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TO: NESCAUM Board of Directors

FROM: Barbara Morin and Lisa Rector, NESCAUM

RE: Reproducibility of Test Results in Step 2 Stoves

DATE: September 4, 2020

Development of new test methods for residential wood heating appliances has been part of Northeast States for Coordinated Air Use Management's (NESCAUM's) research agenda for the last eight years. As part of that initiative, NESCAUM purchased and tested several Step-2 certified appliances at contracted research laboratories during the past two years. The primary intent of that research effort was to determine how testing procedures affect emission performance measurements. To establish a foundation for this research, baseline particulate matter (PM) emission performance testing was conducted on the study devices using current certification test procedures. Note that the research lab did not attempt to replicate certification results, nor did it follow the detailed instructions manufacturers provide to the labs, which are sometimes identified in test reports.

The results of the NESCAUM baseline tests are also useful for informing discussions regarding the compliance audit specifications in US EPA's 2015 New Source Performance Standards (NSPS) for Residential Wood Heaters. The compliance audit testing program is designed to verify the results of emissions tests performed to certify that an appliance conforms with the emissions limits in the NSPS. The NSPS requires EPA to initiate procedures to revoke an appliance's certification if the emission rate (ER) measured in a compliance audit test, conducted with the same testing method as that used in the certification test, exceeds the applicable NSPS emission standard by more than 50%. The Step-2 NSPS PM emission standard is 2.0 grams per hour (g/h) and stoves that are Step-2 certified using an alternative cordwood method are allowed an ER of 2.5 g/h. Therefore, a stove tested according to a Federal Reference Method (FRM) specified in the NSPS would be subject to certification revocation if the audit measured an ER greater than 3.0 g/h using that method, while the certifications for stoves tested with an approved cordwood alternative method would be revoked if the audit measures an ER greater than 3.75 g/h.

Some stove manufacturers have argued that revocation of an appliance's NSPS certification based on audit test results is not appropriate due to the inherent variability of wood burning emissions. The discussion below evaluates this argument by examining the ERs and the variability of the ERs measured in the certification tests and the NESCAUM baseline tests of the cordwood and pellet stoves in the study. The test results were also evaluated to determine the

likelihood an audit would detect a stove with elevated or inconsistent emissions in the field. Note that the study data refer to the appliances by number rather than directly identifying the stove manufacturer and model.

Step-2 Pellet Stoves

The NESCAUM study evaluated three Step-2 certified wood pellet stoves with differing heat outputs and pellet delivery systems, identified here as Stoves 11, 13, and 14. The study tests were conducted according to the ASTM 2779 method, which is the Federal Reference Method (FRM) used to certify the compliance of pellet stoves with NSPS emission standards. The official certification tests for those stoves also used the ASTM method, a one-day test that integrates multiple burn rates.

NESCAUM tested each of the pellet stoves using several different types of wood pellets. The composition of the pellets significantly affected the PM ERs measured in those appliances. The reports documenting the certification tests for the stoves do not provide specific information about the composition of the pellets used in those tests, so an exact comparison of the results of the certification and study tests was not possible. However, Table 1 compares the certification ER with the range of ERs measured in the study runs that used softwood pellets (pellets 1, 2, 3, and 9) and those that used hardwood or mixed hardwood and softwood pellets (pellets 4, 5, and 6).

Table 1. Comparison of Ranges of Pellet Stove PM Emission Rates for Study Runs Using Softwood and Hardwood/Mixed Pellets with Certification Tests Using Unknown Pellet Types (3 Replicates)

	Study ERs - Softwood Pellets (g/h)	Study ERs - Hardwood and Mixed Pellets (g/h)	Certification Test ER (g/h)
Stove 11	0.67−0.82	1.50−1.77	0.95
Stove 13	0.50−0.64	1.15−2.86	0.79
Stove 14	0.86−1.20	2.18−2.44	1.38

For each stove, the range of study ERs measured in the runs that used pellets containing hardwood was higher than and did not overlap the ER range for the softwood pellet runs. The certification test ERs were, for all three stoves, slightly higher than the range of study ERs in the softwood runs and lower than those in the study's hardwood runs.

The ERs measured in all of the pellet stove study runs were lower than 3.0 g/h, the audit test level that would trigger the initiation of revocation procedures. All of the softwood runs were also lower than the 2.0 g/h NSPS emissions limit for Step-2 stoves. In two of the stoves, however, the ERs in some or all of the hardwood pellet runs exceeded the Step-2 limit.

These results demonstrate that it is reasonable to expect Step-2 pellet stoves to meet the 3.0 g/h audit criterion for revocation of the certification. Because the composition of the pellets has a marked effect on the ERs, it is crucial that test reports include a complete fuel analysis[1] of the pellets used in the test to enable a fair comparison with audit results. EPA should also consider requiring certification tests to use pellets that are representative of the range of wood pellet types in typical consumer use, including hardwood pellets.

Variability in Pellet Stove Tests

To further evaluate the variability of ERs measured in pellet stoves, the study ran three replicate ASTM test runs using pellets from different wood feedstocks in two stoves. The results of those tests are listed in Table 2. These data can be used to evaluate the reproducibility of stove performance with different pellet types. Pellet 1 is a softwood pellet made from eastern pine, pellets 3 and 9 are a single wood species pellet composed entirely of Douglas fir, and pellet 4 is made with a variety of hardwood species but no softwoods. Elemental parameters that may affect emission outcomes, such as ash content, varied widely among the pellet types.

Table 2. Analysis of Emission Rate Variability in Study Tests Using Different Pellet Types.

	Pellet #	Range of Run ERs (g/h)	Mean ER (g/h)	% Difference	Relative Standard Deviation
Stove 10[2]	3	0.46−0.61	0.53	31.3%	13.7%
	4	1.15−1.32	1.22	14.5%	7.1%
	9	0.60−0.71	0.66	18.4%	8.6%
Stove 13	1	0.53−0.59	0.56	11.3%	5.4%
	5	1.94−2.86	2.31	47.1%	21.0%
	9	0.50−0.59	0.56	18.8%	9.4%

Two indicators of variability are displayed in this table. The relative standard deviation is the sample standard deviation of the mean ER for the three replicate runs divided by the mean ER for those runs. The percent difference is the difference between the maximum and minimum ER measured in the three replicate runs divided by the minimum ER for those runs. There was less

[1] At a minimum, wood pellet analysis should include measurements of the following items: fuel moisture content (ASTM E871), ash (ASTM D1102), volatile matter (ASTM D3175), fixed carbon (ASTM D3172), sulfur (ASTM D4239), net calorific value (ISO 1928), gross calorific value (ASTM E711), and weight percentages of carbon, nitrogen, hydrogen (ASTM D5373), and oxygen (ASTM D3176).

[2] Stove 10, when purchased for this study, was certified at Step-1 emission levels. The model name, however, now appears as a Step-2 appliance based on a recent certification test. NESCAUM requested a copy of the original certification test, but the EPA Office of Enforcement and Compliance Assurance denied it.

than a 20 percent difference between the maximum and minimum ERs measured in four of the six sets of replicates and less than a 50 percent difference in all replicate sets.

The relative standard deviations for the replicate runs for all pellet types in both stoves, 5.4 to 21 percent, are well within the range that is generally considered acceptable. Note that in four of the six replicate sets, the tests occurred at two different time periods and the pellets had different moisture contents in those periods, but those factors did not appear to affect reproducibility of the results. As was shown above, the range of ERs in the softwood runs in each stove were substantially lower than in the hardwood runs.

Conclusions on Pellet Stoves

The results indicate that compliance audits are a reasonable requirement for assuring compliance with emission standards for pellet appliances. While ERs were substantially higher in runs with hardwood pellets than with softwood pellets, replicate runs with the same fuel produced reproducible results.

ASTM 2779 does not include specifications about the physical parameters of the pellet fuel used for testing. Because the composition of the pellets has a marked effect on the ERs, it is crucial that test reports include an elemental analysis of the pellets used in the test to enable a fair comparison with audit results. EPA should also consider requiring the use of pellets that are representative of the range of wood pellet types in typical consumer use, including hardwood pellets, in certification tests for these appliances.

Step-2 Cordwood Stoves

The NESCAUM research included the assessment of six Step-2 stoves. One of those stoves was certified using the EPA Method 28R (M28R) crib wood test, and the other five stoves using the ASTM 3053 cordwood method. M28R is a Federal Reference Method in use since 1988 and ASTM 3053 has been designated by EPA as a Broadly Applicable Alternative Test Method. Manufacturers have the option to choose either of these test methods to achieve certification. As of September 1, 2020, certification testing of 52 percent of EPA Step-2 certified cordwood stoves used the ASTM cordwood method.

M28R requires four days of testing at different burn rates. The NESCAUM study tested only three of the four M28R burn rate categories. For the unit that was certified using M28R, a comparison of the ER for each burn category included in the NESCAUM study with the ER for the corresponding burn category in the certification test is shown below. ASTM 3053 testing is a two-day test with three burn rate categories. Complete ASTM 3053 tests were performed in the

NESCAUM baseline testing. For the five ASTM 3053 certified appliances, the discussion below compares the results of the complete study and certification tests.

M28R: Certification Testing versus Baseline Research Testing

The study included one Step-2 stove, Stove 7, that was certified using the M28R crib-wood test method. Table 3 compares the results of the Stove 7 certification test runs with NESCAUM test runs at comparable burn rates. The study and certification test data were consistent in all burn categories tested. The greatest difference between the study and certification test ERs was in the Category I low load burn; in that burn category, the ER measured in the study was 31 percent (0.15 g/h) lower than in the certification test. All ERs measured in the Stove 7 M28R runs were substantially below the level that would trigger revocation in a compliance audit. Note that the ER measured by NESCAUM for Stove 7 using the ASTM test, 0.86 g/h, was well below the Step-2 limit.

Table 3. Comparison of Stove 7 M28R Certification Test Results and Study Results for the Burn Categories Included in NESCAUM Study

Burn Category	Study ER (g/h)	Certification Test ER (g/h)	% Difference
Category III	0.43	0.54	-20%
Category II	0.57	0.55	4%
Category I	0.33	0.48	-31%

ASTM 3053: Certification Testing versus Baseline Research Testing

The study included five stoves certified using the ASTM 3053 cordwood test method. NESCAUM conducted ASTM 3053 baseline tests on each of those stoves using the fuel species identified in the corresponding certification test report. Table 4 shows each stove's firebox size and emissions control approach and compares the certification and study test ERs measured in the stoves.

Table 4. Comparison of ASTM Cordwood Stove Certification Test Results and Study Results

Stove ID#	Control Approach	Firebox Size	Study ER (g/h)	Certification Test ER (g/h)	% Difference
Stove 9	Non-Catalytic	Medium	17.9	1.52	1077%
Stove 12	Hybrid	Large	2.24	1.94	16%
Stove 15	Non-Catalytic	Small	2.14	2.11	1%
Stove 16	Non-Catalytic	Large	6.82	1.54	343%
Stove 17	Hybrid	Medium	1.16	0.91	27%

The percent difference is calculated as the difference between the study ER and the certification test ER divided by the certification test ER. In three of the stoves (Stoves 12, 15, and 17), the study ERs were slightly higher than the certification results but were below the NSPS limit for certification tests performed with cordwood methods (2.5 g/h) and substantially below the level that would trigger the initiation of revocation procedures (3.75 g/h).

In Stoves 9 and 16, however, the study ERs were considerably higher than the ER reported for the certification tests and were substantially above the Step-2 emissions limit, an indication that the stoves would be unlikely to perform consistently at Step-2 certification levels in the field. The ERs measured for the stoves in the study would trigger the initiation of revocation proceedings in a compliance audit.

The ER measured in the Stove 9 study test was more than ten times the certification test ER and seven times higher than the Step-2 limit. The research team sent this appliance to a second laboratory and the high emission values were replicated at that laboratory. Additional testing data showed that Stove 9's performance was much more variable than in any other stove assessed in the study, even when fueling, operational, and laboratory procedures were held constant. Typically, Stove 9 performed at levels substantially above emission standard thresholds. Lower emissions rates were measured on some days, but that level of performance could not be reproduced.

A review of the certification test report for Stove 9 suggests that the certification testing used fueling procedures that do not reflect normal operating procedures. While the test method used for certification, ASTM 3053, is silent on fuel length and placement parameters, EPA's Stack Testing Guidance, which applies to all NSPS testing, stipulates the following elements:

- *"[T]he Act requires that facilities continuously comply with emission limits."*
- *NSPS and MACT programs further require that such tests be conducted under representative operating conditions.*

- *"EPA recommends that performance tests be performed under those representative (normal) conditions that… are likely to most challenge the emissions control measures of the facility with regard to meeting the applicable emission standards, but without creating an unsafe condition."*

The fuel used in the certification test was 37 percent shorter than the maximum log length specified in manufacturers owner's manual (contained in the test report). The use of shorter fuel pieces provides additional space for air to circulate. The resulting change in the air to fuel ratio strongly influences combustion parameters, which in turn reduce ERs.[3] EPA's Testing Guidance stipulates that certification tests must use fuel pieces of at least the maximum length used in the field in order to assess performance under conditions that correspond to the maximum emission rate, and shorter fuel pieces do not conform to this guidance. If a compliance audit of this stove had been conducted, those discrepancies, as well as the unstable performance of the appliance, would likely have been detected.

The study ER measured for Stove 16 would also have triggered the initiation of revocation procedures. A NESCAUM review of the certification test report for that stove found significant data quality issues with that test. The review also determined that a non-typical fueling approach was used. Although the information in the test report was incomplete, a review of the report and the owner's manual for that stove indicated that the fuel used in the certification test was 25 percent shorter than the longest length recommended in the owner's manual. As discussed above, tests that use shorter piece lengths tend to measure ERs that are considerably lower than those that would occur with typical fueling procedures. The ASTM method is not prescriptive on fuel length and placement. An EPA audit test, however, that conformed with the EPA's Testing Guidance stipulation for testing to be conducted under conditions consistent with the maximum emissions rate would likely have measured a higher ER and would have detected the data quality issues in the certification test.

The elevated and variable ERs in Stoves 9 and 16 and the issues identified in the certification tests of those stoves highlight the value of audit testing to identify which units are not likely to perform well consistently in the field. Removal of compliance audit procedures will eliminate a critical mechanism to assure the integrity of the regulatory program.

[3] Sun, J. *et al.*, Impact of Primary and Secondary Air Supply Intensity in Stove Emissions of Size-Segregated Particulate Matter and Carbonaceous Aerosols from Apple Tree Wood Burning, 202 *Atmospheric Research* 33-39 (2018).

Variability in Cordwood Testing

In addition to the baseline testing, NESCAUM assessed appliance performance variability in five Step-2 cordwood stoves using an alternative cordwood protocol, the Integrated Duty Cycle (IDC) Cordwood Stove Protocol, which is designed to be representative of typical field operating and fueling conditions. The protocol varies a number of parameters, including heat demand, air settings, load size, and piece geometry, in a single test run. The protocol requires three replicate test runs to be conducted, allowing for an assessment of inter-run variability, even when an audit is not performed. The results of the IDC test runs for the six Step-2 stoves studied are shown in Table 5.

Table 5. PM Emission Rate Variability Using Alternative IDC Cordwood Stove Testing Protocol.

Stove ID	Control Approach	Range of Run ERs (g/h)	Mean ER (g/h)	Relative Standard Deviation	% Difference
Stove 7	Hybrid	1.23−2.00	1.63	24%	63%
Stove 9	Non-Catalytic	3.78−34.85	23.27	84%	822%
Stove 12	Hybrid	2.73−4.68	3.44	31%	71%
Stove 15	Non-Catalytic	1.70−3.58	2.94	37%	111%
Stove 16	Non-Catalytic	11.10−15.73	13.65	17%	42%
Stove 17	Hybrid	1.79−2.22	1.94	13%	24%

As in Table 2, this table shows two measures of variability for the IDC runs, the relative standard deviation of the ERs, and the percent difference between the maximum and minimum ERs in the three replicate runs. Except for Stove 9, which, as discussed previously, also did not perform consistently in the baseline testing, the relative standard deviations were in a range that is generally considered acceptable, 13 to 37 percent.

The ERs measured using the IDC alternative protocol for Stove 7, 12, 15, and 17 would not trigger the actions required when audit testing shows results greater than 150 percent of the standard. As in the baseline testing, however, the IDC ERs for both Stove 9 and 16 were substantially above the certification values and would trigger revocation proceedings. The considerably elevated emissions measured in those stoves, using both the baseline and alternative testing protocols, is evidence that the poor performance is attributable to poor combustion design rather than test method variability and precision issues.

Although the variability in the Stove 16 test runs was within acceptable parameters, the ERs in all runs in that stove were consistently elevated, suggesting that certification values for this appliance are not representative of in-use performance. Stove 9's run variability was an outlier in

the study, and its highly variable performance across testing methods supports the need for replicate testing and compliance audits.

Conclusions on Cordwood Stoves

The results of the baseline and alternative testing of cordwood stoves provide evidence that compliance audits are reasonable and necessary for assuring that those appliances conform with emission standards. Baseline and alternative test protocols measured ERs for four stoves was consistently below levels that would trigger revocation actions. The study identified two stoves with substantially elevated and, in one, highly variable emissions that would trigger further compliance activity. Analysis of additional data from the study indicated that elevated or variable emission levels did not result from test method precision or variability issues but instead were an indicator of elevated emissions performance. Problems with the certification testing procedures and operation of those two stoves would likely have been detected by compliance audits.

Conclusion

Taken together, the results of NESCAUM's analysis indicate that the compliance audit requirement is reasonable and would be an effective tool for compliance assurance if fully implemented. The study was able to reproduce certification test results in both pellet and cordwood stoves according to the audit criteria specified in the NSPS, when those certification tests were conducted appropriately. Furthermore, the analysis demonstrated that an audit would likely identify substantial issues associated with unrepresentative operating and fueling procedures and with appliances that have highly variable performance.

The compliance audit requirement in the NSPS rule provides a mechanism for avoiding the inappropriate certification of high-emitting stoves. NESCAUM's research indicates that replicate testing, such as is used in compliance audits, provides critical compliance assurance procedures necessary to maintain the integrity of the regulatory program. The data also suggest that the emissions measured in audits of well-designed appliances that have been certified using appropriate testing procedures will be acceptable within the tolerances specified in the current 2015 NSPS for Residential Wood Heaters.