DOE Bioenergy Technologies Office (BETO)

2023 Project Peer Review

AUTOMATED WOOD STOVE UFEC23

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Systems Development and Integration Session A

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ISB MARKETING

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Project overview

CONTEXT

- 2018 - Wood Stove Design Challenge
  - Innovation Award
  - 2nd place for Automated Stove
- Today
  - Consumers…
    - Are less exposed to wood heating
    - Misunderstand the combustion process
    - Make human mistakes that influence combustion's efficiency
  - Market…
    - Will be more and more influenced by tighter environmental regulations

Green Box (Baseline) at 2018 Wood Stove Challenge

We need to adapt to market!

Goal

How to create an efficient and user-friendly woodburning heater?

Is it possible to increase efficiency on wood heater even with a large flame viewing area?

Is it possible to economically monitor smoke emissions in real time?

Is it possible to incorporate Machine Learning to prevent smoke events?

Approach

TECHNICAL APPROACH

Preparation	✓ Baseline verification	June 2020
	✓ Condition lifted	March 2021
	✓ Market analysis	June 2021
	✓ Setting an emission test bench at ECS	September 2021
Development	✓ Concept design and result 50% from target	December 2021
	✓ First Alpha prototype	June 2022
	✓ Second Alpha prototype	December 2022
	☐ Beta Prototype (with production team)	March 2023
Fine tuning	☐ Certifications	June 2023
	☐ 25-field test production	September 2023

POTENTIAL CHALLENGES

1. Have a firebox volume or dimensions that would be harmful for:
   - Emission and efficiency;
   - Smoke spillage in the room when the door is opened;
   - A flame viewing glass that gets dirty in a short period of time.
2. Have a smoke sensor that:
   - Fouls very quickly;
   - Does not support the heat of the flue pipe;
   - Has a low resolution or variability between sensor to another.
3. Develop a combustion algorithm that gives good EPA emission results, but:
   - Behaves badly with real-life users;
   - Burns too fast on low fire, and/or too slow on high fire;
   - Is too reactive, which gives unsteady combustion (creates more smoke events than preventing them).
4. Do multiple days of testing while missing important data point for AI testing
   - Not the right sensors.
   - Not able to prevent smoke events.

COMMUNICATION AND COLLABORATION

- Weekly meetings between PI (SBI) and lab technician at ECS;
- Weekly meetings with project manager, engineers and lab technicians;
- Montly meeting of product port-folio managers;
- Quarterly meetings of board committee and with ISB Marketing president.

DIVERSITY, EQUITY AND INCLUSION

Creating a welcoming workplace

- Policies and practices to make employees feel valued and respected
  - Actively recruiting a diverse workforce
  - International recruiting initiative
  - Non gender based local recruiting policy
  - Ensure pay and promotion opportunities are equitable for all employees
- Clear, transparent and accountable process for employees to report incidents and address issues
  - Discrimination
  - Harassment
  - Infringement of personal information
- Fostering a culture of inclusion
- Evaluating and adjusting Environmental, Social and Governance (ESG) initiatives

Progress and Outcomes

PREPARATION

June 2020 – September 2021

IDEATION PROCESS RESULTS

inbe™

Heating efficiency

- Self-regulating control providing over 75% efficiency (artificial intelligence)
- Ventilation from below
- Good heating system

Ease to use

- Remote control (integrated thermostat)
- Notification when to add wood
- Mechanical control in the event of power outage

Decorative design

- Recessed (Classic)
- Visible techno indicators (remote control or luminous indicator)
- Technological design through remote control or heating system

LB2 | DESIGN

ECS AND BASELINE

- Testing of SBI's Green Box as baseline
- Assist ECS for installation of test bench per ASTM E2515
- Training of laboratory technician on how to test per ASTM E3053 and CSA B415.1-10
  - Testing on known "regular" stove
- Collaboration for database information required and on Test plan development
- Test on regular basis to provide big dataset for AI.

Key milestone
Install an emission test bench at ECS

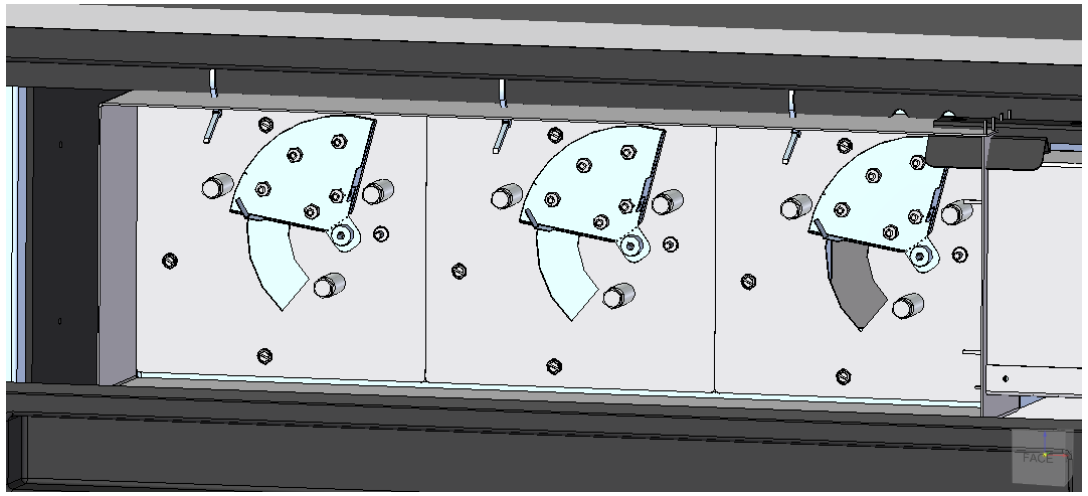
DEVELOPMENT

December 2021 – March 2023

AIR INTAKES & ELECTRONICS

- Developed a PCB and a combustion algorithm based on different parameters:
  - Thermocouple inside the firebox and before heat exchanger;
  - Reload button, thermostat input and door switch;
  - Combustion sequences (Ignition, stabilization, combustion, carbonization)
- Uses 3 different regulated air intakes :
  - Primary below the coal bed;
  - Primary above glass (known as air-wash);
  - Hybrid Secondary (a mixed of lower and upper secondary air).

Key milestone
Start testing and certification phase if 1.8 g/h can be met



Air intakes of UFEC23

Latest generation of control board

Computational Fluid Dynamics (CFD)

- Usage of CFD software to make a model that fairly represent the combustion process.
  - Mesh and radiation sensitivity studies
  - Transient and steady-states analysis
  - Experience and optimization parametric studies
- Use to compare models to another. Not to predict particulate matter emissions. Also use to solve smoke spillage issues.

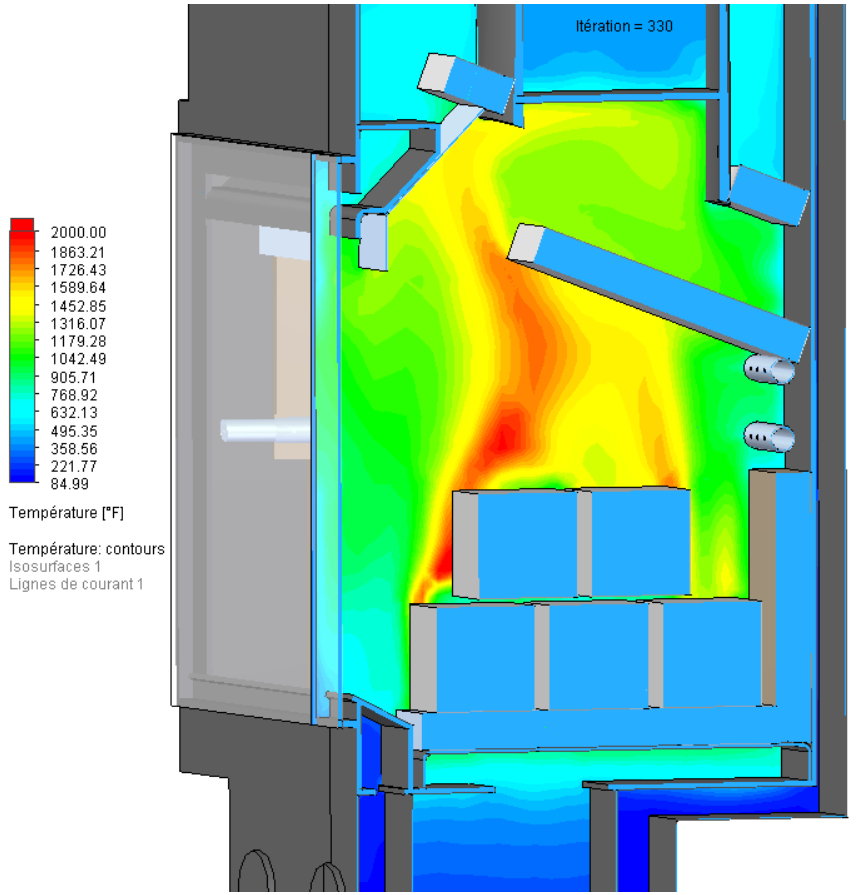
	3D model	Physical test	Difference
Flue temp [°F]	504	475	6.1%
CO_2 (% Mass)	14.72	15.04	2.2%
Wood Gas flow rate [lb/s]	0.0025	0.0020	25%

Comparison between 3D models and real model testing.

Key milestone

CFD model - 10% increase residency time for particulate analysis

Should focus on CO_2 measurements not residency time

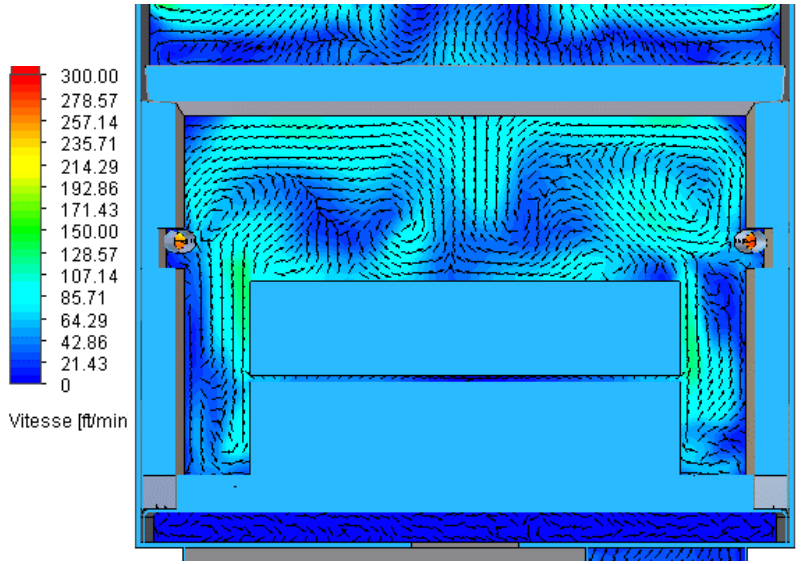


Temperature diagram at 0.0027 lb/s of wood gas, steady state

COMBUSTION

- Developed a firebox capable of reaching high level of efficiency with 80% HHV on low fire.
  - Testing different approach on new “survey-based” firebox and on regular stove firebox.
  - Design that improves residency and mixing in the combustion chamber
  - Multi orientation baffles and heat exchanger
  - Three firebox zones: loading zone, flame mixing zone and transition to heat transfer zone.

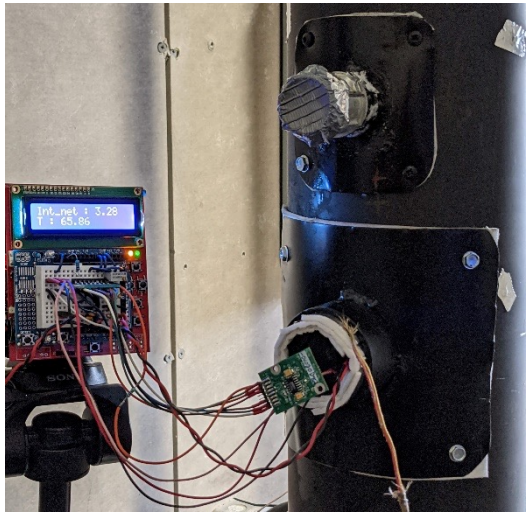
Concept Design (left) and Alpha prototype (right)

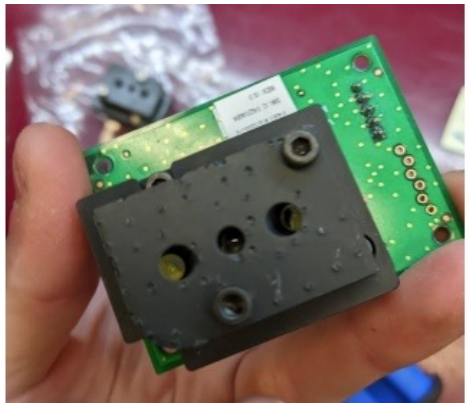


Velocity of hybrid secondary air supply : mixing zone above the fuel pieces

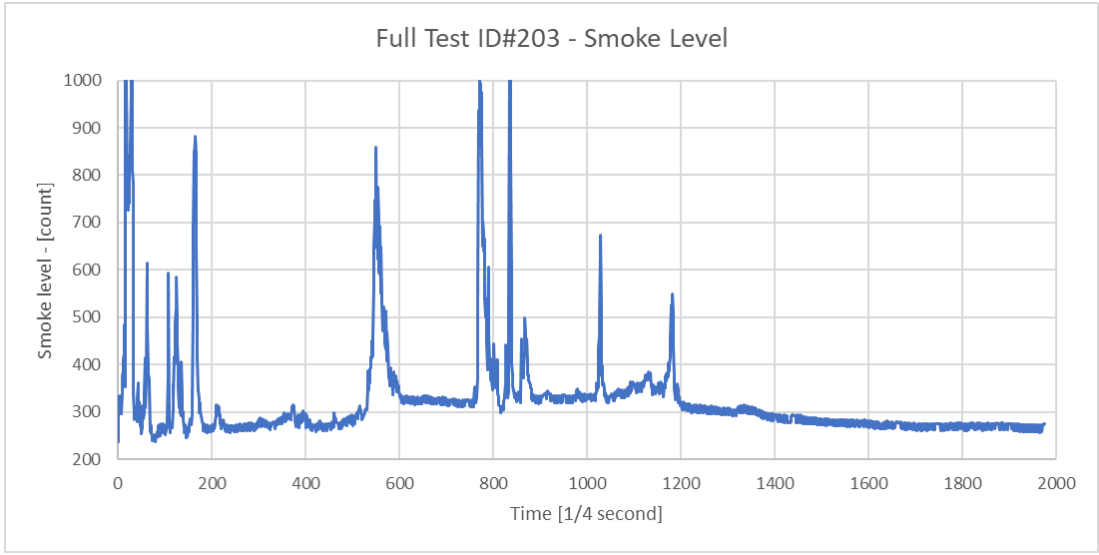
SMOKE SENSOR

- Smoke sensor is made of an optical sensor paired with a combinaison of 2 light sources. The light beams reflect on smoke and the light is scattered to the optical sensor.
- Multiple chambers to prevent particulate accumulation on the lens of the optical sensor.
- Smoke sensor signal can be treated to provide different information:
  - Low vs high slope, Positive vs negative slope, Low vs high variability, Absolute level, clean and cold value.
- Different smoke behaviours are currently under study to proceed to the best possible air intakes feedback.





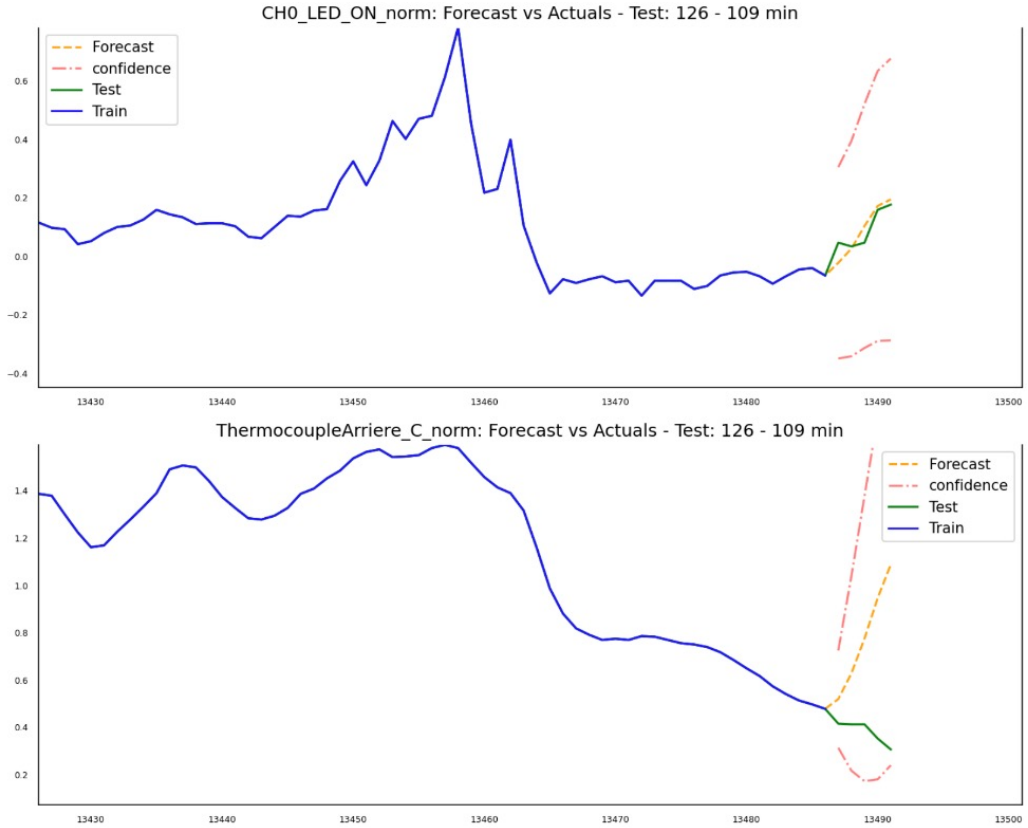
First prototype (left) and patent pending prototype (right)



Typical plot of smoke sensor signal

Artificial Intelligence (AI)

- More than 100 conform tests were recorded at every minute in a database.
- AI scientist did tests on Vector Autoregressive (VAR) Processes : a statistical correlation approach
- Preliminarily, smoke level can be predicted based on inner firebox thermocouple signal behavior from last 5 minute or less.
- Works most of the time.
- Current step is to re-test at a sampling rate of 1 dataset per 15 s instead of 1 dataset per minute.
- Following step, is to implement the logical in the source code of the PCB.



Forecast of smoke level plotted on a split train test

Key milestone

Have 100 tests (emission and random) done for AI prediction

Model used: statsmodels/vecm.py at main · statsmodels/statsmodels · GitHub

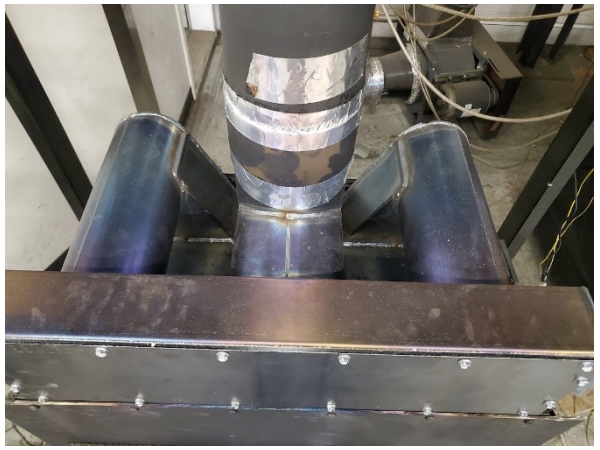
RESULTS TO DATE

Parameters	Burn setting	Baseline (06/17/2020)	UFEC23 (02/10-14/2023)	Difference
Emission rate (g/h)	High	3.24	1.22	62% reduction
Efficiency (% HHV)	High	65%	77%	12% increase
Emission rate (g/h)	Low	2.58	1.09	58% reduction
Efficiency (% HHV)	Low	64%	81%	17% increase

Minimum emission reduction was 50%; current reduction is at least 58%

Minimum efficiency increase was 5%; current increase is at least 12%

Key milestone
Have 40 emission testing with ASTM E3053
Still some variability in the results



Top view of first heat exchanger prototype

Iso view of second heat exchanger prototype

FUTUR STEPS

FUTUR STEPS

Development	✓ Concept design and result 50% from target	December 2021
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	✓ Second Alpha prototype	December 2022
	☐ Beta Prototype (with production team)	March 2023

- Finalize combustion algorithm to include a smoke feedback
- Finalize aesthetics and air distribution kit
- Negotiate with EPA for an alternative test method (ATM)
- Scheduled certification with test lab

Fine tuning	☐ Certifications	June 2023
	☐ 25-field test production	September 2023

- Attest the technology transfer from SBI to ECS
- Make multiple test on one unit from field test prototype production
- Have 25 automated stove installed in homes for heating season 2023-2024.

Impact

State of technology

- With automation, particulate matter emissions will be much lower in real-life use.
  - Needs to be confirmed by the variability testing – In progress
- A smoke sensor can be added even without automation
  - To prevent smoldering and creosote build-up
  - To increase combustion efficiency (smoke is fuel, fuel is money)
  - To collectively increase air quality.

Commercial Potential

- Field testing will serve to confirm the pros and cons of the heater as well as generating more real-life data to feed the AI. It will also confirm the efficiency of the technology in real life utilization regarding emission performances.
- Depending on the feedback, the product will be manufactured as-is, or re-certified if sensitive dimensions or components need to be improved.
- At the end, ECS will have a product on their Empire Stove brand, and SBI will have one or more product in Valcourt, Osburn or Enerzone brands. Other products could be made as OEM for other manufacturers.
- Sales prevision 2023-2027 : 6650 individual heaters ($17,971,000)
    - 2900 zero-clearance fireplace ($10,852,00) and 3750 free standing stoves ($7,119,000)

Summary

KEY POINTS

- This new technology has to be a commercial success. Ease of use and a remarkable design might be the key.
- The fireplace developed can reach 80% of efficiency on low fire, without catalyst.
- CFD can be helpful to compare models and run parametric studies.
- Optical smoke sensor developed can be used to act on the air intake to go back to good burning condition.
- Signal for the optical sensor is currently under test in order to make a forecast of the smoke using artificial intelligence.

Quad Chart Overview

Timeline
- 2020-06-17 (Baseline verification)
- 2021-03-10 (condition lifted)
- 2024-04-30 (End of project)

	FY22 Costed	Total Award
DOE Funding	(10/01/2021 – 9/30/2022) $458,638	(negotiated total federal share) $1,277,012
Project Cost Share *	$92,553	$257,760

TRL at Project Start: 3
TRL at Project End: 7-8

Project Goal

Developed an automated stove that will compensate for any "bad action" from the consumer due to his/her misunderstanding of the combustion process.

End of Project Milestone

25 automated wood heaters will be installed in homes. The last milestone is a report including a summary of installation surveys, a summary of behaviour surveys and the list of improvement.

Funding Mechanism

DE-FOA-0002029, AOI 3: Efficient Wood Heaters, year 2019.

Project Partners
- Stove Builder International (SBI)
- Empire Comfort System (ECS)

Questions?

Additional Slides

Publications, Patents, Presentations, Awards, and Commercialization

- Presentation of the project during 5th Wood Stove Design Challenge on April 26, 2022.
- Patent pending on smoke sensor. Filed in US on January 5, 2023 (63/478.570).

GOAL

How to create an efficient and user-friendly woodburning heater?

Is it possible to increase efficiency on wood heater even with a large flame viewing area?

Is it possible to economically monitor smoke emissions in real time?

Is it possible to incorporate Machine Learning to prevent smoke events?

- Efficiency:
  - Particulate matter emission rate below 1.2 g/h using ASTM E3053
  - Particulate matter emission rate below 2.0 g/h regardless of the loading method
  - Efficiency above 75% HHV overall (without catalyst)
  - Performance target of AOI3: Efficient Wood Stove
    - 50 - 80% reduction of emission
    - 5 - 15% improvement in efficiency
- User-friendly
  - Exceptional fire view
  - Easy to operate, reliable and safe
  - Aesthetically pleasing
  - Cost-effective to manufacture

Project Partners

ISB Marketing (Recipient):

- Sister company of SBI and ECS
- Only management
- Based in Illinois

Stove Builder International (SBI) (Sub-recipient):

- North-America manufacturer of mostly solid-fuel heaters
- Two plants in Québec, Canada and one plant in Virginia
- R&D laboratory based in Canada

Empire Comfort System (ECS)(Sub-recipient):

- US manufacturer of mostly gas heater and BBQ
- One plant in Illinois and Missouri
- R&D laboratories in Kentucky and Illinois

«To do list»

1. Firebox
2. Smoke sensor prototype
3. Combustion algorithm for the new firebox design
4. Identify challenges with the new firebox design
5. Computational fluid dynamics (CFD)
6. Standardized database for future artificial intelligence (AI) testing
7. Improve parameters (smoke sensor, combustion algorithm, heat exchanger, secondary combustion) and reduce risk (flame loss, smoke spillage)

UFEC23 Freestanding Fireplace

CRITICAL DECISION

FREESTANDING VS FIREPLACE

Design a freestanding woodburning heater instead of fireplace

- Target users prefer the fireplace (29%) but still like the freestanding (26%) even if the fireplace is double the price
- Technical parts need to be accessible even when the unit is installed in a home
- It is harder to access parts with a fireplace than a freestanding unit

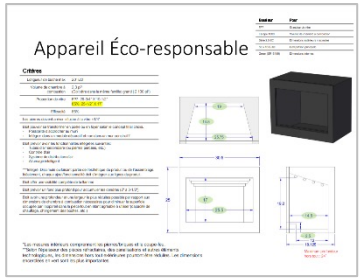
- Risk
  - Slim margins or smaller popularity for the technology if we offer the free-standing first
  - Have a difficult access to technical parts – Harder troubleshooting

- Solution
  - 25 first units will be freestanding to facilitate the troubleshooting

IDEATION PROCESS - 2021

Intern research

Preliminary development criteria:
June 14th



Survey 1
Interview

Survey report: April 28th
Interview report: May 7th

Entretiens

Concept development

5 renderings : October 14th

Prototype development

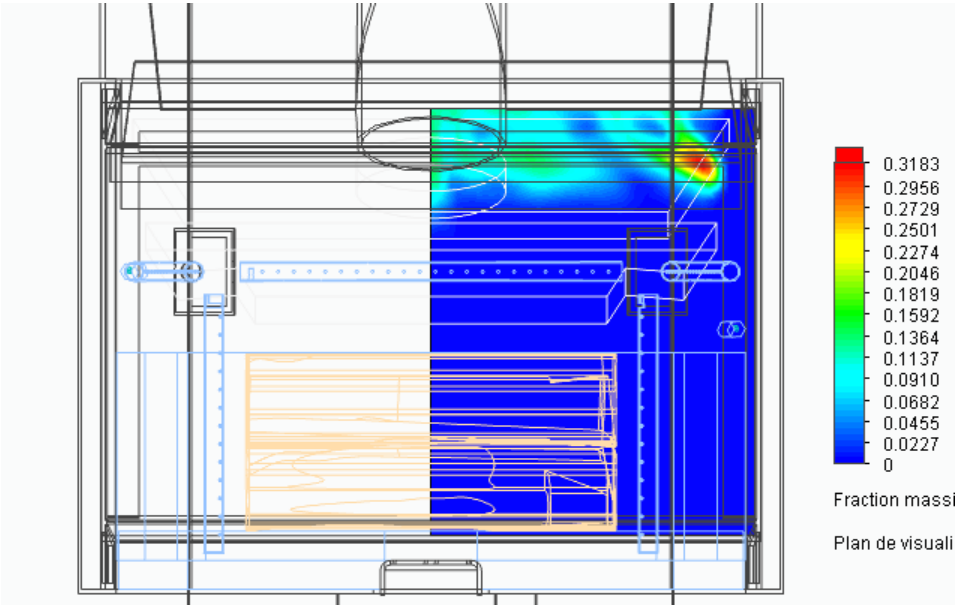
Physical prototype: October 28th

Survey 2

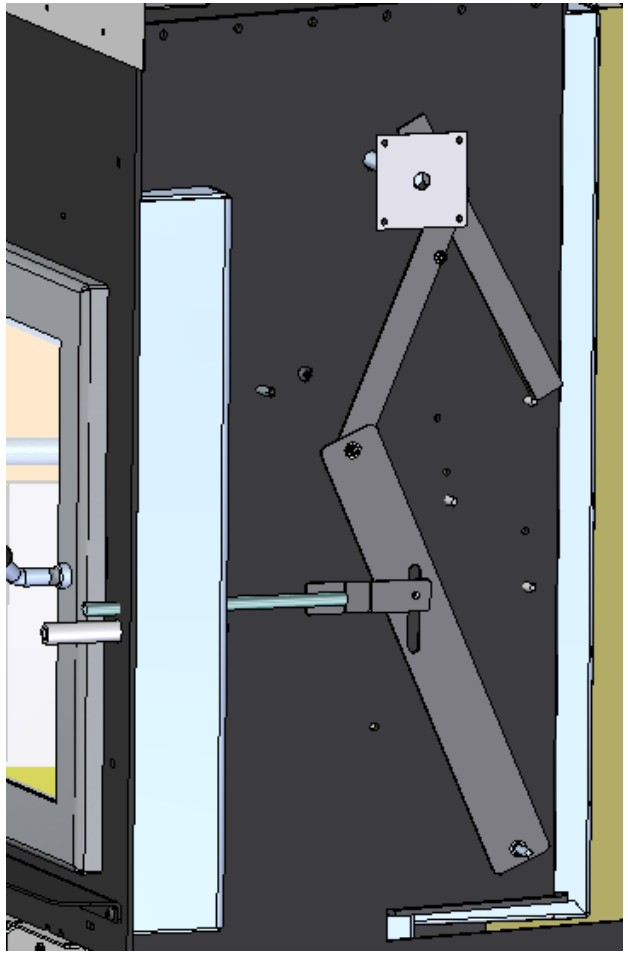
Online results sorting tool:
November 24th

SMOKE ISSUES

- First firebox design was spilling smoke in the room when door was opened.
  - Caused by poor velocity conservation in one big section change
- CFD helped confirming the issue and finding solution
- One solution was to add a bypass mechanism.
  - Made it automatic with the door opening.
- The by-pass allow the possibility to add more restriction when the door is closed.
  - Addition of a heat exchanger.

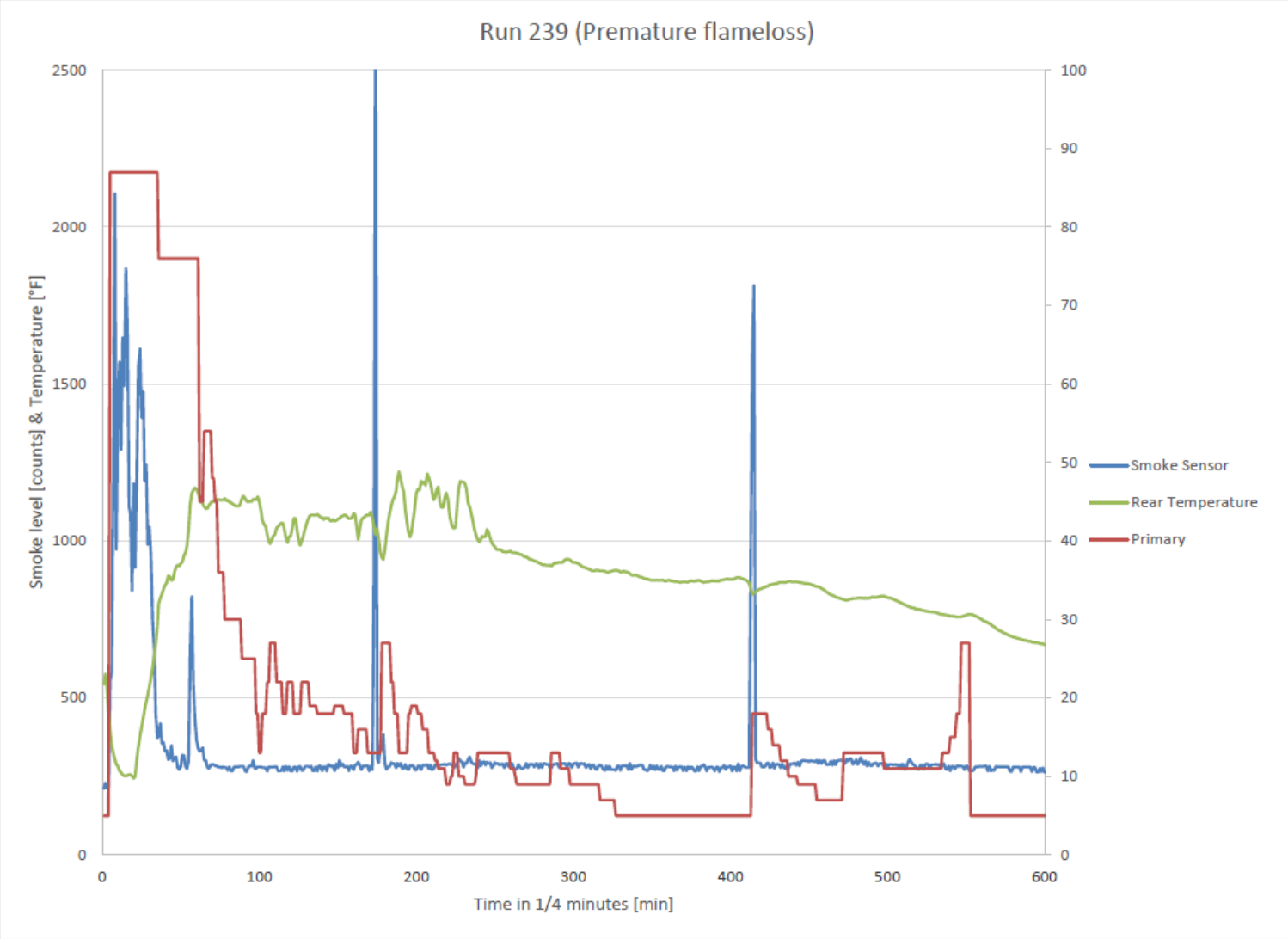


CFD symmetrical result of mass fraction of combustible product out of the door opening



Automatic by-pass mechanism

Artificial Intelligence (AI)



Smoke level, primary air and firebox temperature