is referred to as the ‘After Activity.’ Participants were not asked to identify specific science questions as with the ‘Before Activity’; therefore, the results regarding science priorities from the Before Activity were assumed unchanged. Rather, a prioritization of measurements and actions needed to provide the high-quality data for the science questions discussed previously was requested. It was instructive to recreate measurement prioritizations after these comprehensive discussions and note the resulting recognition of the need to weigh options against each other. The results are provided in Table 3.

Table 3. Results of the prioritization of measurement strategies activity after breakout discussions and considering prioritizations due to resource limitations. Red: high priority; yellow: higher priority; green: highest priority.

	Size Distrib-ution	Hygroscopic Activity and CCN	Optical Properties	Gas Phase Aerosol Chemistry	Aerosol Composi-tion	System Configura-tion and Operation	Documenta-tion Outreach Communicat ion	Total
	10 7 4	1 5 3	7 9 4	2 1 3	5 5 6	8 8 10	3 1 6	36 36 36
Total	21	9	18	6	16	26	10	108

The objective prioritization reflected in the exercise is consistent with the summary of the discussions that occurred throughout the breakout sessions. Other needs not originally considered in the design of the workshop discussions, but that came to light during those discussions, were resources for instrument characterization and calibration process development, improved communication to the data user community, and improved documentation. During the breakout discussions, it became clear that documentation, outreach, and communication for users was a critical need that is not yet realized.

Table 4 shows the rank (by total vote) for the individual Before and After Activity measurement strategies, as well as overall rank of the combined Before and After Activity measurement strategies. While not statistically significant, there was a pooling of results for higher priority for System Configuration and Operation; Documentation, Outreach, Communication; Aerosol Composition; Optical Properties; and Size Distribution measurement strategies, and a pooling of results of lower priority for Hygroscopic Activity and CCN and Gas-Phase Aerosol Chemistry measurement strategies. There was largely no difference between the results of the Before and After Activities, and those that did exist were more or less refinements of the Before Activity after the Breakouts, which allowed more in-depth discussions of the actual measurements made at all the ARM sites.

Table 4. Results of the rank of measurement strategies activity by total before and after workshop discussions.

	Size Distribu-tion	Hygrosco-pic Activity and CCN	Optical Proper-ties	Gas-Phase Aerosol Chemistry	Aerosol Composi-tion	System Configura-tion and Operation	Documentation Outreach Communica-tion
Rank - Before	5	4	2	6	1	3	-
Rank - After	2	6	3	7	4	1	5
Combined rank total	7	10	5	13	5	4	5
Combined rank	3	4	2	5	2	1	2

Specifics on approaches to implementing these prioritizations are given in the next section.

4.2 Summary of Measurement and Data Product Recommendations

4.2.1 System and Instrument Priorities

Several priorities and points of consensus emerged from the workshop discussions regarding aerosol instrumentation and geophysical quantities measured. Points of consensus were:

1. A full (~3nm to ~30 µm dry diameter), size distribution with the SMPS, UHSAS, and APS should be measured as a first priority at all sites.

2. Diffusion drying (rather than heating) should be used to the extent possible in all cases to control sample RH, and that RH should be consistently held at a sufficiently ‘low’ value that reduces ambiguity in particle size and scattering properties. Theoretical analyses and pilot studies will be required before implementing the drying strategy.
3. Temporal sampling resolutions should be maintained at the most appropriate for each particular measurement, with integration strategies left to the data user.

Prioritization of other measurements/instruments can generally be represented by the following list; however, consensus was not established for this list and it is expected that priorities would change depending on location or the focus of the study.

- 3.1. Dry extinction, scattering, and absorption (CAPS, NEPH, PSAP/TAP/AETH)
- 3.2. Composition, (ACSM, SP2 in limited spatio-temporal sampling mode, PILS)
- 3.3. One- or two-column CCN scanning in current operating mode
- 3.4. Direct absorption measurement by new technique (requires development via SBIR or other)
- 3.5. Fixed ‘high’ RH scattering (NEPH at high humidity, ~ 90%)
- 3.6. Ambient extinction (open path extinction cell, new purchase)
- 3.7. Hygroscopic growth factors (HTDMA, after characterization)
- 3.8. CCN, size distributed (in-line with SMPS; precludes current operational mode of CCN)
- 3.9. Ozone
- 3.10. Carbon monoxide
- 3.11. Other gas-phase measurements (PTR-MS, NOx)

The list above includes a direct measure of aerosol absorption by a new technique (3.4). It was noted that:

4. Support for the development of a new direct absorption instrument might come from a DOE SBIR and that the topic be considered for an upcoming call for proposals.

Given the theoretical importance of aerosol hygroscopicity but the lack of consensus in determining the best practical method for its measurement, the option of providing a kappa measure that could be achieved by reconfiguring instruments that ARM currently deploys gained some traction.

5. Reconfiguration of a two-column CCN with one being used for the conventional scanning of supersaturations for activation statistics and the other column receiving flow from the SMPS.

4.2.2 Locational and Sampling Priorities

The first locational priority expressed by the group was:

1. A single comprehensive site from which to study aerosol process is desired over smaller sampling suites spread across more locations.

The obvious choice of locations is the SGP given the potential for integration with a range of ancillary measurements and the focus on development and improvement of high-resolution models. The need to develop remote sensing for continuous sampling of the full column aerosol was highlighted and the heavy instrumentation at the SGP site, and the possibility of increased profiling by UAS in the near future, lend further support to maintaining a premier set of aerosol measurements at this site. The need to develop remote-sensing measurements and data products for continuous sampling of the column aerosol was highlighted.

The second priority was:

2. Maintain an ARM Mobile Facility AOS for proposal-driven campaign activities.

Given the focus of the ASR aerosol community on process understanding, this is viewed as a critical capability of the ARM Facility. It is also the most comprehensive, campaign-deployable system in the U.S., so this capability should be preserved.

The third priority was:

3. Move the Oliktok Point AOS to Barrow for long-term operations after the AMF3 deployment period is completed.

The importance of the Arctic to global climate understanding and the many outstanding questions on aerosol impacts in this region make it a highly desired capability to maintain.

Currently, ARM infrastructure includes an additional AMF and a fixed site in the Eastern Northern Atlantic (ENA). These are highly valued capabilities for which support is desired if resources permit. Thus, there was a consensus for:

4. Continued operational support for the additional AMF and ENA AOS.

While not discussed in any depth at the current workshop, a framework for efficient aerosol measurements within these capabilities could be addressed to tailor measurements to the specific needs of the location or facility (i.e., not necessarily requiring the full list under 4.2.1).

Finally, strategies for supporting additional measurements were addressed:

5. Operating a MAOS facility with specialized – primarily gas-phase and detailed aerosol composition – measurements.

It was agreed that these associated instruments are probably too resource-intensive to operate continuously. Options for episodic operation discussed were: i) running a suite of specialized instruments for a year at fixed sites to gain understanding of the seasonal cycle, ii) running the suite for short durations approximately four times in a year to characterized the seasonal cycle, then rotating to other locations, or iii) running in IOP mode driven by specific needs and/or proposals, but no consensus was reached as to the best one. Again, specific frameworks for operation could be discussed more fully when the layout of fixed and mobile sites and available resources are better known.

4.2.3 Data Product Development

Clear priorities were expressed for time expenditure by ARM translators, developers, and principal investigators (PIs) serving as scientific expertise in developing aerosol data products.

1. The ongoing AOS Harmonization effort was viewed as essential and should be completed.

This effort addresses several aspects of the data that are required for accessibility, proper understanding and use by scientists, and simply improving the quality of data provided to the user of the ARM Archive. Data documentation and communication issues are further detailed below, but AOS Harmonization provides other benefits such as uniformity in calibrations, corrections, and quality control applied to the data. It is a necessary first step in offering high-quality, science-ready data to the community.

Specific value-added products (VAPs) were recommended by the group:

2. A merged size distribution VAP, to create a continuous particle size distribution across different instrument measurements, given the importance and wide use of the aerosol size distribution measurements.
3. Two types of closure experiments:
   a. Among measured optical properties (extinction, scattering, and absorption) as a function of one (green) or three (blue, green, red) wavelength(s) in the visible range
   b. Among optical properties, size distributions, and chemical composition.

These experiments would indicate which measurements are consistent with others and which are not, providing opportunities for improving measurement quality and/or improving stated uncertainties of some quantities. Additionally, if automated, they could be used by the Data Quality Office and mentors as an indicator of instrument health. Since the focus of the ARM aerosol data user is on aerosol processes, this latter experiment would also ease the use of and build confidence in the use of disparate but related aerosol properties used to better understand aerosol source and evolution.

4.2.4 Needs for a High-Quality, Successful Aerosol Measurement Program

4.2.4.1 Instrument and System Characterization

Naturally, discussions during the workshop turned to measurement quality. Since the rapid expansion of the AOS suite, new and more complex instrumentation has required added effort to conform these measurements to ARM protocols, notably continuous operation. It was noted that in some cases there was little time for mentors to fully characterize new instruments in the lab before deployment. Such characterization would enable a level of familiarity and expertise that would i) ensure that accurate measurements are made, ii) allow proper configuration of the instrument for ARM operation, iii) facilitate troubleshooting in the field and assisting field technicians, and iv) detect subtle errors in the measurements. While the CCN and ACSM are now seeing intensive time investments for characterization, the HTDMA was noted as a new and relatively complex instrument that would benefit from such intensive characterization. The larger message was that:

1. Mentors should be afforded more time, not only in the lab, with the instruments, especially with new instruments, and also with AMF instrumentation between deployments.

Specific instruments and system components that require dedicated characterization to improve the quality and usability of the data provided by ARM were also highlighted:

2. Complete the characterization of AOS inlet efficiency for the size range of aerosols measured through continues support of AICE.
3. Provide a characterization of existing corrections to filter absorption measurements that are used to process ARM PSAP and aethalometer data.

4.2.4.2 Calibration Protocols

A discussion of instrument calibration focused on the unique operating protocol within ARM. While there are calibration standards for some in situ aerosol measurements, not all have an accepted process. To provide greater user confidence in the data, it was suggested that any WMO or other widely accepted calibration process, where one exists, be officially adopted by ARM and carried out by mentors. In the absence of such an existing process, one that reflects the needs and requirements of the Facility should be developed and carried out by ARM mentors.

1. Clearly define calibration protocols for all in situ aerosol measurements, either by adopting widely established protocols or developing in-house, ARM-specific protocols.

4.2.4.3 Documentation and Communication

Finally, data accessibility and usability was an unplanned yet prominent discussion throughout the workshop. It was noted that the ARM Archive can be confusing for aerosol data users in several ways. The data level and what it represents, especially for QA/QC, is not always clear when searching for data. The state of the data set for corrections and calibrations applied is also not always easy information to locate. Some of these issues will be addressed and remedied by the AOS Harmonization effort working with the Archive to make this information more visible to the user. But, workshop participants thought that it was critical – on par with making the highest-quality, calibrated measurements – to improve data access through easier understanding of what aerosol data is available at the Archive and where to find it.

1. Improve ARM Archive data access through more direct and simplified understanding of what is available, where to find it, and what post-processing protocols were applied.

The same was true for the availability of particular measurements at any given site, location, or within a given measurement facility, an important feature not only for a user searching for data, but also for a prospective ARM PI writing a proposal. While not all prospective PIs will be aerosol scientists themselves (and thus not necessarily intimately familiar with the ARM measurement suites in the various AOS), an explicit listing of what is available in which location/system, and the measurements, geophysical parameters, and data products it will provide is needed. This amounts to restructuring the AOS web pages to provide a more transparent and simple interface with the user community. This effort was considered an equally high priority with developing new data products.

2. Restructure AOS web pages to provide a transparent and simple interface for the user community.

4.3 Scenarios for Cost-Efficient Operation

The priorities outlined above fall into several categories. Given limited resources, scenarios for how to implement recommendations while integrating priorities from different categories in a single list is desired. While most discussions at the workshop were not guided primarily by resource limitation scenarios, the group was asked to consider how the above priorities would be ranked in the case of withdrawal of partial support for the ARM aerosol measurement program.

The consensus at this workshop was to first preserve measurements over other activities such as data product development, which could be commenced at a later date if support became available. However, the need to provide a reasonable and sustainable suite of measurements across all AOS, and to limit measurement suites based on locational needs, was also recognized. Deploying different suites of aerosol measurements at the different ARM sites complicates the distribution of mentor, translator, and developer time, but this approach benefits the science while maintaining efficiency. A prioritization of deployments and tasks is provided below based on the workshop outcomes. Further definition of instrument lists for each location beyond the highest-priority comprehensive measurement site was not done; that task could be accomplished between the AMSG and site science teams in the future. It must be noted that consensus was reached only on some of these issues. This is one realization of a prioritized scenario agreed upon by the workshop participants, although other scenarios could be argued.

1. Deploy a comprehensive AOS to SGP (4.2.2.1). Measurements in this system would include:
   - Size distribution (~3nm-~30 µm dry diameter; SMPS, UHSAS, APS)
   - Number concentration (CPCf, CPCu)
   - Two-column CCN scanning in current operating mode
   - Dry extinction, scattering, and absorption (CAPS, NEPH, PSAP or TAP and AETH)
   - Composition (ACSM, SP2 in limited spatio-temporal sampling mode)
   - Ambient extinction (open path extinction cell, new purchase if resources allow)
   - Hygroscopic growth factors (HTDMA, after characterization)
   - *f*(RH) (NEPH with humidograph system after development and characterization)
   - Ozone
   - Carbon monoxide
   - SO_2 and nano-SMPS
   - NOx
2. Maintain an ARM Mobile Facility AOS (4.2.2.2). Measurements in this system would include:
   - Size distribution (~3nm-~30 µm dry diameter; SMPS, UHSAS, APS)
   - Number concentration (CPCf, CPCu)
   - Two-column CCN scanning in current operating mode
   - Dry extinction, scattering, and absorption (CAPS, NEPH, PSAP or TAP)
   - Composition (ACSM)
   - Hygroscopic growth factors (HTDMA)
   - Ozone
   - Carbon monoxide
3. Maintain and ENA AOS and AMF2 AOS at a level of complexity similar to #2 as funding for ‘large’ efforts permits (4.2.2.4).
4. Complete AOS Harmonization (4.2.3.1).

5. Measure the full dry size distribution (~3nm-~30 µm; SMPS, UHSAS, APS) at all ARM sites where AOS are deployed (4.2.1.1).
6. Develop and implement sampling protocols for episodic deployment of gas-phase measurements (PTR-MS, PILS) to be determined by ALWG and AMSG, possibly proposal driven (4.2.2.5). Consider housing complex instrumentation for episodic deployments at DOE laboratories.
7. Develop a drier system for the AOS to bring sample to 'low' RH without or with minimal heating (4.2.1.2).
8. Develop improved ARM aerosol instrumentation and measurements web pages with associated improvements to information accessible from the Archive (4.2.4.5).
9. Provide mentor resources for instrument characterization and development of calibration protocols (4.2.4.1).
10. Complete Aerosol Inlet Characterization Experiment (AICE) exercise to characterize inlet particle losses across the full measured size distribution (4.2.4.2).
11. Support a full characterization of filter absorption measurement corrections (4.2.4.3).
12. Develop calibration protocols (4.2.4.4).
13. Develop a Merged Size Distribution VAP (4.2.3.2).
14. Support the development and adoption of a new, direct absorption measurement, potentially through a DOE SBIR (4.2.1.4).
15. Move AMF3 AOS to Utqiaġvik (Barrow) after Oliktok Point deployment period has ended. Determine sensitivity of instruments and suitability for measurement of background Arctic aerosol (4.2.2.3).
16. Develop automated closure procedures for related aerosol property measurements (4.2.3.3).
17. Reconfigure CCN and size distribution instruments to provide size-resolved CCN measurements and kappa values (4.2.1.5).

Many details of the practical implementation of these recommendations are not included here, but would be addressed by the AMSG as the higher-level plan is established.

Given a specific resource limitation scenario, the prioritization list might be revised to support smaller efforts where larger ones cannot be supported, yet some funding remains. In this case, the list above could be shifted to accommodate different levels of funding. It is difficult to prioritize for cost-efficiency purposes without knowledge of the costs of these efforts. The workshop participants did not have such information on which to base the outcome. There was strong support for cost analyses of the above activities from which ARM could make more informed decisions, but those analyses are far outside the scope of this report.

5.0 References

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McComiskey, A and RA Ferrare. 2016. Aerosol Physical and Optical Properties and Processes in the ARM Program, Meteorological Monographs, No. 57, American Meteorological Society, eds., doi:10.1175/AMSMONOGRAPHS-D-15-0028.1.

Penner, JE, RJ Charlson, JM Hales, N Laulainen, R Leifer, CR Molenkamp, T Novakov, J Ogren, LF Radke, SE Schwartz, and L Travis. 1992. Priority Recommendations for Aerosol Measurements in the ARM Program, Lawrence Livermore National Laboratory Report UCRL-AR-112918.

Appendix A

Agenda and Workshop Format

AMSG Strategic Planning Workshop
February 14-16, 2017

Day 1: Tuesday, February 14

8:30 AM	Welcome and Logistics (Hickmon)
8:40 AM	Workshop Charge (Mather)
9:00 AM	Workshop Deliverables and Outcomes (McComiskey)
9:15 AM	Participant Introduction (Sisterson)
9:30 AM	AOS Measurement Overview (Springston)
10:00 AM	AOS Harmonization and Data Products Overview (Flynn)

BREAK 10:30 – 10:45 AM

10:45 AM	Science Drivers and White Papers Overview (McComiskey)
11:15 AM	Science Priorities Identification Activity (Group)

LUNCH 12:30 – 1:45 PM

1:45 PM	Measurement Areas I: HTDMA, Size Distributions, and *f*RH MA I Overview (15 min) Breakout Groups I.A, I.B, I.C (90 min)

BREAK 3:30 – 3:45 PM

3:45 PM	Measurement Areas I: HTDMA, Size Distributions, and *f*RH MA I Group Summary (45 min)
4:30 PM	Measurement Area II: Optical Property Consistency and Aerosol Composition MA II Overview (15 min) Breakout Groups II.A, II.B, II.C *part 1* (45 min)

ADJOURN Day 1 5:30 PM

Group Dinner – pay your way

Day 2: Wednesday, February 15

8:30 AM Measurement Area II: Optical Property Consistency and Aerosol Composition
continue Breakout Groups II.A, II.B, II.C (45 min)
MA II Group Summary (45 min)

BREAK 10:00 – 10:15 AM

10:15 AM Measurement Locations and Siting Issues
Boutique instruments, MAOS operational strategy, siting and sample contamination mitigation strategies

11:45 AM Measurement Area III: System Configuration and Operation
MA III Overview

LUNCH 12:15 – 1:30 PM

1:30 PM Measurement Area III: System Configuration and Operation
Breakout Groups III.A, III.B, III.C (90 min)

BREAK 3:15 – 3:30 PM

3:30 PM Measurement Area III: System Configuration and Operation
MA III Group Summary (60 min)

4:30 PM Integrating Strategies, Priorities, and Costs Discussion (Mather)

ADJOURN Day 2 5:30 PM

Dinner on your own

Day 3: Thursday, February 16

8:30 AM Integrating Strategies and Resolution of Option Conflicts

BREAK 10:30 – 10:45 AM

10:45 AM Outcome Reporting Plan

Appendix B

Workshop Participants

ARM Facility
Jim Mather
Nicki Hickmon
Jimmy Voyles

Co-Chairs
Allison McComiskey
Doug Sisterson

Participants – AMSG
Manish Srivastava (representing Jerome Fast)
Stephen Springston
Connor Flynn
Art Sedlacek
Gannet Hallar
Chongai Kuang
Mike Ritsche
Allison Aiken
Josh King

Participants – External Invitees
Tim Onasch
Yan Feng
Ernie Lewis
Don Collins
Qi Zhang
Gavin McMeeking
Kerri Pratt

Call-in Participants
Jessie Creamean
Nicole Riemer
Pat Sheridan
Jim Smith
Jason Tomlinson
Jian Wang

Appendix C

White Paper Directive

C.1 Aerosol Measurement Science Group (AMSG) Strategic Planning Workshop White Paper Directives

January 24, 2017

Dear AMSG Strategic Planning Workshop Participants,

Thank you for agreeing to participate in the AMSG Strategic Planning Workshop. The overarching goal of the workshop is to determine the efforts required to make existing ARM aerosol measurements meaningful and useful in addressing current programmatic (ARM/ASR/CESD) science questions. A summary of aerosol-relevant science questions/directions is provided here to help guide this effort. These points have been extracted from a range of sources including the ASR Science Plan 2010, CESD workshop reports, Aerosol Life Cycle Working Group meetings, and white papers and breakouts of ALWG associated focus groups.

The AOS Committee and AMSG have worked in the past to establish a list of core measurements that is consistent with these science directions (also provided below) and has, to a large extent, been implemented by ARM. Our workshop discussions will be centered on what can be achieved with ARM's existing instrumentation and measurement infrastructure.

We ask you to prepare a white paper (~1-3 pages) in response to the following questions and considerations prior to the workshop to provide a backdrop for the technical measurement discussions that are planned. We expect your responses to be driven by your own personal background and experience, therefore it is not necessary to address each of these questions for the range of science objectives and measurements presented here. Please strive to address the primary questions and work in the secondary considerations as appropriate.

Primary Questions

- What are current impediments to using ARM measurements for addressing ASR/CESD aerosol science issues?
- To what extent is the current array of ARM measurements and data products appropriate and adequate for addressing ASR/CESD aerosol science issues?

- How can we move treatment of these measurements forward to provide useful data to the community?
- Are there measurements or synergies that you consider critical to addressing current gaps in aerosol science (guided by the programmatic questions/direction provided here?)
- Do these measurements and related data products have different requirements for use in process understanding and predictive modeling?
- What are the requirements of the measurements for these purposes, e.g. temporal resolution, accuracy/uncertainty, measurement synergy, etc.?

Secondary Considerations

- What observations, observational strategies, or data products have been missing? Please consider near-term (<5 years) and long-term (5-10 years) goals, even if the latter requires development of capabilities (i.e., measurement technology does not currently exist.)
- Consider locational priorities and whether there is a uniform core configuration of measurements/data products or whether measurements strategies should vary with location and the related science objectives. Assume here that resources are constrained so that it may not be possible to deploy all instruments to all sites so that providing a clear understanding of the most critical measurements at any given location may be important.
- Consider measurements strategies – what measurements should be core or run in a long-term and continuous manner with the highest levels of quality control versus what 'boutique' measurements can be run in IOP mode to gain the most information with efficient use of resources.
- How are remote-sensing and airborne measurements required to answer the critical science questions and how should they be integrated with ground-based measurements?

C.2 Science Drivers for AMSG Strategic Planning

The following is a distillation of objectives and directions from various sources: the ASR Science Plan 2010, CESD workshop reports, Aerosol Life Cycle Working Group meetings, and white papers and breakouts of ALWG associated focus groups. Links to the original documents are provided when possible.

ASR Science Plan 2010 (http://asr.science.energy.gov/publications/program-docs)

The overarching goal related to aerosol: improve understanding of the roles of aerosols in the climate system and specifically to decrease uncertainty in radiative forcing by aerosols. The following topics are detailed:

New Particle Formation – understand the molecular processes leading to the nucleation and growth of new particles

Aerosol Aging and Mixing State – improve understanding of the composition, size, and surface properties of aerosol by coagulation, condensation, and surface reactions, and the state of aerosol mixtures with various external and internal mixing morphologies; SOA formation processes and parameterizations;

influence of aging on black carbon optical and microphysical properties; development of bulk parameterizations based on single-particle knowledge

Aerosol Direct Radiative Forcing – accurate determination of aerosol optical properties and hygroscopicity from size distributions, composition, and morphology for model parameterization improvements; use of local and column radiative closure; better understanding of the absorption properties of black carbon containing particles for direct and semi-direct radiative forcing

Natural versus Anthropogenic Influences on Aerosol Properties – distinguish natural and anthropogenic influences on aerosol radiative properties

ALWG Focus Groups (http://asr.science.energy.gov/science/working-groups/focus-groups)

New Particle Formation – development of accurate models that predict new particle nucleation and growth rates and CCN compositions through a better understanding of physico-chemical properties and mechanisms; development of mechanistic models and incorporation into regional- and climate-scale models to quantify the effect of new particle formation on climate

Aerosol Aging and Mixing State – sensitivity of climate-relevant properties of particles to the aerosol mixing state and the level of complexity needed to represent these properties in models; the level of morphological detail sufficient to represent aerosol atmospheric lifetimes, optical, and cloud nucleating properties accurately; science questions:

> Q1: What is the impact of mixing state on the climate-relevant properties of aerosol particles?
>
> Q2: What mixing state information should be included in models that quantify aerosol climate impacts?
>
> Q3: What mixing state information should be measured in the field and in the lab?
>
> Q4: How can we connect measurements (lab and field) to each other and to modeled mixing state information?

Secondary Organic Aerosol – processes of SOA formation and reactivity that are missing in global climate models and have large potential implications on radiative forcing areas of study:

- Viscosity/phase
- Growth mechanisms
- Sulfate as a trigger or regulator for SOA production and properties.

DOE CESD Workshops

Absorbing Aerosol (http://asr.science.energy.gov/publications/program-docs)

- What are the contributions of black carbon (BC), brown carbon, and dust to aerosol absorption across the solar and terrestrial spectrum and how do these vary with atmospheric conditions (e.g., relative humidity [RH])? How can these contributions be attributed to source (e.g., natural versus anthropogenic)? How might these contributions change in a changing climate?
- There are large model/measurement discrepancies in aerosol-radiation interactions (ARI) forcing by BC. Measurements of AAOD using existing surface-based, remote-sensing networks (AERONET,

SKYNET, ARM Facility) also include contributions from brown carbon (BrC) and dust, which must be subtracted to quantify BC specifically. What are the contributions to these discrepancies from uncertainties/inaccuracies in the measurements, in AAOD separation (BC versus BrC versus dust), and in BC inventories, versus those that are intrinsic to the models (e.g., transport, aging timescales, relating concentration to absorption)? Can these discrepancies be reduced with current in situ techniques?

- What are the spatial and temporal scales necessary to accurately capture absorbing aerosol (AA) processes? What is the best way to represent AA size distributions, optical and microphysical properties, and their evolution in models? To what extent are model/measurement discrepancies due to model representation versus measurement uncertainty? What factors govern the vertical distribution of AA on local and regional scales?
- Combustion of biomass and biofuels is a major source of AA. However, other co-emitted species can alter the optical properties, lifecycle, and thus net forcing from AA. What factors and processes control the net radiative effects of AA? How do these factors and processes vary by region and across scales? How might they behave in a changing climate?
- Given the unique ability of AA to redistribute energy through the atmospheric column via localized heating from absorption, what are the impacts of AA on atmospheric thermodynamics, atmospheric circulation, and surface-atmosphere feedbacks (especially cloud responses)? How might these responses change in a changing climate? How do these impacts affect the hydrological cycle, both regionally and globally? What are the impacts of surface albedo change due to deposition of AA and how might this change in the changing climate?

Atmospheric Testbed (https://www.arm.gov/research/publications/search?publication-type[1][0]=Workshop%20Report)

The AMT consists of a fully coupled meteorology-chemistry-aerosol model, the Weather Research and Forecasting (WRF) model with chemistry (WRF-Chem), and a suite of tools to evaluate the performance of aerosol process modules through comparisons with a wide range of measurements collected during DOE field campaigns.

Current work focuses on: (1) evaluating the representation of secondary organic aerosol (SOA) in models; and (2) determining the importance of aerosol chemistry treatments in terms of aerosol number, size, and effects of hygroscopic properties on droplet and ice nucleation, and subsequently on cloud properties and precipitation.

Evaluation data sets: Aerosol microphysical, optical, and cloud nucleating properties, meteorological, cloud, and trace gas measurements from in situ and remote-sensing instruments deployed on the surface and aircraft; satellite platforms. AMT data sets focus on the characterization of aerosol microphysics, optical, and cloud nucleating properties at the surface and aloft, using both surface- and aircraft-based observations collected by advanced instrument suites deployed as part of ARM/ASR field campaigns.

High-Resolution Modeling (https://www.arm.gov/research/publications/search?publication-type[1][0]=Workshop%20Report)

From the perspective of routine high-resolution modeling, key measurements are the vertical distribution of aerosols and its diurnal and seasonal cycles. Some knowledge of aerosol composition obtained indirectly via absorption and hygroscopicity measurements are useful.

ARM-EU Workshop (https://www.arm.gov/research/publications/search?publication-type[1][0]=Workshop%20Report)

What is the distribution of aerosol properties for the Atmospheric Model Intercomparison Project (AMIP) period (i.e., since 1979)?

- climatologies of ω_0, g, and CCN and IN concentrations

What is the coupling among microphysics, aerosols, and cloud dynamics as a function of scale and d regime (e.g., vertical velocity or stability)?

- Aerosol profiles and characteristics (size, shape, concentration, etc.)
- CCN (ideally CCN as a function of supersaturation) and IN

Aerial Observations Needs (https://www.arm.gov/research/publications/search?publication-type[1][0]=Workshop%20Report)

Measurement Priorities:

- Frequent vertical profiles of aerosol number and size, preferably down to sizes of a few nm
- Aerosol inlet (i.e., isokinetic and CVI)/ sampling lines characterization (i.e., transmission efficiency, size cut-offs) and improvement; need ability to measure interstitial aerosol without artifacts
- Capability to sample/analyze super-micron aerosols with aerosol mass spectrometers
- Frequent vertical profiles of aerosol absorption, techniques other than filter based needed at ambient RH, include ultraviolet (UV) wavelengths
- Development of IN aircraft instruments that are smaller, lighter, commercially available, cover all relevant sizes, including super- micron, and measure all relevant freezing processes; include collection of IN for post-analyses
- Miniaturization and validation of numerous online instruments to measure: CCN, gases, aerosol size distribution, composition (e.g., with micro-fluidic techniques, electro chemical sensors).

C.3 AMSG Recommended Core Configuration of Aerosol Observing System (AOS) Capabilities

The following list details the recommended suite of instruments for AOS at all ARM sites.

Number and Size
CPC 3772 – Condensation Particle Counter (> 10 nm)
μCPC 3776 – Ultra-Fine Condensation Particle Counter (> 2.5 nm)

Number and Size
SMPS – Scanning Mobility Particle Sizer (10 nm-500 nm)
UHSAS – Ultra-High-Sensitivity Aerosol Spectrometer (50 nm-1 µm)
APS – Aerodynamic Particle Sizer (500 nm-20 µm)
HTDMA – Brechtel Humidified Tandem Differential Mobility Analyzer
CCN200 – Cloud Condensation Nuclei (Model number in cell)
Composition
ACSM/Q – Aerosol Chemical Speciation Monitor - Quadrapole/Time of Flight
Optical Properties
CAPS – Cavity Attenuated Phase Shift Monitor (channels in cell)
Neph, Dry – Nephelometer, Dry RH Scanned
TAP (PSAP) – Tricolor Absorption Photometer
Aethalometer (Model number in cell)
1-10-µm Impactor (Model in cell)
Gases
CO – Carbon Monoxide/Nitrous Oxide/Water Vapor
CO – Carbon Monoxide by NDIR TEI 48C
$CO/CO_2/CH_4/H_2O$ EchoTech Spectronus
O_3 – Ozone
Meteorology
WXT520 – Weather Sensor

The following lists other existing aerosol and gas measurement resources owned by ARM.

IOP/Specialty
NO_x – 3-Channel: NO, NO_2, NO_y
PTRMS – Proton Transfer Reaction Mass Spectrometer
PILS – Particle Into Liquid Sampler
SP2 – Single-Particle Soot Photometer
Other
n-SMPS – Nano Scanning Mobility Particle Sizer
SO_2 – Sulfur Dioxide
Neph, Amb – Nephelometer, Ambient + humidograph
GHG – Green House Gases (CO_2, CH_4)
Picarro CO_2/CH_4/H_2O (distinct from GHG instrument)
Sunsetted (available for IOP)
PASS-3 – 3-Wavelength Photo Acoustic Soot Spectrometer (10/01/2015)

Accompanying this are two documents to aid in understanding the location and justification of instrument of these lists:

- AOS_CorePriority_location_AMSG012017.xlsx: spreadsheet containing location of existing instruments on the core configuration and others lists above
- AOSbaseline_reccomendation032014.docx: this 2014 document is outdated in its list of recommended instruments but provides the initial justifications for the measurements to the ARM Facility made by the AOS Committee, a group preceding the AMSG asked to provide such recommendations to ARM.

Appendix D

Before Activity to Rank Science Questions and Measurement Strategies

Individual ballots cast for the Before Activity to rank aerosol science questions and aerosol measurement strategies. Participants were provided 6 “ballots” – 2 green (highest priority), 2 yellow (higher priority), and 2 red (high priority).

Measurement Area	Science Question(s)	Measurement Issue	High Priority	Med. Piority	Low Priority
Gas Phase Aerosol Chemistry					
	AAMS	Measurements from AOSes are mainly point sources. Few measurements of composition. Almost none of morphology.	X		
	SOAF	Measrement of organic gasses (semi-volatile and lower volatily) in addition to VOCs. Measurements of NO, NO2, SO2, NH3.	X		
	NPF	SMPS and HTDMA data are most usefeul. Key measurement needed is gas phase composition - especially organics. A one year record would help a lot. Also, it is important to measure g(RH) of small particles.	X		
	AAMS, SOAF	Tracegas: Are NOx measurements core? They provide oxidant age. Can they be operated at cost?	X		
	SOAF	Gas - phase needed for aerosol closure.		X	
	NPF	Gas phase to aerosol closure. Number concentrations. Growth rate.		X	
	SOAF	VOC measurements. Measurements of common trace gasses at all sites/facilities (Nox, SO2, CO, O3). Measurements related to aersosol areas.		X	
	AAMS	AOSes are informative for aerosol particle concentration but less informative for AAMS than NPF. Overall, AOSes are less useful for ASR Science Plan with the exeption of CO primarily for help with local source ID.			X
	Other	Need high quality data under budget constraints. Is continuous data needed?			X
	SOAF	Need have gaseous precursor measurements to understand SOA formation.			X
	Other	Ammonia and amines are important contributors to aersosol production at the SGP. Some measure of the seasonally varying gas phase concentations would be useful.			X
	DRE, AAMS, NAI	Need aerosol and composition closure. Need ACSM + size disrtibution + βap + trace gasses.			X
	SOAF	Need collocation of PTRMS measurements with AMS measurements, need very much a process-level requirements, and need aircraft with fixed site.			X

Size Distributions					
	NAI, NPF	Coarse aerosol missing at many sites. Problem with local contamination.	X		
	IRE	Issues: Source and sinks (wet deposition), and vertical distributions.	X		
	NAI, SOAF	Need mass distributions instead of size dsitribution. Assumptions must be made to convert size to mass. Better to get a direct measure of mass through direct measure by CPMA or APM (new instrument needed).		X	
	NPF, SOAF, AAMS, IRE	Need for size distribution VAP "harmonizing" across all size ranges from ultrafine to coarse.		X	
	NPF	Size distribution is important for cross calibration of aerosol chemistry (ACSM) and also optical properties.		X	
	DRE, IRE	Need to have size distribution measurements for coarse particles.		X	
	Other	Need integration of different size measurements. Need nucleation mode size distribution.		X	
	Other	Need development of QC'ed products for these instrument systems (largely left out of the normalization to date). Size distributions are useful for many of the science drivers, but especially high resoltuion modeling.		X	
	Other	Need size distribution harmony by putting all size distributions into dN/d log Dp. Need calibrated concentrations.			X
	DRE	Need coarse mode optical properties. It is difficult to get accuarate data for D > 1 mciron due to losses, truncation, and artifacts.			X
	DRE	Need size distributions + chemcial composition of partciles in the D = 1 - 10 micron range.			X
	NPF	Need to understand the extent to which NPF events are regional and the spatial uniformity of the prodcution rate for those that are. It would be helpful to have (for ~ 1 year) two or more CPCs (or SMPSes - although at greater cost) in ~50 to 100 km radius around the SGP.			X

Aerosol Partical Composition					
	AAMS, NAI, SOAF	Need refractory aerosol composition for coastal and dust infuenced sites. Undersatnding local contamination.	X		
	NAI, SOAF, NPF, AAMS	Need high quality data products that best facilitate/serve scientific effects related to QA/QC, VAPs, and enhancement. Need additional mesurements (e.g., filters) for redundancy, validate current measurements, and expand capacity. Need more advanced instruments for more information.	X		
	SOAF, DRE, IRE	Need to get a process level understanding to improve model representation. Need measurements of properties - volatility and viscosity. Need gas and particle phase chemical composition.	X		
	AAMS, DRE	Need to measure different absorbing aerosol categories. Need VAP for BC vs BrC quantifications of other absorbing aerosol?	X		
	NPF	Requires vertical measurements of ultrafine size distribution, composition, and gas-phase chemistry. Don't have vertically - resolved distributions and detailed chemistry. Growth, how prevalent, what controls, how abundant?	X		
	DRE	Size-resolved chemcial compositions in vertical profiles.	X		
	NPF	Size-resolved chemical composition, especially at < 50 nm diameters.		X	
	AAMS	Need coarse-mode partcile composition measurements to better undertand dust mixing state with other aerosols for radiation and ice nucleation properties.		X	
	Other	Need ice nuclei measurements.		X	
	DRE, NAI	Incomplete composition information that could be filled in with filter observations.		X	
	DRE, AAMS, NAI, SOAF	Bc and BrC: Can we do this despite uncertainties in absorption and BrC? (Closure with ACSM, SMPS, PSAP, CLAP, TAP, CAPS, AETH, NOx, and SO2?)		X	
	NAI	Need to establish pre-industrialized state of organic aerosol.			X
	Other	Need high-quality data under budget constraints. Is the continous data being used?			X
	DRE	Composition measurements of a consistent size range with hygrosopicity and optical properties.			X
	IRE, NPF, SOAF	Need raw data for future analyses from high-level instruments. Need IOP/high-level charateristics and measurements.			X

System Configuration (temperature, RH, heating vs drying, size cuts)					
	AAMS,DRE	Need mesurements to have closure studies of aerosol optical properties. Need chemical compostion and size distributions to undertand the changes in mixing state and size or aerosols that drive optical properties changes. Need to have measurements near the source region and downwind along the plume tracks. Need surface and column closure measurements of aerosol optical properties.	X		
	DRE	Need RH control and in-situ measured propeties at ambient RH.	X		
	DRE	Need charaterization of aerosol inlet, manifold, and transmission to and within instrumentation. Need to understand conditions that affect measurements (size cut, RH, etc.). These are fundamentals that all other (measurements) should build on.	X		
	Other	Important for comparison for measurements at all sites. Need to consider how aerosol inlet configuration impacts measurements of aerosols size, chemistry and hygroscopicity		X	
	Other	Site location and local source identification is important. Need local source characterization to find specific markers to ID source components in sampling. This is likely to include gas phase (NOx, CO, VOC) and particle (number, size, chemcial composition) composite markers.		X	
	NAI, DRE	Need to define anthropogenic radiative forcing (the anthropogenic contribution) of aerosol through better understanding of source and evolution. Linking composition and optical properties - need to be made at common sampling conditions.		X	
	SOAF	Need to undertsand how T/RH affect SOA phase,formation, and properties. Need volatility measurements - in response to T and RH.		X	
	Other	Need to develop a preferred set of harmonized data products for better presentation in the Data Discovery tool. Really a metadata exercise. All science issues are improved under a more general system configuration category.		X	
	DRE	Sampling is an issue. Impactor as f(RH) is not simple! Nothing is dry. Little control in newer AOSes.		X	
	Other	Need better user access to ARM data. Documentation is not accessible.		X	
	DRE	Need data continuity - old AOS data vs new data. Need identification of an absorption "gold" standard: extinction - scattering or PSAP (TAP,CLAP).			X
	Other	QA/QC is under resourced for remote intalls. Assuming ideal operation for extended periods is naive.			X
	Other	Need characterization of inlets and samling lines. Need more information shared with users.			X
	IRE	Need vertically resolved measurements of hygroscopic, optical, and other properties. There is a lack of vertically resolved measurements and a lack of measurements at other RH.			X
	DRE, NPF, SOAF, NAI	Need site-specific process studies targeting the science drivers unique to each site. Need tailored sampling for higher-level comlexity instrumentation at different sites.			X

Hygroscopcity Activity and CCN					
	IRE, DRE	CCN Closure and total scatter and extinction. Do we have all the pieces we need? (I think so.)		X	
	Other	Better desription of CCN and hygroscopic properties. HTDMA and CCNc datasets are most useful. For a size-resolved K(sub) and K(super) desciption, the SMPS could be connected to one of the CCN columns.		X	
	IRE	Need to know water uptake and hygroscopicity measurements. Need standard calibrations and VAPs from f(RH), CCN, and HTDMA. (High end yellow - possibly green.)		X	
	DRE	Need impacts of water uptake on optical properties: Need f(RH) for extinction and absorption.		X	
	AAMS, IRE, DRE	Need single particle composition information. lifetime and fate of aerosols - removal fates; in and below cloud scavenging; aerosol hygroscopicity and nucleation potential.		X	
	IRE	Faster scanning CCN is a great development.		X	
		This is important but it does not line up with the ASR Science Plan. (Comment written later - yes it does - RDF)			X
	NAI, DRE	Need high quality hygroscopicity measurements with stable conditions over seasons and locations with very different climates. Understanding the water uptake of aerosol by compositon (and anthropogenic trends).			X
	AAMS	Need - how to represent impact on forcing?			X
	DRE	Need to measure size, chemistry, composition and optics - dry and wet and ambient - to do closure study.			X
	IRE	CCN and hygrospocity should be linked to SOA processes.			X
	IRE	Need to coordinate with the Best Estiamte CCN products development.			X
	Other	Hygroscopic actvity and CCN are important to many science questions,			X

Optical Properties					
	DRE	Reduce βap uncertainty to get optical property closure. Need to assess PSAP/CLAP/TAP corrections vs. CAPS-Neph, PASS, PTI, SP2, ACSM + size, and AETH2 spot.	X		
	DRE	Absorbing Aerosol - σabs. How good is good enough? Σssa = 2% is hard. This determines priority of corrections and alternative techniques. PTI required.	X		
	DRE, NAI	Link historical filter measurements of aerosol absorption to newer techniques. Need to stop beating this dead horse of aerosol filter measurements? Overall we have to measure SSA within 2%. Need to deploy 1 wavelength PASS?	X		
	DRE	How good does it nreally need to be? Can we make ABE2 by integrating AOD, AAOD, AOS, sonde + lidar? This is independent of improving βap itself. Vertical distribution of aerosol and heating rate profile	X		
	DRE	Impact of coating on aerosol and response to water uptake.	X		
	DRE	Need wider wavelength ranges sampled consistently across optical properties to match with remote sensing capabilities. Linking detailed aerosol properties to remote sensing observables.	X		
	DRE	Needs for optical properties: chemical closure, absorbing aerosol (BC, BrC), contribution of BB to absorbing aerosol = primary and secondary, and vertical profiles.	X		
	DRE	Better understanding of vertical distribution of aerosol. Lidar data are currently most useful. It would be helpful to have a prodcut that provides a "best" lidar product. UAS may help. It may also be worth considering using UAS to collect and return samples.	X		
	DRE	Vertical profiles of aerosol optical properties and physical attributes are needed. There have been limited opportunities to sample in vertical profiles due to the cost (aircraft). Effects of temperature and RH need to be extrapolated to the surface.	X		
	DRE	Absorbing aerosols: No direct measurements of absorption. Large uncertainties with indirect measurements and filter biases. Need online high time resolution direct measurement of absorption.	X		
	DRE	Aerosol absortpion at shorter wavelenghts (near UV). Role of BrC in climate forcing? Role of BrC bleaching or material loss with age?	X		
	DRE	Need absorption measurements as function of wavelength.	X		
	DRE	Need size-resolved and spectrally resolved absorption coarse-mode measurements near source regions and downwind to understand the evolution of aerosol optical properties. Need vertical profiling of extinction and absorption. Need closure studies of aerosol properties and chemical compositon to undertand the underlying mechanisms that drive optical changes.	X		
	DRE	Vertical distribution of absorbing aerosol 24/7. Lack of drone-sized absoption measurements that have been validated.	X		
	DRE, AAMS	Fundamental links between chemical and physical attirbutes and bulk optical properties.	X		
	DRE	Optical properties are important for aerosol direct radiative forcing.		X	
	DRE	Need identifocation of relative importance of chemical mixing state versus morphological mixing state on optical properties. There is a paucity of datasets readily available for particle-resolved modeling studies.		X	
	DRE	What is the ambient forcing? Need measurements of ambient RH. Measurements are at low RH (dry particles), thus difficult to translate these to ambient conditions.		X	
	DRE	Need measurements at an extended wavelength range, better filter characteization, and chemical composition. What are the contributions of BC and BrC to aerosol absorption?		X	
	SOAF, DRE	Need to know brown carbon SOA. How does BrC SOA evolve with aging in the atmosphere?			X

Appendix E

After Activity to Rank Measurement Strategies

Individual ballots cast for the After Activity to rank aerosol measurement strategies. The science priorities were assumed unchanged from the results in the Before Activity and provided in Appendix D. Participants were provided 6 “ballots” – 2 green (highest priority), 2 yellow (higher priority), and 2 red (high priority).

Size Distributions					
		Size distribution is most important for science questions. Need to have size distribution over full size range. Need APS at all sites.	X		
		Size distribution is the prioiry measurement. Top priority is 10 nm to 10 microns.	X		
		Need to create a merged size distribution product with chemistry.	X		
		Need SMPSes at all sites.	X		
		Need to create a merged size distribution product (requires chemistry).	X		
		Need APS at all sites.	X		
		Need SMPSes at all sites.	X		
		Need APSes everywhere. Rationale: Upcoming marine and desert campaigns - in addition to exisiting sites having these measurements might precede the need for merged size distribution prodcuts, through that goul	X		
		Need full size distribution measurements - suggest a combination of uCPC or nano-SMPS + SMPS + APS.	X		
		Size distribution is the priority measurement.	X		
		Need APS everywhere (or at least add size distribution from lower resolution OPC from at least 1 - 2.5 microns).		X	
		Need tor create merged size distibutions.		X	
		Need SMPS at all sites.		X	
		Need APS everywhere.		X	
		Continue PM1 for impactor size cut.		X	
		Need full merged dry size distribution at all sites with high-level of QA/QC for each instrument's data.		X	
		Size distribution is a priority - need APS everywhere . Also, need SMPS at all sites.		X	
		Need dry APS.			X
		Link with remote sensitivity to evaluate if surface measurements are representative.			X
		Size distribution is a priority measurement.			X
		Size distribution is a priority measurement.			X

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