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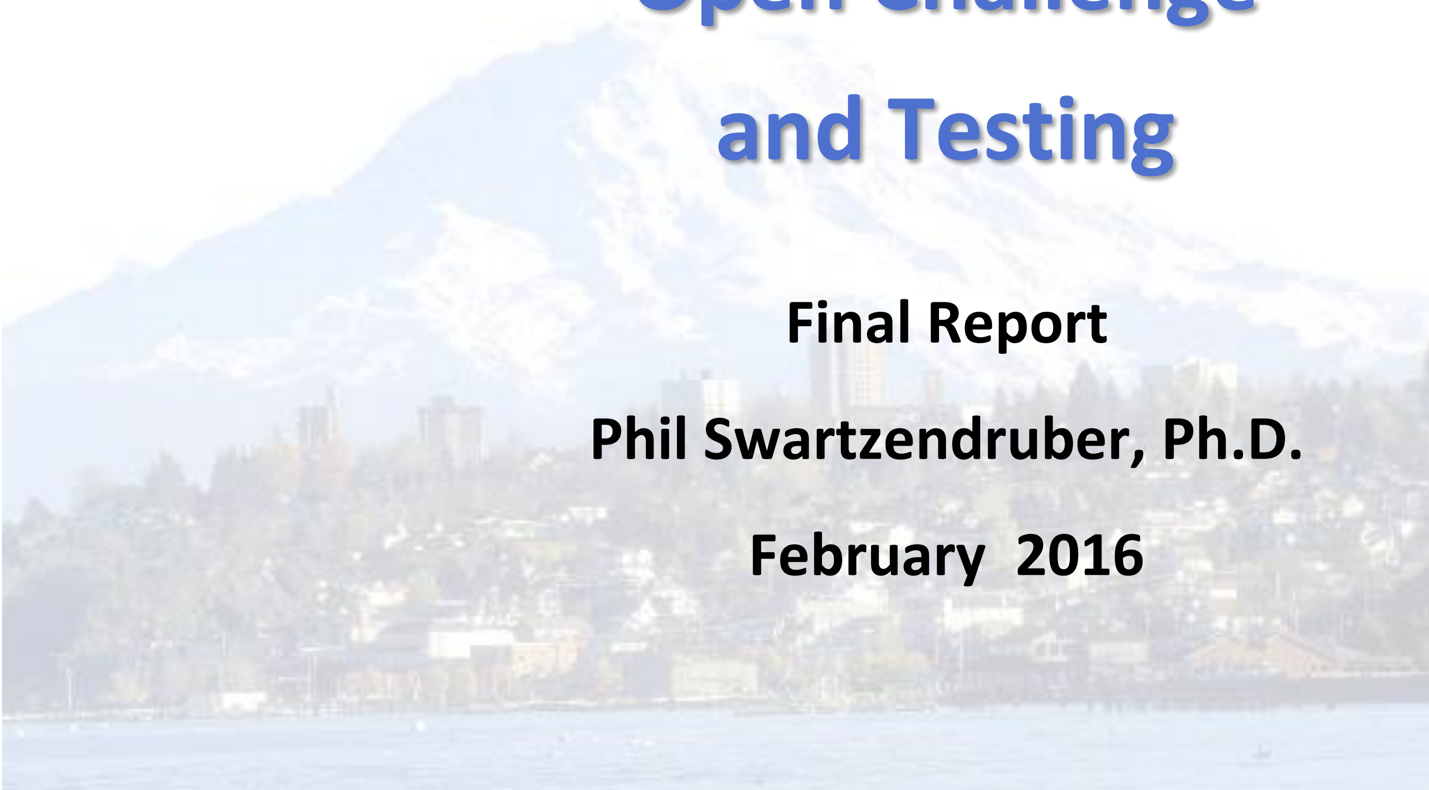
Puget Sound Clean Air Agency

Woodstove Retrofit Open Challenge and Testing



Final Report

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Contents

Executive Summary

Residential wood combustion (RWC) is the largest source of toxic polycyclic aromatic hydrocarbon (PAH) air emissions in the Puget Sound, and the largest contributor to poor air quality in the wintertime. Existing uncertified wood stoves are a major component of RWC emissions. Replacing uncertified stoves with newer, certified stoves or different forms of heat is a common approach, but the cost is prohibitive for many households, and for subsidy programs. In principle, a retrofit could offer a similar reduction in emissions at a significantly lower cost. But, at the beginning of this project, there were no commercially available, accepted, or otherwise recognized retrofits, and it was unknown if such technology existed.

The Puget Sound Clean Air Agency, working with WA Dept. of Ecology, obtained a National Estuary Program grant to seek out and test new retrofit technologies that could significantly reduce PAH and fine particulate matter (PM) emissions. The program had two parts: first, conduct an open search for new or emerging technologies and select the three best candidates. Then, test the candidates in an EPA accredited laboratory. The Woodstove Retrofit Open Challenge ran in Sept-Nov of 2014 and received 32 submissions. Four submissions, MF Fire (MF), GraceFire (GF), ClearStak (CS), and Grahn(Gr), were identified as good candidates and were recommended for testing.

The tests were conducted on two uncertified stoves that were thought to be good representatives of the broader population of uncertified stoves. The MF, GF, CS, and Gr devices reduced PM by about 57%, 80%, 90%, and 90%, respectively. The GF, CS, and Gr devices reduce PAHs by about 83%, 88%, and 71%, respectively. All devices also reduced CO emissions by roughly 40-90%. The Technical Advisory Committee for the Challenge felt that the three devices (GraceFire, ClearStak, and Grahn) had met all of the Challenge targets for performance and probable cost and reliability.

THIS PROJECT HAS BEEN FUNDED WHOLLY OR IN PART BY THE UNITED STATES ENVIRONMENTAL PROTECTION AGENCY UNDER PUGET SOUND ECOSYSTEM RESTORATION AND PROTECTION COOPERATIVE AGREEMENT GRANT PC-00J20101 WITH WASHINGTON DEPARTMENT OF ECOLOGY. THE CONTENTS OF THIS DOCUMENT DO NOT NECESSARILY REFLECT THE VIEWS AND POLICIES OF THE ENVIRONMENTAL PROTECTION AGENCY, NOR DOES MENTION OF TRADE NAMES OR COMMERCIAL PRODUCTS CONSTITUTE ENDORSEMENT OR RECOMMENDATION FOR USE.

Background

Residential wood combustion is the largest source of PAH air emissions in the Puget Sound, and the largest contributor to poor air quality in the wintertime. Each year in the Puget Sound, about 300,000 tons of wood are burned, with over 100,000 tons being burned in uncertified stoves. Removal and replacement of stoves can be prohibitively expensive for many homes, and the cost of alternative fuels (e.g. natural gas, or wood pellets) also limits the appeal of switching.

The Puget Sound Clean Air Agency (PSCAA) has run stove changeout programs since 2007. The programs have assisted the removal, upgrade, or replacement of more than 3,000 devices. The budget for the changeout programs has always been limited. So, in order to maximize cost-effectiveness, the more recent programs have only allowed switching to a non-wood form of heat, and have only provided a $1,500 incentive, except for income qualified households. This created two significant obstacles. First, since changeouts typically cost $3,000-$4,000, only a fraction of applicants who have applied to our program were able to afford to follow through. The second obstacle was that many households did not want to switch away from wood heat for one or more specific reasons including: free or relatively cheap fuel; radiant heat output; and non-dependence on utilities.

A simple, inexpensive retrofit device or technology that reduces the pollution from existing stoves would have the potential to significantly reduce PAH and PM2.5 emissions at a much lower cost compared to a new stove or different form of heat. And, it would keep wood burning as an option for households where there are significant problems with changing stoves or forms of heat.

Prior to this challenge, we unaware of any retrofit device or technology that could significantly reduce emissions and be safe, reliable, and inexpensive. We had heard of a range of claims about approaches that include fuel additives, mechanical filters, baffle systems, wet scrubbers, electrostatic precipitators, catalysts, and reburners. But at that point, none of the devices had robust test data and all appeared to have one or more fatal weaknesses: A) too expensive and complicated; B) require significant care, monitoring, or maintenance; C) have significant technical limitations that render them ineffective, unreliable, or hazardous.

Program Structure

In collaboration with the Washington Dept. of Ecology (Ecology), PSCAA received a National Estuary Program (NEP) grant to seek out and test potential new woodstove retrofit technologies. The grant proposed a two-step process: first, conduct an open challenge, and then test the best candidates. A Technical Advisory Committee (TAC) was created to provide input and review on the challenge goals, evaluation criteria, selection of the semi-finalists, and the final evaluation.

Table 1. Members of the Technical Advisory Committee.

Name	Organization	Role or Comment
Phil Swartzendruber	PSCAA	Project Manager, coordinates with the TAC, WA Ecology, and facilitator/consultant
Sara Harrold	PSCAA	from Planning, Analysis, and Forecasting
Walter Zylowski	PSCAA	representing Quality Assurance and Monitoring group
Brian Renninger	PSCAA	representing engineering
Rod Tinnemore	WA Dept. of Ecology	WA State perspective and residential wood burning expert
Zach Hedgpeth	EPA Region 10	EPA perspective on control technology
John Ackerly	Alliance for Green Heat	Nonprofit, advocacy for clean wood heating, experience running similar challenges

Open Challenge

The goal of the open challenge was to reach out to, and motivate participation from, as many high quality ideas or prototype devices as possible. There were three tasks or issues:

- Developing a set of target characteristics and an evaluation framework for potential devices or technologies with a range of development stages including only theoretical designs through functioning prototypes.
- Create an incentive framework so that the Grant's objectives and public funds are protected, while maintaining and enhancing motivation for inventors and developers.
- Broadcasting, publicizing, advertising, or reaching as many potential individuals in related technical fields as possible throughout the globe.

Target Characteristics

The target characteristics were developed in consultation with the TAC. The criteria were used quantitatively for the evaluation of submissions for selecting semi-finalists to be tested. They were also used qualitatively for the final evaluation after testing has been completed. The criteria used a rubric with five general characteristics, and three levels. Each levels had a low and high sublevel and points were assigned to each sublevel so evaluations could be composited. From lowest to highest, the categories and (low, high points) were: Not Met (0,1); Adequate (2,3); Ideal (4,5). Receiving a score less than 2 suggests that a device should be disqualified although exceptionally strong performance in all other categories could be considered under limited circumstances. The full rubric is attached as Appendix A. The categories and a brief discussion of their respective issues are:

i) Expected Reduction of PM2.5 and PAH throughout the full burn cycle.
- <50% is Not Met; >50% is Adequate; >75% is Ideal
- A 50% reduction and a cost of ~$800 is where the cost:benefit ratio becomes significantly better than changeouts. Performance less than this would be difficult to justify even in ideal circumstances.
- A reduction of 50-75% could be a good cost:benefit in a number of situations, but would not result in emissions that were comparable to new, high performance devices or performance under the new NSPS (New Source Performance Standard).

ii) Robustness, Reliability, and Safety of Device
- Not Met: likely to fail or cause safety risk, user can't tell if device is failing, and requires frequent adjustment or monitoring
- Adequate: unlikely to fail or cause risk, common failures are identifiable, failures can be reasonably easily by user/owner
- Ideal: does not present any safety risk, failures are rare or easily identifiable and easily resolvable by owner/user

iii) Final Cost to Owner/User
- Not Met: purchase and installation is >$1,000; requires annual maintenance of >$200, and has lifespan of< 10 years before replacement.
- Adequate: purchase and installation is < $800; annual maintenance is <$200, lifespan of at least 10 years.
- Ideal: purchase and installation is <$600; annual maintenance is < $100, lifespan of > 10 years.

iv) Overall Potential for Being Widely Adopted
- Not Met: can't be manufactured with existing technology; device is unappealing; performance can't be defined and adapted to regulatory framework
- Adequate: can be manufactured but price may be high; device is aesthetically neutral; performance can be fit into existing regulatory framework; some maintenance, monitoring, or power is required
- Ideal: already have multiple potential manufacturers; device is aesthetically neutral; little to no maintenance, monitoring, or power is required

v) Ability to be Tested in a Laboratory (only applies for evaluating submissions)
- Not Met: no prototype exists and one can't be fabricated in time for testing
- Adequate: a prototype exists but may require some repairs or modification
- Ideal: a fully functioning prototype exists that does not require any repairs or modifications

Incentive framework

For the challenge to be successful and retrofits to have potential, inventors and manufacturers need to have sufficient incentive to accept the risk and commit resources. Therefore, a modest profit motive is a reasonable assumption, which requires an intellectual property (IP) or manufacturing advantage. In the regulatory framework, technology development can create conflicts of interest and generate incentives for patent squatting. In this case, manufactures in an existing market (new woodstoves) do not have an incentive to develop a replacement or improved technology (retrofit) that would reduce the size of their existing market. And, at the inception of new, competing technology that could have a regulatory incentive (e.g. requiring retrofits on all existing stoves), the developer of a new technology could sell the patent, without licensing anyone to manufacture, to a party who has motive to not license it, such as a manufacturer of existing technology.

To reduce the potential risk of patent squatting, we worked with an IP attorney (Frank Abramonte, Seed IP, Seattle, WA) to develop a framework and legal terms. In order to obtain detailed information about the challenge and ultimately submit a solution, the IP owner was required to agree to the terms. The terms granted PSCAA a “conditional nonexclusive royalty-free license” (CNRFL) in exchange for accepting the testing. The CNRFL would grant PSCAA the right to use the IP, royalty free, if the IP owner did not attempt to commercialize the product within four years of accepting the agreement. Thus, if the IP were sold and not commercialized within four years, PSCAA would have the ability to license it, royalty free, to a manufacturer.

Broadcasting and reaching potential solvers, inventors, and IP owners.

The typical approach for reaching inventors and finding new technologies is to hire a consultant to manually reach out to a network of contacts, who also reach out to their contacts, and so on, until a suitable technology is found or a time or financial limit is reached. This process generally takes many months or years and can cost hundreds of thousands of dollars. More recent approaches have relied on existing groups connected through social media (Facebook, Twitter, listservs, email , etc) and various electronic forums to create webs of individuals with knowledge of, and direct connection to potential inventions and technologies.

A new version of this networking is known as crowdsourcing. In crowdsourcing, an idea or a technical solution is sought from a large crowd of individuals who have unique skills, knowledge, and interest and are willing to invest time. A problem or challenge is posed for a finite period of time and anyone is free to submit a solution. At the end of the challenge solutions are evaluated and any, or the best, qualifying solution may be given an award in exchange for transfer of intellectual property rights or the potential for further funding or collaboration.

The most successful organization for small-scale crowd sourcing is InnoCentives, Inc. There have been other challenges, and other organizations that run larger challenges, e.g. Ortieg Prize (crossing the Atlantic), Ansari X-Prize (non-government trip to space in two weeks), but the challenges are significantly more ambitious and the prize money is significantly beyond the scope of this project.

We contracted with InnoCentives, Inc to promote and host the open competition. The competition opened Sep 29, 2014 and closed Nov 21, 2014. The InnoCentives website hosted all of the information about the challenge, and provided an infrastructure for submitting and organizing solutions. The forum also required all interested solvers to agree to a set of terms that included the incentive and IP framework described previously.

At the end, 186 individuals signed on to read the challenge details, and there were 33 submissions. Of the 33 submissions, several were duplicates, a few were incomplete or offered minimal detail and had no data. Eleven complete submissions were sent to the TAC for evaluation.

Evaluations and Selections

The TAC members individually reviewed the 11 submissions and gave numerical rankings based on the Rubric in Appendix B. From the aggregate statistics of the individual rankings, there were five submissions that were clustered at the top. Since the program could nominally only test three devices, the TAC met and discussed the submissions with the goal of reaching consensus. After several extended discussions, a consensus was reached on the four best, but one could not be reached on the three best devices. Ultimately, the TAC recommended that evaluating four devices in a first round, and then reducing to three devices for the second round would an acceptable path forward. The four devices were: ClearStak Pollution Control Device, the Grahn Afterburner, the GraceFire Emission Control Device (StoveCat), the MF Fire Afterburner.

Testing and Quality Assurance Project Plan

On Sept 12, 2014, an RFP was opened for testing services. From this initial RFP, there were no responses within the designated period, and so the period was extended. Informal feedback from several labs indicated that an impending NSPS revision was causing a flood of testing demand. And, the retrofit testing project was large enough that it would sequester most of a lab's resources and preclude their ability to test for existing clients. So, the RFP was revised and re-released on Jan 13, 2015. Three bids were received and OMNI-Test Laboratories, Inc, in Portland, OR was selected as the winner.

Testing Protocol

The testing protocol was developed with the hope of evaluating the PAH and PM reduction performance of each device across a range of uses. The relevant parameters affecting emissions include: 1) type/make of uncertified stove, 2) wood moisture, and 3) burn rates. To produce the most reliable emission reductions data, baseline (reference) emissions had to be measured for each stove without a retrofit device, at each set of parameters tested.

A quality assurance project plan (QAPP) was developed in order to comply with NEP grant requirements and to help ensure that testing was conducted in a robust and meaningful manner. The QAPP was developed with the assistance of the WA Dept. of Ecology NEP QA Coordinator and OMNI-Test Laboratories. The QAPP described in detail the testing protocol, testing methods, and data quality objectives for the test. While the full QAPP is not attached to this report, key components are described below and the full QAPP is available upon request.

Testing was conducted as close to the QAPP and EPA methods as was possible. Stove operation followed Method 28, the PM sampling followed 5G-3, and PAH sampling followed EPA Compendium Method 0010. Several deviations from strict adherence to these methods were required. The deviations and further details are described in the Lab Final Report (Appendix C) section 2.1.1.

Below is an excerpt from the Testing Plan describing the testing matrix.

Test Matrix

The testing conditions for reference runs without a retrofit device, and then test runs with the retrofit device(s) will be conducted per the following table. The tests will include two stoves and two parameters: high or low burn rate, and higher or lower wood moisture. There are four combinations of these two parameters, which are labeled **A-D**. Parameter Pair **A** will not be tested because it represents the best combustion conditions.

The test sequence will be as follows. Stove #1 will be setup and duplicate baseline tests (with no retrofit installed) will be performed under conditions **B**, **C**, and **D**. If any of the pair of runs under each condition have large relative standard deviations (>40%), replicate runs may be conducted until the relative standard deviation is less than 40%. Each of the four semi-finalists will then be tested once under conditions **B**, **C**, and **D**. The retrofits are indicated in Table 2 by Roman numerals I, II, III, IV. The three best performing devices will be selected to continue for a second round of testing on the second stove. If the results of the first round of tests do not reveal statistically significant differences, any or all of the devices may be tested again under condition **B**, **C**, or **D**.

Next, stove #2 will be setup and duplicate baseline tests (with no retrofit installed) will be performed under conditions **B**, **C**, and **D**. If any of the pair of runs under each condition have large relative standard deviations (>40%), replicate runs may be conducted until the relative standard deviation is less than 40%.

Each of the three remaining semi-finalists will be tested under all three conditions, **B**, **C**, and **D,** on stove #2. These are indicated in Table 2 by Greek characters α, β, γ. Tests may be repeated, up to the budget limit, in the event of inconsistent results.

Table 1. Test condition parameter pairs. Note test condition pair A will not be used.

Parameter Pair ID	Burn Rate	Wood Moisture
A	HIGH	lower
B	LOW	higher
C	HIGH	higher
D	LOW	lower

Table 2. Testing matrix. Four retrofits will be tested on Stove 1 and are identified by Roman numerals I, II, III, IV. The three best retrofits from Stove 1 will be tested on Stove 2 and are identified by Greek characters α, β, γ. Baseline tests are indicated by bl.

	Test Conditions ID		
Stove	**B**	**C**	**D**
1	*bl* x 2	*bl* x 2	*bl* x 2
1	I	I	I
1	II	II	II
1	III	III	III
1	IV	IV	IV
2	*bl* x 2	*bl* x 2	*bl* x 2
2	α	α	α
2	β	β	β
2	γ	γ	γ

Stoves

The two uncertified stoves selected were a Schrader and a Princess. The Schrader model was unknown, but appeared to very similar to numerous stoves removed in Washington State through our Changeout and Bounty programs. It had a medium sized firebox (1.6 ft^3) with no internal baffling or secondary combustion structure. The combustion air was controlled by dual spin draft knobs on each of two front doors. The Princess had a larger firebox (2.1 ft^3) and also lacked any internal baffling or secondary combustion structure. But, the Princess did have an air supply door that was mechanical actuated by a bimetallic thermostat coil in order to maintain a more uniform burning rate. Section 2.2 of the Lab Report contains pictures and further description of the stoves.

Results

Tables 3-6 in the Lab Report summarize the testing results on a run by run basis. Note that woodstove emissions are not reported as concentrations because this metric is not directly useful for assessing impacts or stove performance. Both emissions rates (e.g. grams/hour) and emission factors (e.g. grams/kg of fuel) are reported and analyzed because they relate most directly to impact on air quality and the combustion quality, respectively. Overall, the stove testing data appeared to be of sufficiently good quality. There were only two areas of note, but these were not inherent to the testing method and are likely insignificant. The first is that two of the retrofits had significantly reduced performance during testing on the second stove. This is discussed below in **Round 2**. The second potential issue is that the PAH analysis required a (chemical) separation step to properly isolate the desired EPA 7-PAHs. The analysis of the full suite of PAHs found the total PAH mass was dwarfed by other PAH species. In order to better isolate the EPA 7-PAHs, a separation/filter step was added. See the lab report (Appendix D) for further information.

Round 1

The Schrader stove was tested 6 times to establish baseline emission rates and factors. The burn rate for the low burn rate tests (1.4-1.8 kg/hr) was not as low as desired or as would be required for the lowest category for EPA testing (0.8 kg/hr). But, since the stove's performance was likely representative of real stoves and was consistent, it was decided to accept the lowest burn rate that was achievable with spin draft control knobs fully closed. The higher burn rate was 3.4-3.7 kg/hr. The baseline testing demonstrated a strong inverse relationship between burn rate and emission factor, as is generally observed in simple combustion boxes. The baseline emission factors were in the range of 30-40 g/hr. The baseline emission factors ranged from 9 g/kg for the high burn rate runs to about 24 g/kg for the low burn rate runs. After baseline testing, each device was installed and tested three times, once in each of test conditions (parameter pairs) B, C, and D.

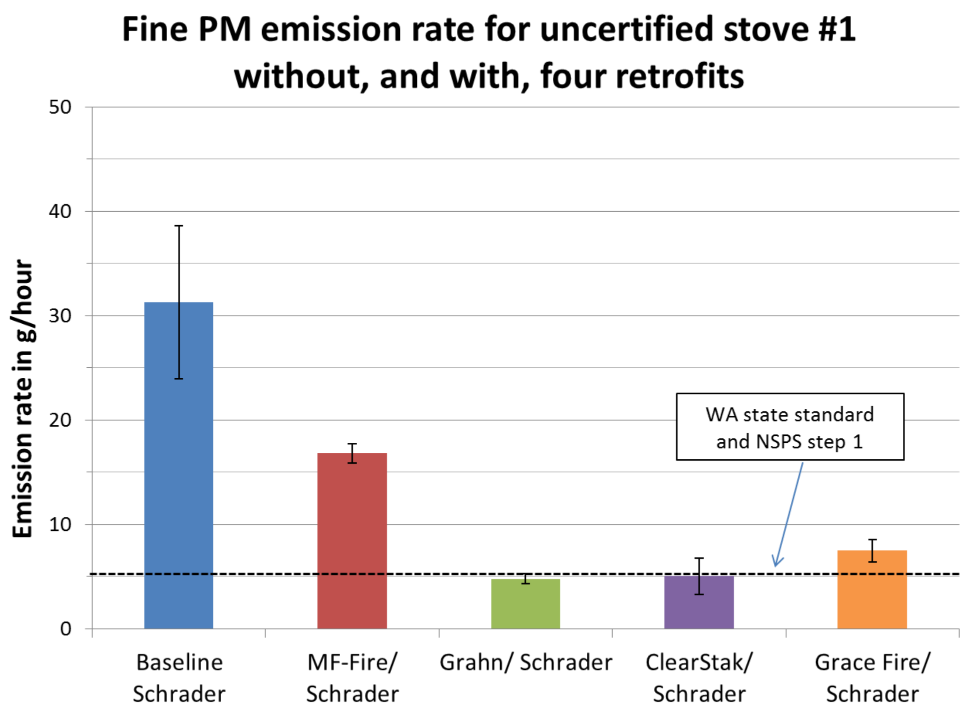
The average results (as emission rates) from Round 1 are plotted below in Figure 1. The fine PM emission rates with the MF-Fire device were about 40-60% compared to baseline (a 60-40% reduction). The Grahn and ClearStak devices appeared to have the best performance with mean reductions of about 86%, while the GraceFire device was close, with a reduction of about 80%. (The error bars indicate ± 1 σ.)

Based on the Round 1 results, the Grahn, ClearStak, and GraceFire devices were the best performing and continued on to further testing on the second stove (Round 2).

Round 2

Round 2 was conducted similarly to Round 1 except that there were only three devices to test and there were sufficient funds to allow a fourth test on each device. Six baseline tests were performed with low burn rates in the range of 1.5-1.7 kg/hr, and high burn rates of 3.4 and 4.8 kg/hr. Emission rates ranged from 36-69 g/hr, while emission factors ranged from 14 g/kg at high burn rates to about 35 g/kg at low burn rates.

Figure 1.

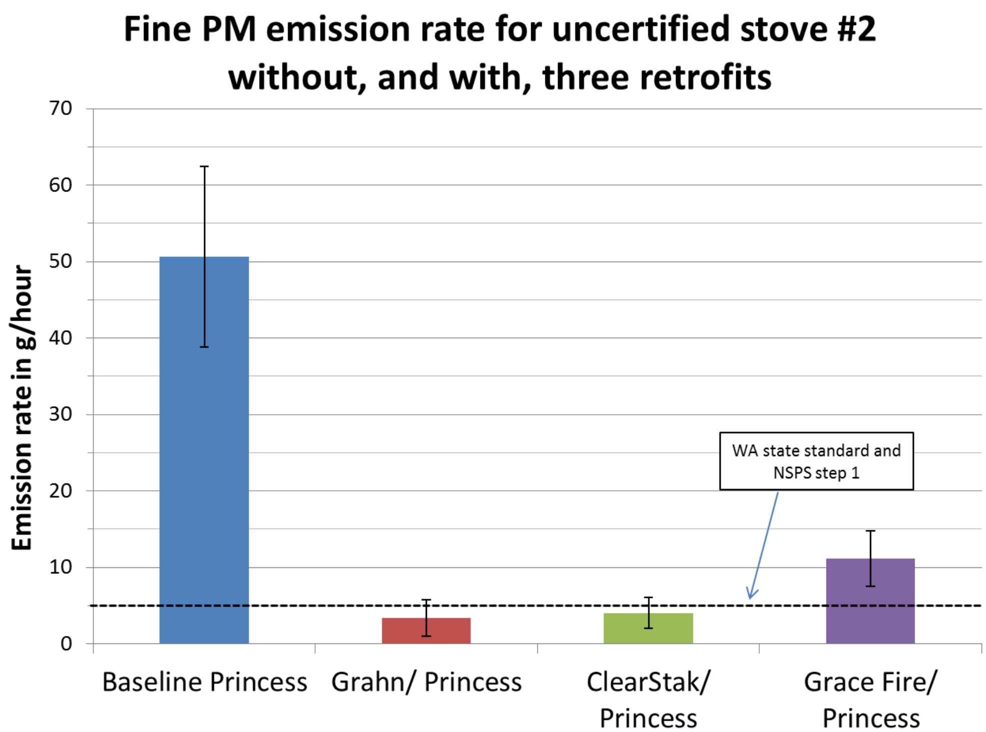


For both the ClearStak and Grahn devices, the performance dropped significantly after the first test. Visible emissions were apparent from both devices, and the web interface on the ClearStak device showed inadequate catalyst temperature. Inspection of both devices after their respective fourth test revealed that there were mechanical problems. On the Grahn device, a critical part that had been fabricated from aluminum had melted, which allowed exhaust to bypass the counterflow-combustion channels. A replacement part was fabricated from stainless steel and the device was retested two additional times. On the ClearStak device, the catalyst had become dislodged consistent with a designed safety feature in the event of excessive pressure. The catalyst was replaced and the device was tested two additional times.

Analysis

The primary metric for PM reduction performance of the retrofits was the percent reduction in the emission factor (EF). The EF was chosen because many of the test runs with the retrofits installed had substantially different burn rates compared to the designated testing conditions. The EF generally has a strong inverse relationship with burn rate. This makes it possible to generate an expected EF for any burn rate and thus compensate for reduced emissions due to changes in the burn rate rather than improvement in combustion.

Figure 2. The average results (as emission rates) of Round 2 testing, with outliers removed. The outliers are discussed in the next section (Analysis). (The error bars indicate ± 1 σ.)



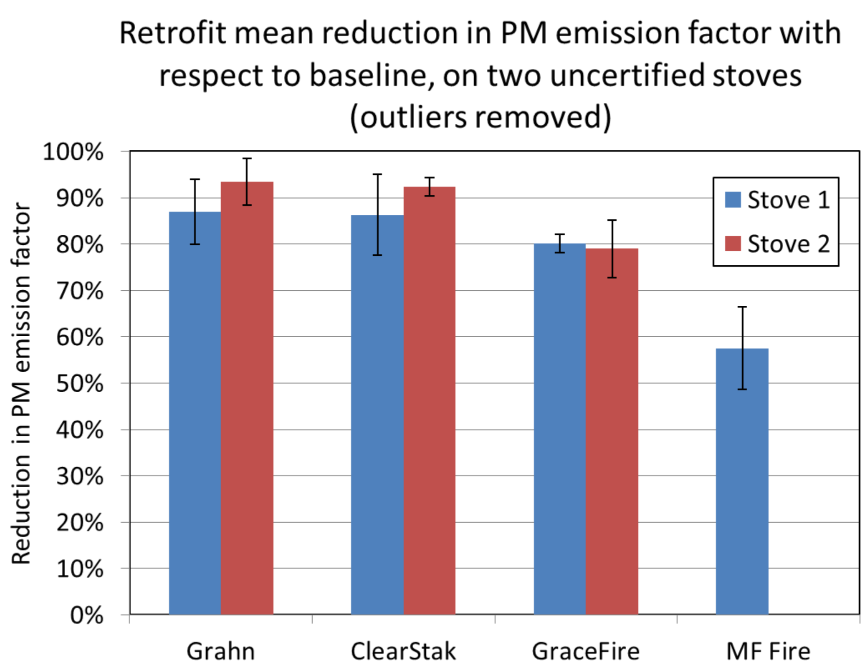
The EF - burn rate relationship of the baseline performance was calculated in three different ways and the stove performance was evaluated for all three. In method 1, each test parameter pair was used as a discrete condition (B, C, D) for the baseline EF. The duplicate baseline runs for each parameter pair were averaged to obtain a parameter pair specific EF. Each retrofit test was compared to its respective parameter pair baseline test regardless of actual burn rate. In method 2, the high burn rate runs and the low burn rate runs were averaged, respectively, and a line was fit between the two averages. For each test run an expected EF from the fit line was calculated. But, a minimum EF was set based on the maximum burn rate run of the baseline tests. All burn rates above this rate had EFs equal to the EF of the maximum burn rate. For method 3, the EF was correlated to the burn rate using reduced major axis regression (RMA) of all individual runs. RMA regression can be more appropriate when the independent variable has a similar amount of uncertainty (or error) relative to the dependent variable and the correlation is moderate to poor. The RMA regression also used a minimum EF based on the maximum burn rate, as was done for method 2.

The three methods produced very similar performance results, and did produce identical rankings. Methods 2 and 3 produced nearly identical performance results and so those values are used for the final plots and summary.

All of the emission reduction data for each device (both stoves) were examined in quantile plots to look for potential outliers. The final three tests in Round 2 of both the ClearStak and Grahn devices were the lowest of their respective sets and appeared to be outliers. Because there was an existing objective reason (dislodged catalyst and melted part, respectively) to believe that those runs could be outliers, they were removed from further analysis.

To maintain consistency, results from the GraceFire device were also examined for outliers and a single value was found to be significantly below the distribution and so was also discarded. For reference, the mean reduction for both stoves, retaining the outliers, for the Grahn, ClearStak, and GraceFire devices would be 79%, 66%, and 76% respectively.

Figure 3. The average reduction performance, with outliers removed. In this plot, a higher number is a better or greater performance. (The error bars indicate ± 1 σ.)



The average reduction for both stoves was 89%, 88%, 78%, and 46% (only Stove 1), respectively, for the Grahn, ClearStak, GraceFire, and MF Fire. Appendix C contains plots and a brief annotation from all figures generated in the course of the data analysis.

Statistical Tests

Per the Quality Assurance Project Plan (QAPP), the numerical objective was to test the null hypothesis against the alternative hypothesis that a selected retrofit reduced the PM emissions by at least 50%. In order to test the hypothesis, a t-test for difference in means was conducted between the means of relative emission factors and baseline. The reference emissions (baseline) were calculated from the emission factor – burn rate equations (Method 3). The test value was the measured emission factor relative to the calculated (expected) baseline emission factor ($E_{retrofit}/ E_{baseline}$). The mean of the

reference (baseline) values was therefore 1. The sample standard deviations were estimated from the errors in the fit equations for the baseline tests, and from the deviations of the individual retrofit runs from their respective means.
The baseline emission factor without the retrofit is $E_{baseline,}$ and the mean emission factor with the retrofit in operation $E_{retrofit}$.

Therefore, we are testing a) against b):

a) the null hypothesis, *H0*, that $E_{retrofit}$ is greater than 50% of $E_{baseline}$.
    i. That is: $E_{retrofit}/ E_{baseline} > 0.50$
b) the alternative hypothesis *H1*, that $E_{retrofit}$ is less than 50% of $E_{baseline}$.
    i. That is: $E_{retrofit}/ E_{baseline} < 0.50$

Since the hypothesis is being tested for each retrofit and not for the full set of retrofits, there is no need for a multiple comparisons correction such as a Bonferroni correction.

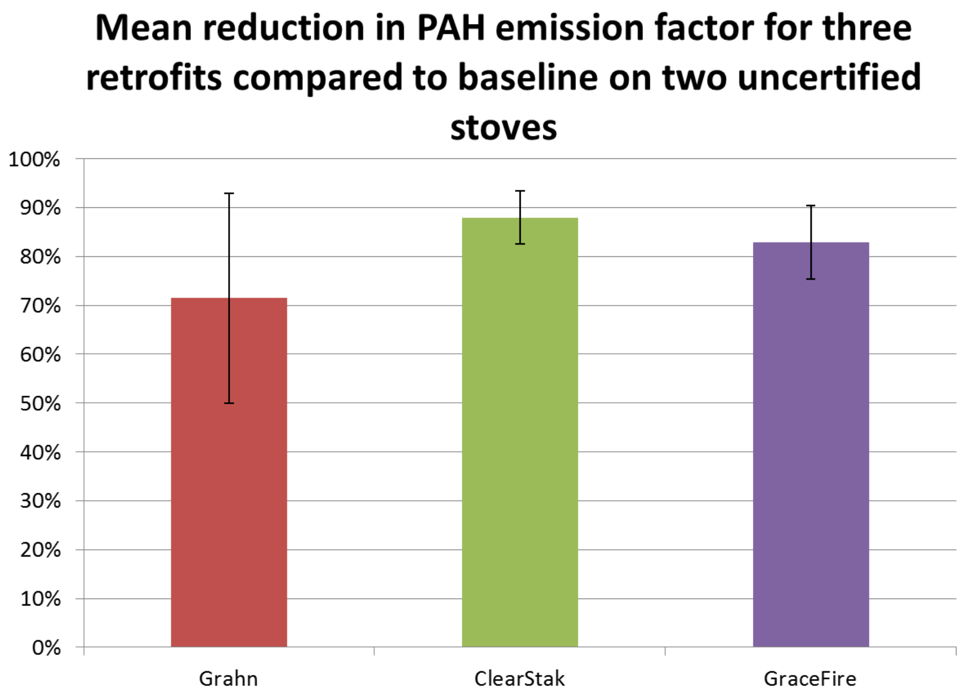
For the stated test statistic, the *p* value (for the difference of means being >0.50) was 0.0018, 0.0021, and 0.0019, respectively for the ClearStak, GraceFire, and Grahn devices. Thus, there is sufficient evidence to reject the null hypothesis that retrofits reduce the emission factor by less than 50%, at a significance of $p < 0.005$.

PAH reductions

A second critical test parameter was PAH emissions. Polycyclic aromatic hydrocarbons (PAHs) are a class of about 100 compounds which are composed of two or more benzene (carbon) rings. Some PAHs can be toxic to humans and wildlife in aquatic ecosystems at relatively low concentrations. PAHs are a natural component of crude oil and are formed from the incomplete combustion of organic matter. EPA has identified a subset of 7 PAHs that are probable human carcinogens. The sum emissions of this subset of PAHs (EPA 7-PAH) is the metric used for this study.

There was a modest to strong correlation among the 7 individual PAHs within each respective test run. There was, however, very little or no correlation between the total PM emission factor and total PAH emission factor in the baseline tests (for both stoves) and with the retrofits. There was a weak relationship between PAH emission factors (EFs) and burn rate in the first test stove. So, the baseline EFs were estimated using a correlation similar to the total PM emission factors. For the baseline tests on the second test stove, there was no clear correlation between the PAH EFs and the burn rate. Therefore, an expected PAH EF as a function of burn rate could not be estimated with good confidence. So, the expected PAH EF was calculated from the average of the two tests within each burning condition parameter pair (B, C, D) of the baseline tests, similar to method 1 for total PM emissions.

Figure 4. The average PAH reduction for each device for all runs on both stoves, with the previously identified outliers removed. (The error bars indicate ± 1 σ.)



Other stove performance metrics

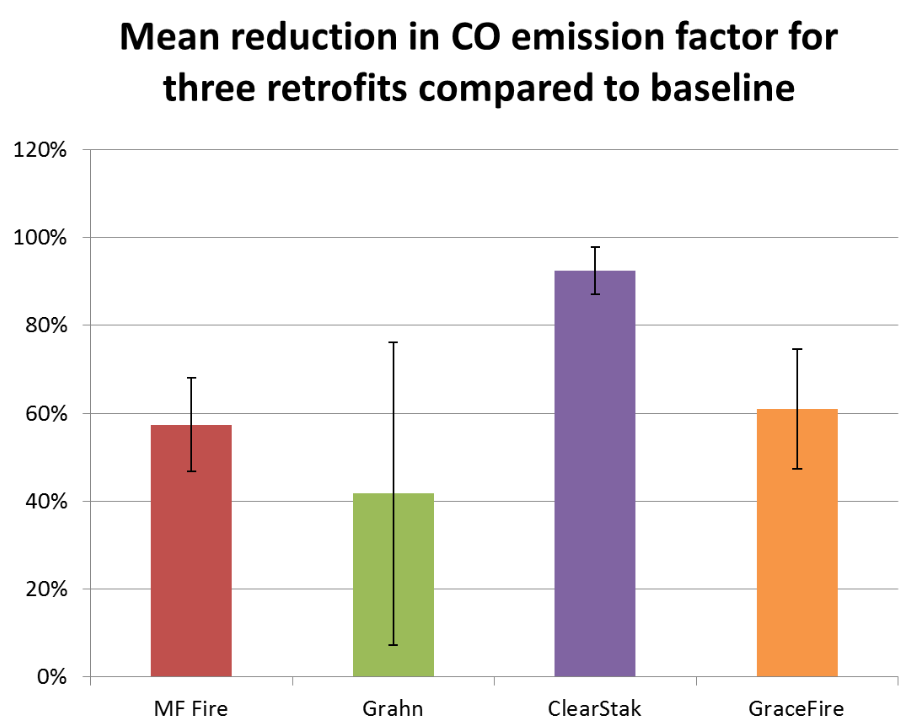
Additional measurements included CO and temperature. See Figure 5. The efficiency (HHV and LHV) was also calculated for all runs. The data are included in the Laboratory Report (Appendix D). Since these parameters were not directly critical to the performance assessment, only a cursory analysis was conducted. The mean CO reduction for the four devices was 43%, 92%, 61%, and 67% (only Stove 1), respectively, for the Grahn, ClearStak, GraceFire, and MF Fire.

Quality Assurance

The testing was conducted in good agreement with the Quality Assurance Program Plan (QAPP). Reasonable effort was made to follow EPA and WA Dept. of Ecology approved methods, but they could not be perfectly followed. These variances are believed to be minor and are described in section in the Final Report from OMNI-Test in section 2.1.1 Method Modifications. Some of the variances were departures from EPA methods and were done intentionally, such as a subset of tests with higher wood moisture. Several others were done due to the unique conditions that retrofits create for the sampling systems, or for adaptions for woodstove testing (e.g. the PAH sampling by Compendium Method 0010).

The study design appeared to be successful in testing or discriminating whether any device had an emissions reduction of at least 50%, under the burning conditions tested, with significance $p < 0.05$ (*p* was actually < 0.005). The performance of the devices was greater than expected and so the study design was more than adequate to reach the desired confidence level. The largest weakness of the study design is that low burn rates were not adequately addressed. This is at least partly due to a conservative approach which tested the broadest null hypothesis – retrofits can't perform well under any condition. Once it has been established that they in fact can perform well under more ideal conditions – and it appears that at least these three do - they need to be tested under more challenging conditions.

Figure 5. The average CO reduction for each device for all runs on both stoves (but only stove #1 for the MF Fire device), with the previously identified outliers removed. (The error bars indicate ± 1 σ.)



Evaluations and Awards

The Technical Advisory Committee (TAC) reviewed all three devices, the rubric, the test results, and the overall objectives. The TAC had a range of opinions as to which device was the best and how the award should be distributed. After discussion with each member of the TAC, a three-way tie was the most broadly accepted conclusion. The TAC did agree that all three devices sufficiently met the challenge criteria to warrant awards, which were also split three ways. Key specific conclusions and concerns included:

- All devices met the pollution reduction goal, but further refinement is encouraged to improve or verify the robustness of the devices and optimize the installation and appearance, and reduce costs.
- Each device appeared to have some advantages and disadvantages compared to the others and therefore may excel in different stove setups or use patterns. Specifically:
  - The GraceFire device is passive and so would likely perform better during a power outage, but the performance appeared to drop (the emission factor increased) with lowered burn rate.
  - The performance of the ClearStak and Grahn devices had weaker, or no, dependence on burn rate, but were more complicated, and so likely would be more expensive.
  - Both the GraceFire and ClearStak devices had relatively small, sleek profiles, while the Grahn device was larger.
  - The ClearStak device included an integrated web based monitoring system that would allow a user to remotely check on the operation and functioning of the stove.
- The devices were not tested under the lowest burn rate required for certification, EPA Category 1, so it is unknown how well these devices would perform under the common practice of loading up stoves and choking them down for overnight slow burns. Future retrofit evaluations should include low burn rate tests (< 0.8 kg/hour) and smolder/chokedown tests.
- Each device used a slightly different approach, which suggests that there may not be one best technology and there may be additional, viable approaches that have not yet been identified.

Additional Information

The appendixes contain additional data and information from the Open Challenge and Testing. Additional, supporting data and files are not included, but are also available. Some of these are available for downloaded at http://dl.pscleanair.org/WoodstoveRetrofitChallenge/ while that site is maintained, and all are available upon request of the Agency. The files and data include:

- Raw output files from the testing runs (80 files, ~ 120 MB)
- Excel worksheet with analysis for PM and HHV,LHV
- Excel worksheet with analysis for PAHs and CO
- Quality Assurance Project Plan (QAPP)
- Project Plan
- InnoCentives Seeker Agreement and Solver Agreement
- Compilation of feedback for the 11 submissions reviewed by the TAC

Appendixes

A. **Screenshots of Open Challenge**

B. **Evaluation Rubric**

C. **Supplementary Analysis plots**

D. **Omni-TEST Lab Final Report**

Appendix A

Figure A-1. Screenshot of the InnoCentive website showing the "Retrofit Residential Wood Burning Stoves for Pollution Reduction" challenge shortly after it posted.

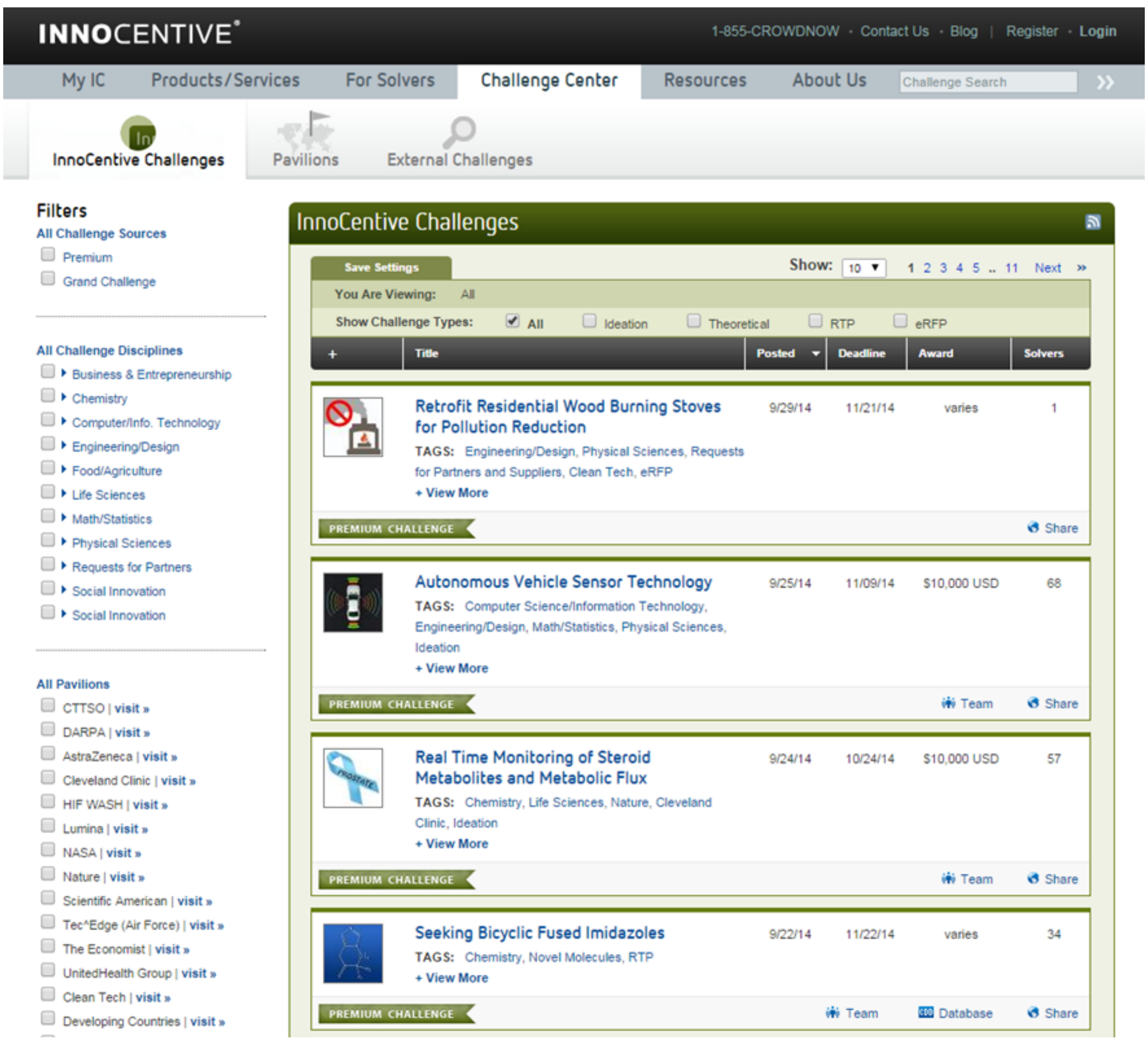


Figure A-2. Screenshot at the end of the challenge showing statistics of when and from where, potential solvers viewed details of the challenge, and submitted solutions.

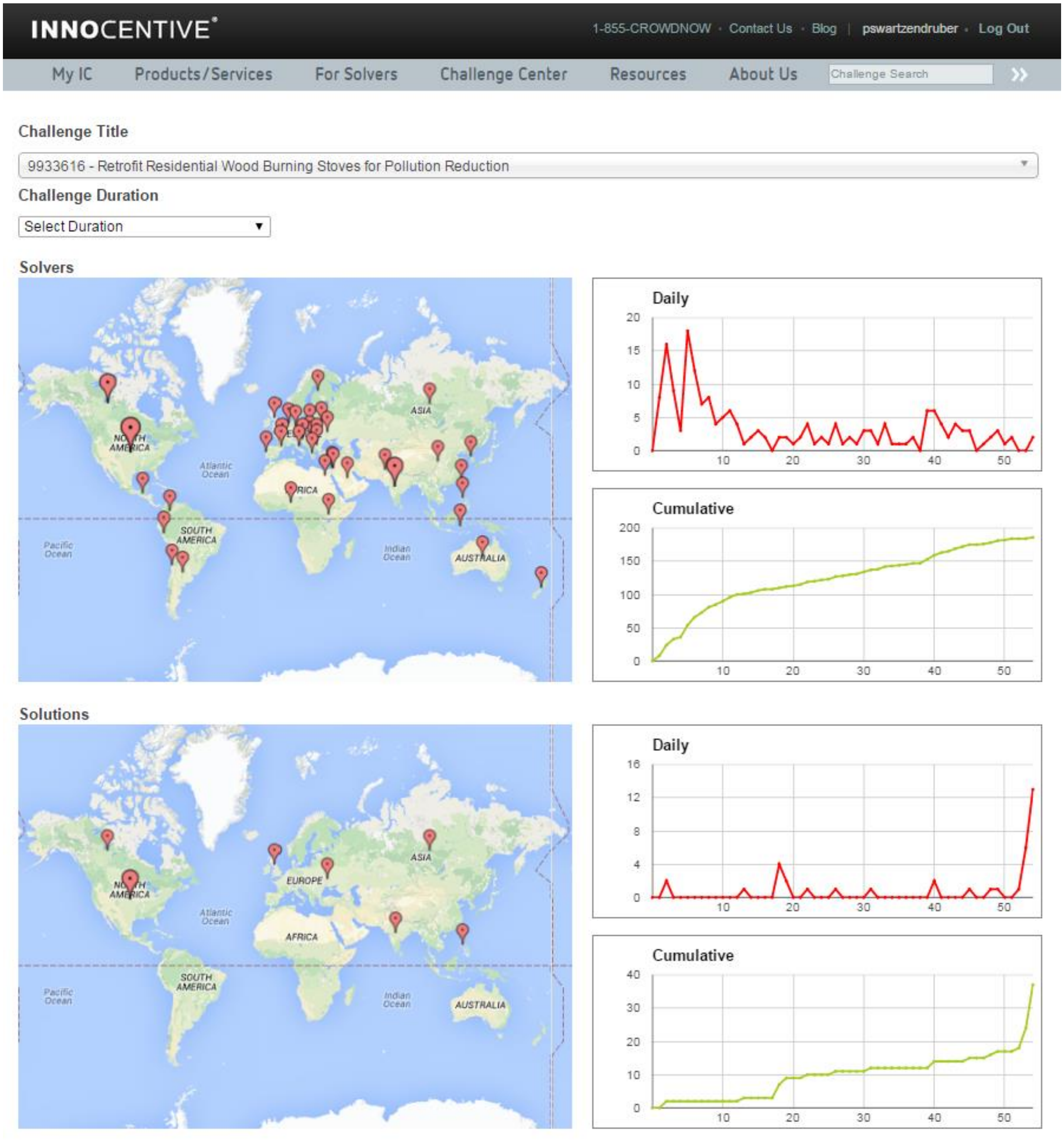
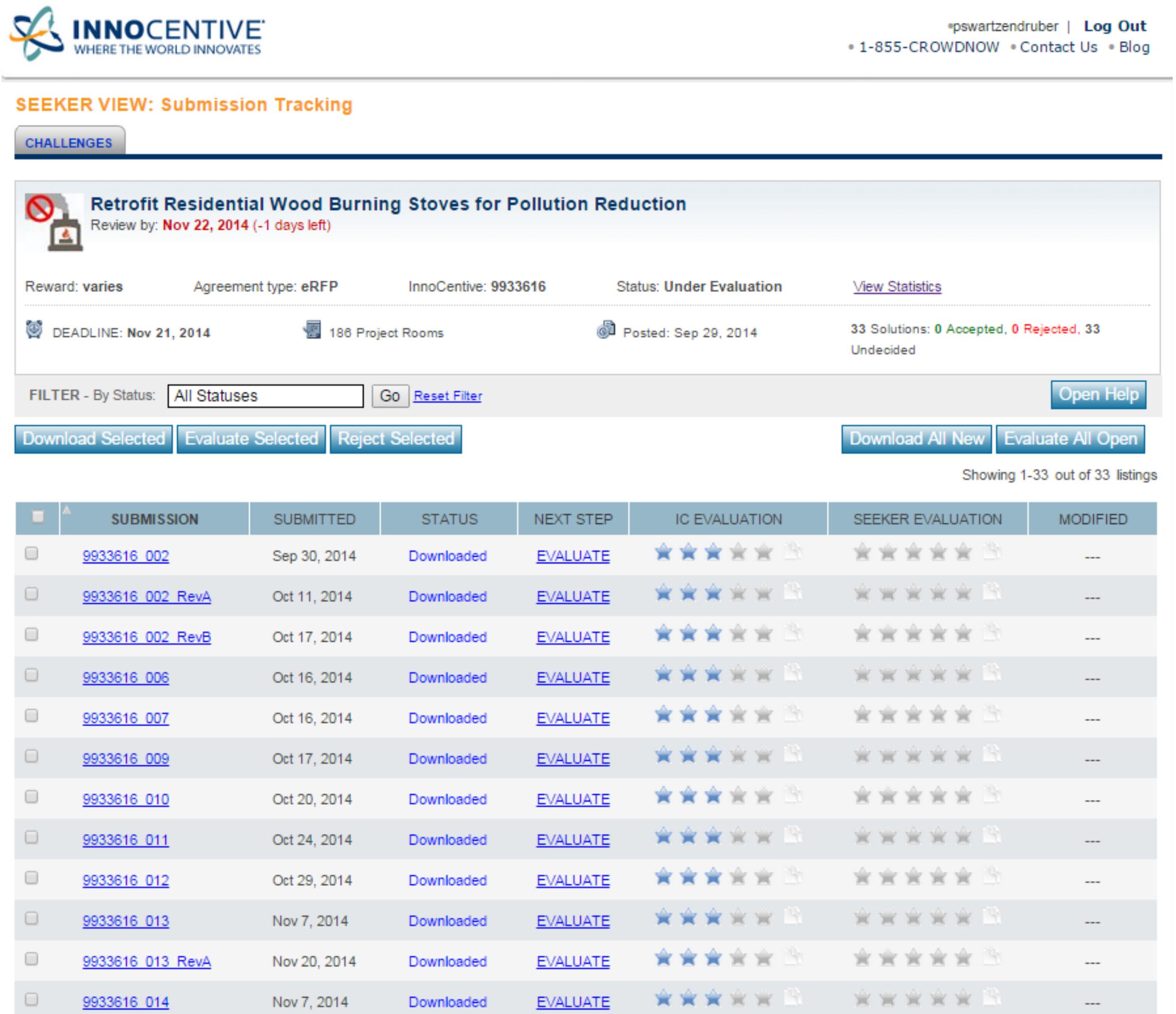


Figure A-3. Top half of a screenshot of the submission tracking page after the close of the challenge. Several of the submissions were revisions to previous challenges.



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SEEKER VIEW: Submission Tracking

CHALLENGES

Retrofit Residential Wood Burning Stoves for Pollution Reduction
Review by: Nov 22, 2014 (-1 days left)

Reward: **varies** Agreement type: **eRFP** InnoCentive: **9933616** Status: **Under Evaluation** View Statistics

DEADLINE: **Nov 21, 2014** 186 Project Rooms Posted: Sep 29, 2014 33 Solutions: 0 Accepted, 0 Rejected, 33 Undecided

FILTER - By Status: All Statuses Go Reset Filter Open Help

Download Selected Evaluate Selected Reject Selected Download All New Evaluate All Open

Showing 1-33 out of 33 listings

SUBMISSION	SUBMITTED	STATUS	NEXT STEP	IC EVALUATION	SEEKER EVALUATION	MODIFIED
9933616_002	Sep 30, 2014	Downloaded	EVALUATE			---
9933616_002_RevA	Oct 11, 2014	Downloaded	EVALUATE			---
9933616_002_RevB	Oct 17, 2014	Downloaded	EVALUATE			---
9933616_006	Oct 16, 2014	Downloaded	EVALUATE			---
9933616_007	Oct 16, 2014	Downloaded	EVALUATE			---
9933616_009	Oct 17, 2014	Downloaded	EVALUATE			---
9933616_010	Oct 20, 2014	Downloaded	EVALUATE			---
9933616_011	Oct 24, 2014	Downloaded	EVALUATE			---
9933616_012	Oct 29, 2014	Downloaded	EVALUATE			---
9933616_013	Nov 7, 2014	Downloaded	EVALUATE			---
9933616_013_RevA	Nov 20, 2014	Downloaded	EVALUATE			---
9933616_014	Nov 7, 2014	Downloaded	EVALUATE			---

Figure A-4. Bottom half of a screenshot of the submission tracking page after the close of the challenge. Several of the submissions were revisions to previous challenges.

9933616_013_RevA	Nov 20, 2014	Downloaded	EVALUATE	---
9933616_014	Nov 7, 2014	Downloaded	EVALUATE	---
9933616_015	Nov 12, 2014	Downloaded	EVALUATE	---
9933616_016	Nov 15, 2014	Downloaded	EVALUATE	---
9933616_017	Nov 16, 2014	Downloaded	EVALUATE	---
9933616_019	Nov 20, 2014	Downloaded	EVALUATE	---
9933616_021	Nov 20, 2014	Downloaded	EVALUATE	---
9933616_022	Nov 20, 2014	Downloaded	EVALUATE	---
9933616_023	Nov 20, 2014	Downloaded	EVALUATE	---
9933616_024	Nov 20, 2014	Downloaded	EVALUATE	---
9933616_025	Nov 21, 2014	Downloaded	EVALUATE	---
9933616_026	Nov 21, 2014	Downloaded	EVALUATE	---
9933616_027	Nov 21, 2014	Downloaded	EVALUATE	---
9933616_028	Nov 21, 2014	Downloaded	EVALUATE	---
9933616_029	Nov 21, 2014	Downloaded	EVALUATE	---
9933616_030	Nov 21, 2014	Downloaded	EVALUATE	---
9933616_031	Nov 21, 2014	Downloaded	EVALUATE	---
9933616_032	Nov 21, 2014	Downloaded	EVALUATE	---
9933616_033	Nov 21, 2014	Downloaded	EVALUATE	---
9933616_034	Nov 21, 2014	Downloaded	EVALUATE	---
9933616_035	Nov 21, 2014	Downloaded	EVALUATE	---
9933616_036	Nov 21, 2014	Downloaded	EVALUATE	---
9933616_037	Nov 21, 2014	Downloaded	EVALUATE	---

Showing 1-33 out of 33 listings

Download Selected | Evaluate Selected | Reject Selected | Download All New | Evaluate All Open

* Denotes that the Solver has been notified and no further changes can be made to the evaluation

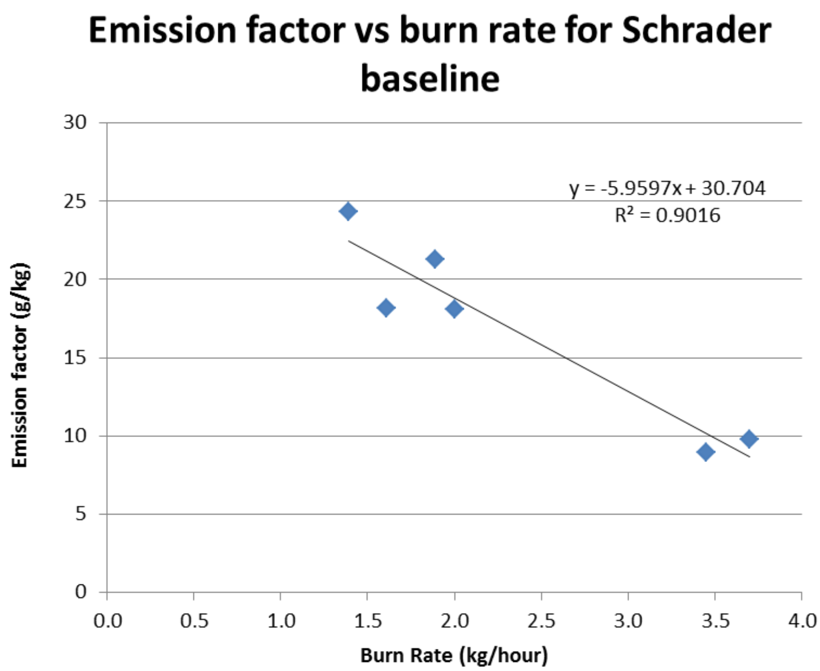
Appendix B

Evaluation Rubric with Criteria and Category Rating

Points→	Not Met (0, 1)	Adequate (2, 3)	Ideal (4, 5)
Expected PM2.5 & PAH Reduction Throughout Full Burn Cycle	Emission reductions of either or both PM2.5 and PAH, on a mass per fuel mass basis, are <50% at low and moderate burn rates.	Emission reductions of both PM2.5 and PAH, on a mass per fuel mass basis, are >50% at low and moderate burn rates.	Emission reductions of both PM2.5 and PAH, on a mass per fuel mass basis, are >75% at all burn rates.
Robustness, Reliability, and Safety of Device	• The device does, or is likely to, fail or create a health and safety hazard for the occupants, the structure, or the surrounding environment. • Any failure is not easily identifiable and resolvable by the user/owner and may require substantial repair or replacement. • The device requires frequent user adjustment or monitoring	• The device does not create a health and safety hazard for the occupants, the structure, or the surrounding environment. • The device may be susceptible to failure due to improper burning or maintenance, or user errors. • Common failures are identifiable and resolvable by the user/owner. • Only uncommon failures require significant maintenance.	• The device does not create a health and safety hazard for the occupants, the structure, or the surrounding environment. • The device is not susceptible to failure despite common user errors or normal operations. • Any failure is easily identifiable and resolvable by the user/owner.
Final Cost to Property Owner/User	• Purchasing and installing the device costs > $1000. • Annual maintenance costs are > $200 • Lifetime of device is limited, so major maintenance or reinstallation required after less than 10 yrs.	• Purchasing and installing the device costs < $800. • Annual maintenance costs are < $200 • Lifetime of device is not limited, so major maintenance or reinstallation is not required for at least 10 yrs.	• Purchasing and installing the device costs < $600. • Annual maintenance costs are < $100 • Lifetime of device is not limited, so major maintenance or reinstallation is not required for at least 10 yrs.
Overall Potential for Being Widely Adopted	• Not able to be manufactured with current technologies or at a low enough cost. • Device is considered aesthetically unpleasant, unsightly, or otherwise is unappealing. • IP owner unlikely, unable, or unwilling to allow manufacture with reasonable market conditions . • Performance of the device is not definable and it is difficult or impossible to incorporate into regulatory framework. • Significant, complicated, or expensive regular maintenance is required.	• Can be manufactured with current technologies, but quantity, quality, or price are less than ideal. • Aesthetically neutral. • IP owner is likely, able, and willing to allow manufacture with reasonable market conditions. • Performance of the device is definable and it is possible to incorporate into regulatory framework. • Modest, simple, or inexpensive maintenance is required. (Replacement of a filter or part or removal and cleaning)	• There are multiple options for manufacturers. Quantity, quality, and price are ideal. • Aesthetically neutral. • IP owner is cooperative, eager, and is actively working to see the device reach the market. • Performance of the device is simple, and fits readily into existing regulatory framework. • No maintenance, or trivial and infrequent maintenance is required (e.g. pressing a button to initiate a cleaning cycle, or replacing a filter)
Ability to be Tested in a Laboratory	• No prototype exists. • Not known how to manufacture, or can't be manufactured in a short time frame, or prototype is too expensive.	• A prototype, functioning or not, does exist. • Can be manufactured or completed in a short timeframe, but may be expensive. • Repairs or modifications may be needed.	• A functioning prototype exists. • No modifications or repairs needed.

Appendix C

Figure C1-a, b. The emission factor vs burn rate for the two test stoves a) stove #1 - Schrader, and b) stove #2- Princess.



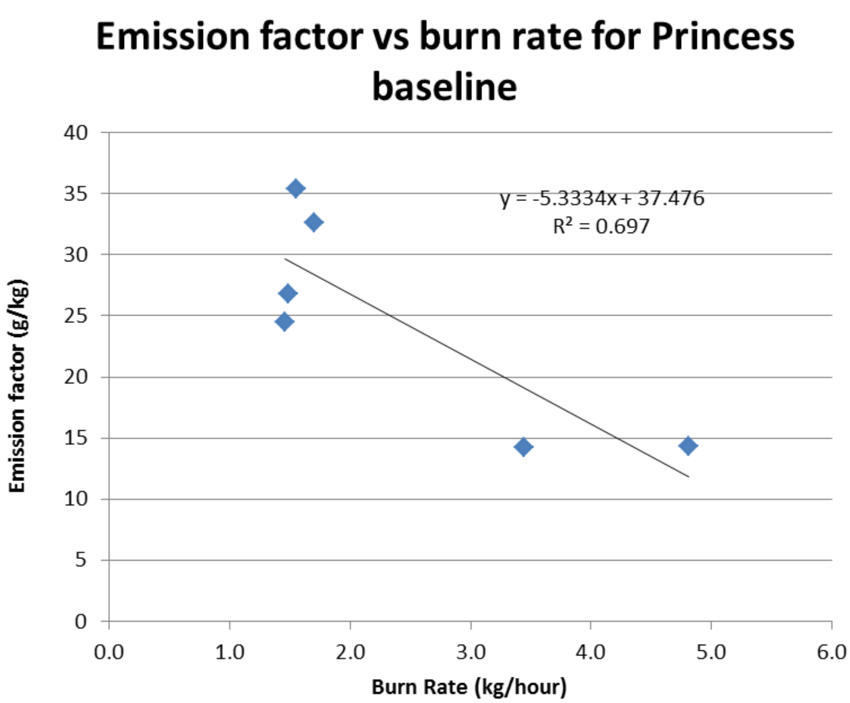
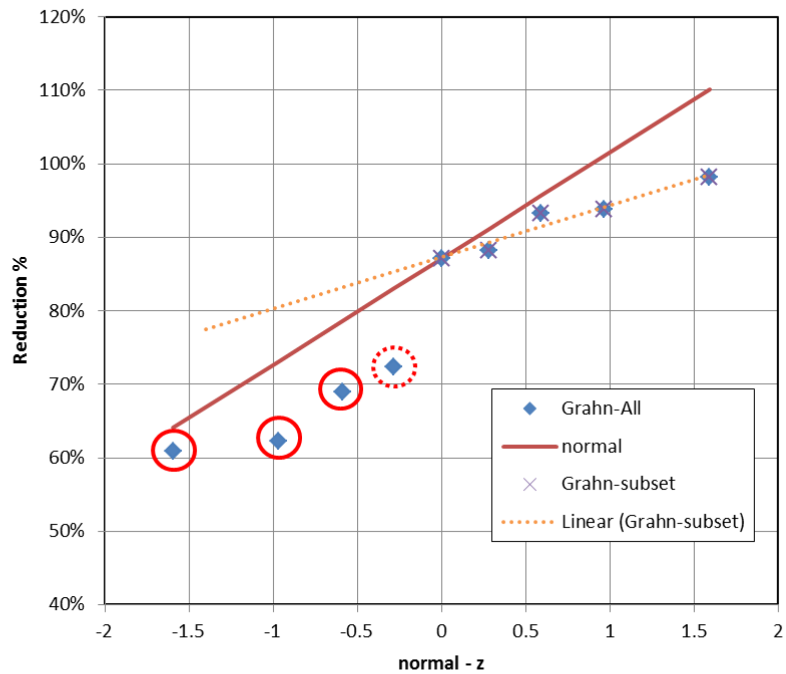


Figure C2-a, b. Quantile plots for all tests on the Grahn device with a) reduction % and b) ln(reduction %) . Candidate outliers that occurred just before the mechanical failure

was detected are circled in red. The dotted red circle indicates a potential outlier that did not correspond to the noted mechanical failure and so has been retained.



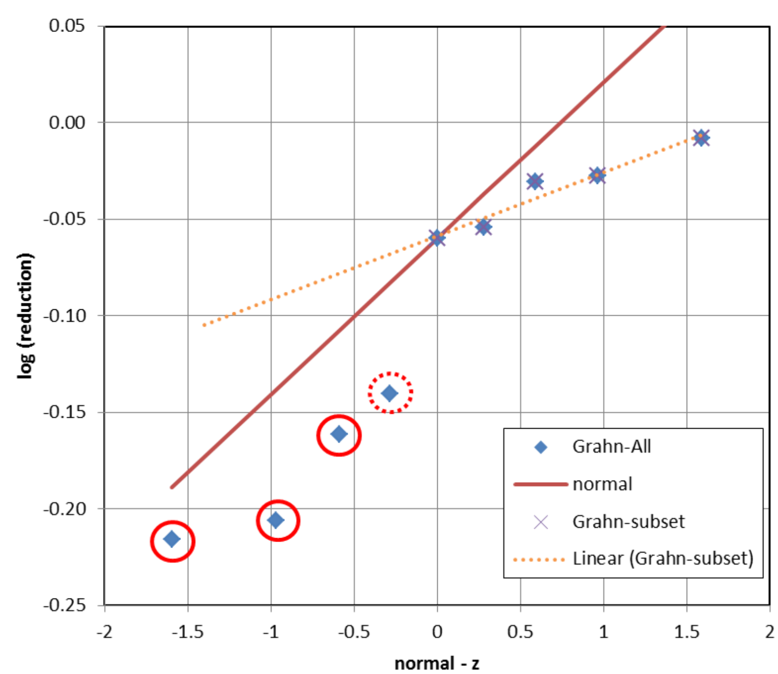
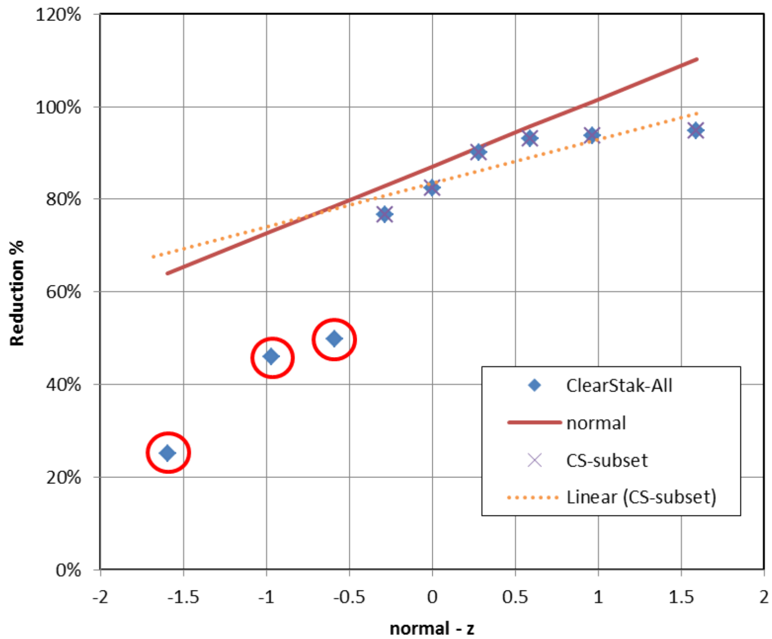


Figure C3-a, b. Quantile plots for all tests on the ClearStak device with a) reduction % and b) ln(reduction %) . Candidate outliers that occurred just before the catalyst became dislodged are circled in red.



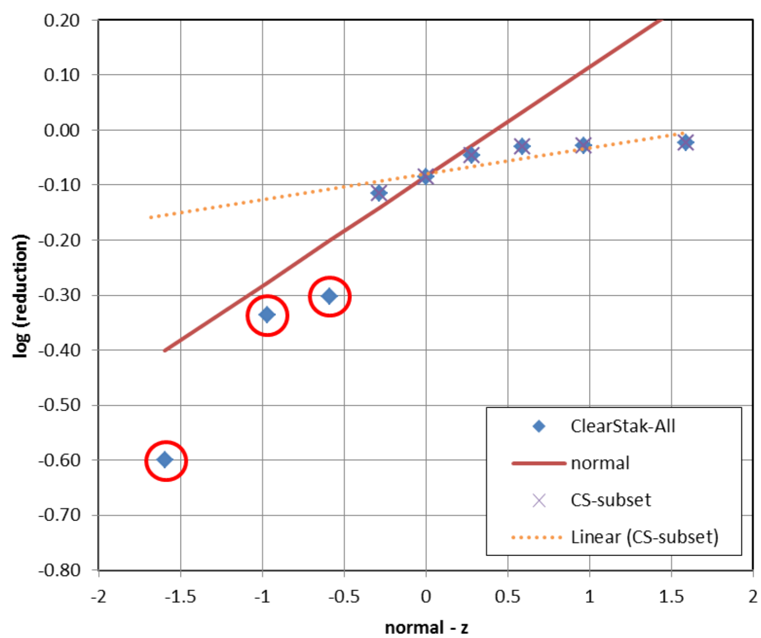
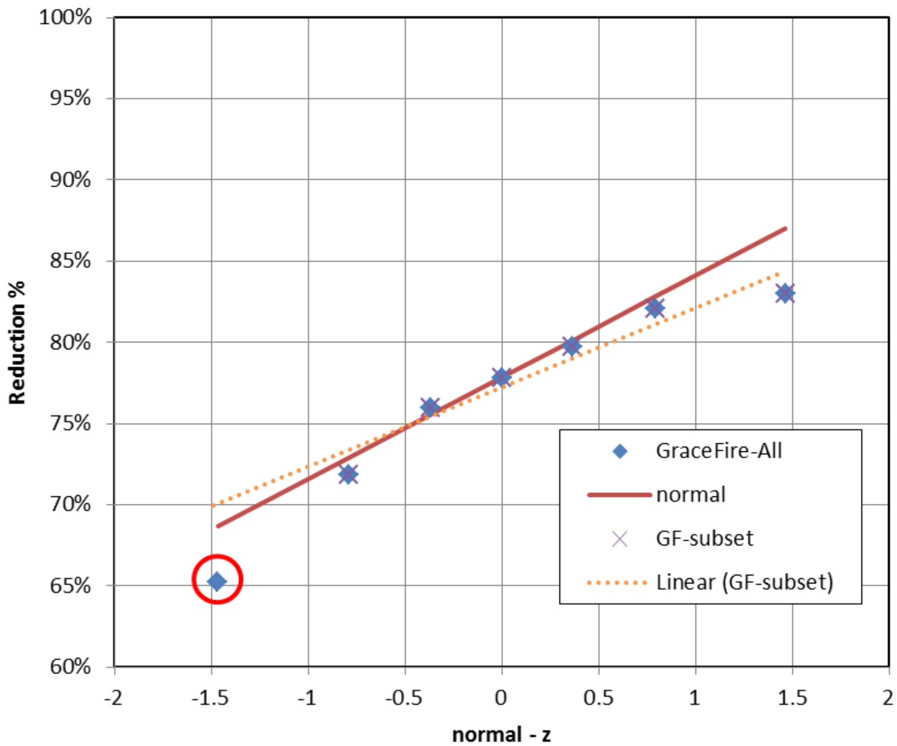


Figure C4-a, b. Quantile plots for all tests on the GraceFire device with a) reduction % and b) ln(reduction %) . A candidate outlier is circled red.



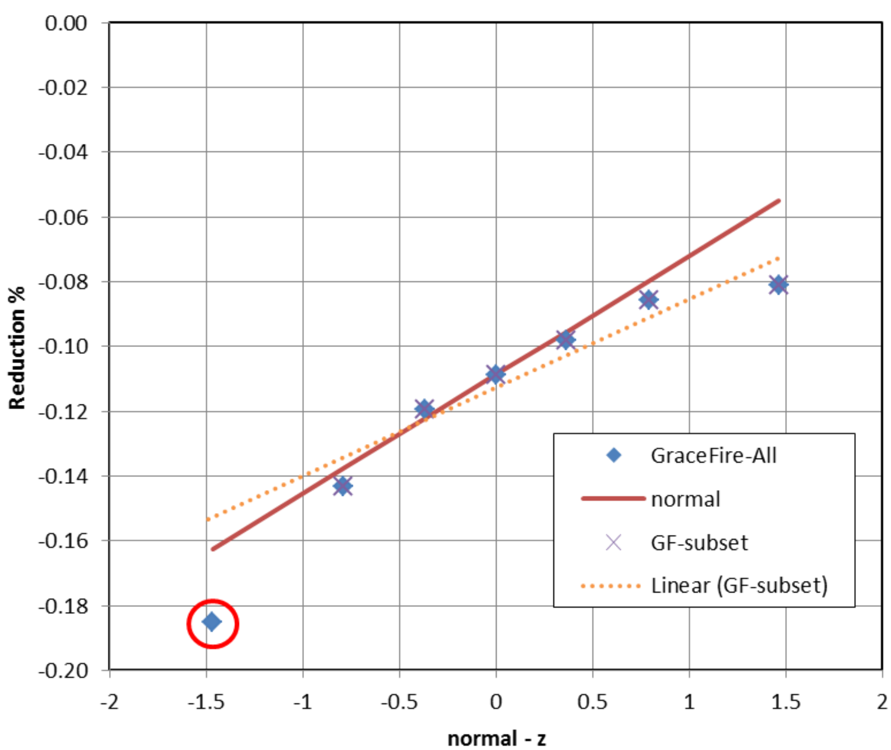
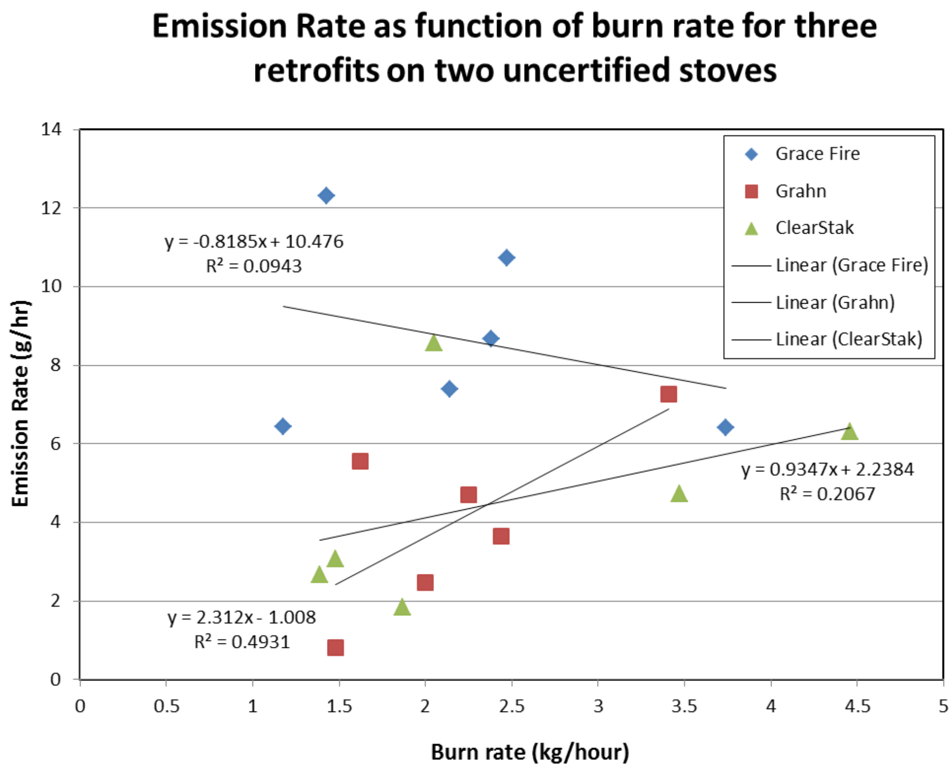


Figure C5-a, b. a) Emission Rate and b)Emission Factor as a function of burn for three retrofits on both test stoves. Previously described outliers have been excluded.



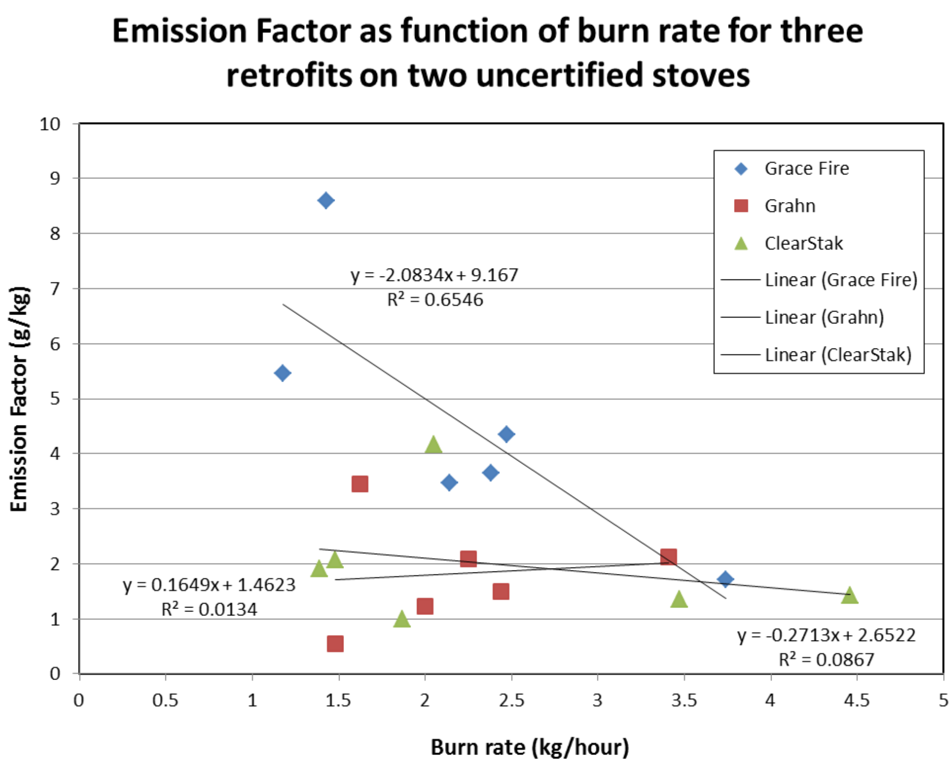


Figure C6. Reduction percent of emission factors as a function of burn rate for three retrofits on both stoves. Previously described outliers have been excluded.

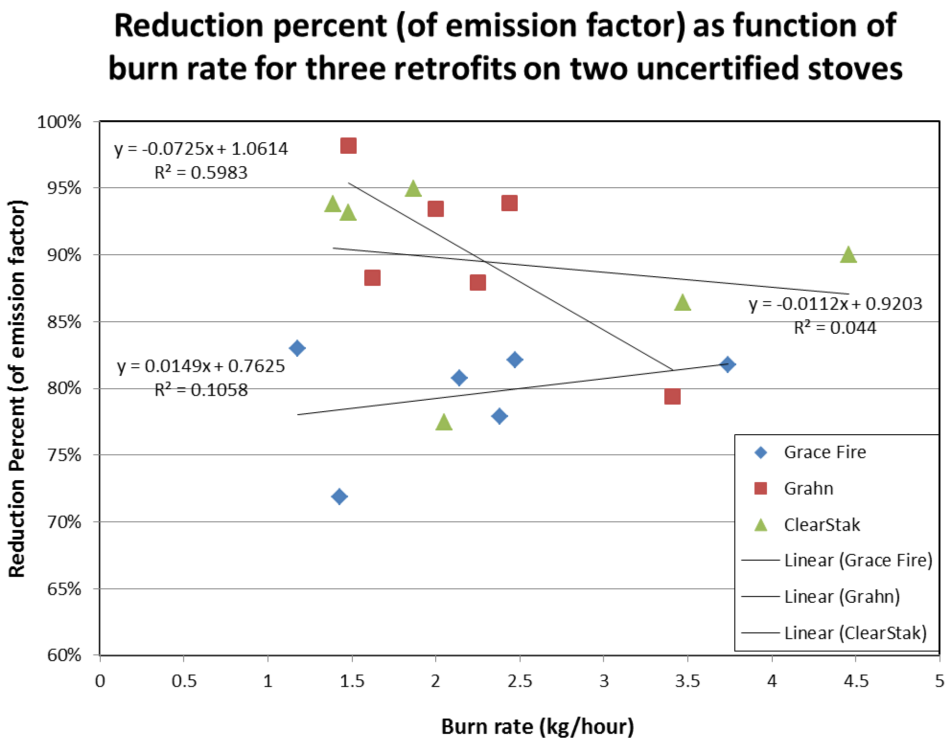


Figure C7. Retrofit mean reduction in PM emission factor with respect to baseline, retaining all potential outliers. This is the same as Figure 3, but with the outliers included. (The error bars indicate ± 1 σ.)

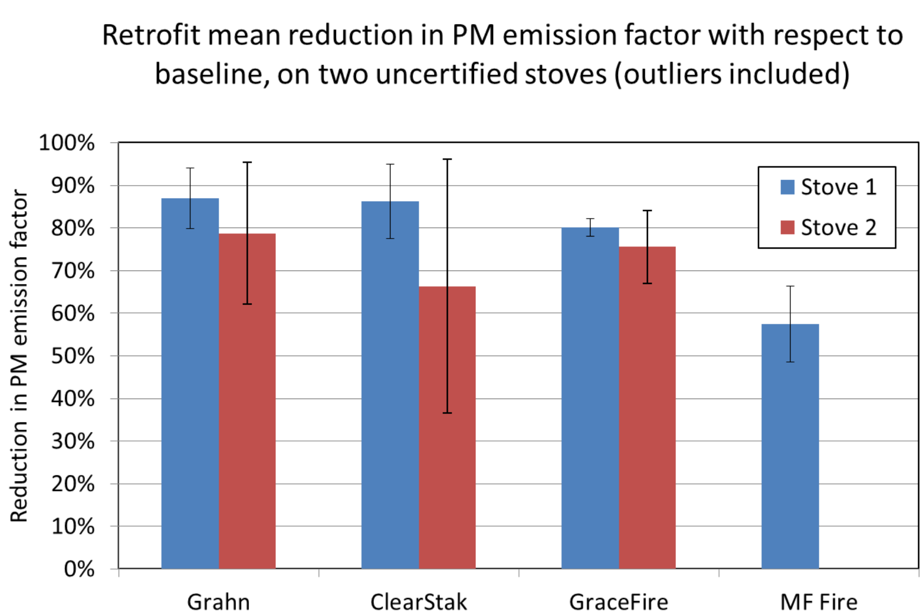
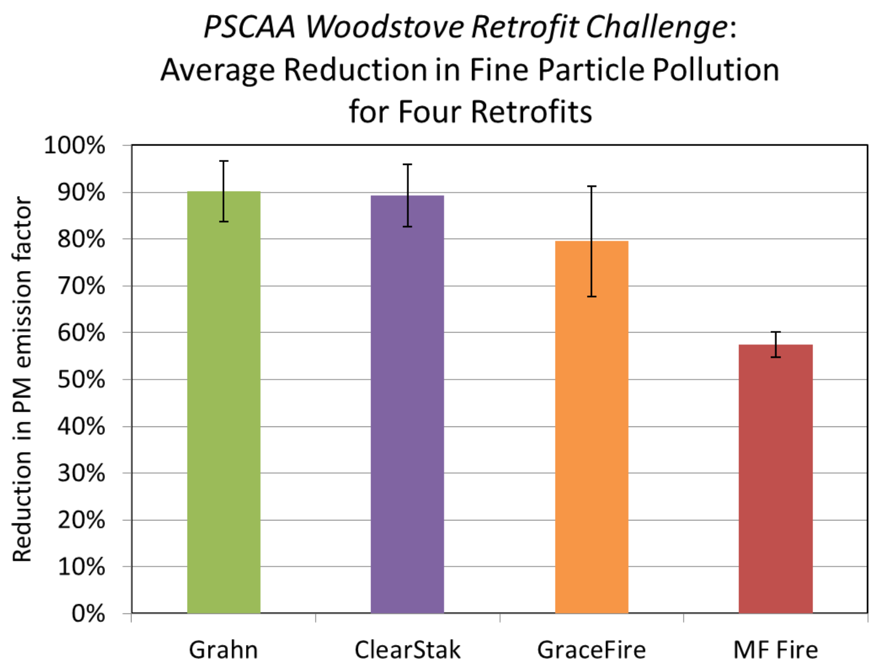


Figure C8. PM emissions reductions, excluding outliers, averaged for both stoves. (The error bars indicate ± 1 σ.)



Appendix D

The Final Report from OMNI-Test Laboratories is attached as a separate document.

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Puget Sound Clean Air Agency

Woodstove Retrofit Open Challenge and Testing Final Report

WA Dept. of Ecology NEP Grant G1400205

Puget Sound Clean Air Agency

Phil Swartzendruber, Ph.D., Retrofit Challenge Project Manager

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