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Field-based safety guidelines for solid fuel household cookstoves in developing countries

Nathan G. Johnson [a,*], Kenneth M. Bryden [b]

[a] The Polytechnic School, Arizona State University, 7171 E Sonoran Arroyo Mall, Peralta Hall Suite 330, Mesa, AZ 85212, USA
[b] Department of Mechanical Engineering, Iowa State University, 1620 Howe Hall, Ames, IA 50011, USA

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ABSTRACT

The burning of solid fuels for cooking creates significant adverse health, social, and economic consequences for more than three billion people worldwide. Recognizing this issue, many groups have worked to develop improved stoves that increase fuel efficiency, decrease fuel use, and reduce particulate emissions. Less attention has been given to developing a standardized process for rating cookstove safety and reducing cookstove hazards. This paper identifies common cooking hazards and seeks to reduce cooking injuries by proposing ten field-based safety guidelines for solid fuel stoves. Each guideline describes an underlying safety principle and is accompanied by a test protocol and a metric to rate stove safety. This incremental rating system enables stove designers, donors, and consumers to track and promote stepwise safety improvements. The protocols use low-cost equipment to allow the many manufacturers of handcrafted cookstoves to assess safety without using sophisticated testing facilities and expensive equipment.

Introduction

Cooking over an open fire or on an ad hoc stove poses unnecessary hardship including disease, injury, pollution, excess time spent gathering fuel, deforestation, and high fuel costs relative to income for more than three billion people (Alam et al., 2006; Barradas, 1995; Ezzati et al., 2000; Grainger, 1982; Johnson and Bryden, 2012a; Mahat, 2003; Mathers et al., 2006; Garcia-Moreno, 2009; Smith et al., 2004; Smith et al., 2010; WHO, 2008; WHO, 2011a; WHO, 2011b; WHO, 2014). This global problem is realized locally in remote communities that, for example, rely on wood burning domestic cookstoves that contribute to over three-quarters of all village energy use with far-reaching effects that permeate daily life—e.g., women spending 65% of their day preparing food, cooking, cleaning, and gathering wood from distances of up to 8 km per round trip (Johnson and Bryden, 2012a; Johnson and Bryden, 2012b). In addition the particulate and carbon monoxide emission of cookstoves pose significant health and safety risks to the users. To address these problems, numerous private, governmental, and non-governmental organizations have worked to develop improved cookstove designs for many years. This work has generally focused on increasing stove efficiency, improving heat transfer to the cooking surface, and decreasing indoor air pollution (Bryden et al., 2003; Chengappa et al., 2007; Mukunda et al., 1988; Prasad et al., 1985; Smith et al., 2004). A variety of test methods and metrics are available for cookstove thermal efficiency and emissions testing, and a number of testing efforts focused on thermal efficiency and emissions have been reported (Jetter and Kariher, 2009; MacCarty et al., 2010). Several investigators have examined the human health effects from exposure to particular matter and carbon monoxide emissions and the safety of cookstoves based on the cookstove emissions (Alnes et al., 2014; Ezzati et al., 2000; Grabow et al., 2013; Smith et al., 2004; Smith et al., 2010; WHO, 2014). In contrast, little attention has been given to developing a structured process to rate and improve cookstoves on direct-contact hazards that cause burns, cuts, and scalds. That latter safety concern lags behind studies of emissions and exposure, and is therefore the sole focus of this work to help bring contact-related safety concerns to the forefront of cookstove discussions.

Solid fuel cookstove designs and production techniques are highly varied (Fig. 1), and the heterogeneity poses a challenge to creating a universally applicable stove safety test procedure. To date, many of the cookstoves manufactured have been hand-crafted and produced in small volumes by local artisans, household businesses, and workshops. Only recently are solid fuel household cookstoves being mass-produced in high volumes for use in the developing world.

Improving the safety of handcrafted cookstoves is a challenging issue that is unlikely to be addressed in the near term by national product standards. National and international stove safety standards are based on the premise that stoves are produced in high volumes at close tolerances using industrial equipment. Although these standards are suitable in industrialized economies with testing laboratories and regulatory bodies, the protocols and approval processes are poorly

* Corresponding author at: 7171 E Sonoran Arroyo Mall, Peralta Hall Suite 330, Arizona State University, Mesa, AZ 85212, USA. Tel.: +1 480 727 5271.
E-mail addresses: nathanjohnson@asu.edu (N.G. Johnson), kmbryden@iastate.edu (K.M. Bryden).

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Fig. 1. Basic solid fuel cookstoves (clockwise from upper left): wood stove made from clay, wood stove made from metal, coconut husk and wood stove made from clay and bricks, charcoal stove made from metal, charcoal stove made from metal, rice hull stove made from metal.

suited for use by small-scale producers in developing countries that face financial and logistical barriers to laboratory stove safety evaluation. To reach the highly distributed network of low-volume stove producers, safety tests would ideally be completed in the field at low cost.

This paper introduces ten field-based safety guidelines for solid fuel household cookstoves. Each guideline is accompanied by a safety principle, a testing protocol, and a metric to rate stove safety for direct-contact hazards. The protocols use low-cost equipment to allow the numerous manufacturers of hand-crafted stoves to assess safety in the absence of expensive testing facilities and equipment. An incremental rating system is used to allow stove designers, donors, and consumers to track and promote stepwise safety improvements. These procedures and ratings facilitate the consideration of cookstove safety during engineering design alongside other cookstove merits such as efficiency and reduced emissions. Although the focus of this work is on hand-crafted stoves, the protocols can be applied to manufactured stoves, and testing may occur in a laboratory environment. The guidelines provided here are focused on cookstoves and are not intended to be applied directly to stove whose primary purpose is space heating.

Background

A limited amount of statistical data is available on the hazards resulting in injuries recorded from solid fuel cookstoves (Diekman et al., 2014; Mathers et al., 2006; Garcia-Moreno, 2009; Peck et al., 2008; WHO, 2008; WHO, 2011a; WHO, 2011b; Barradas, 1995). Much of what is known is qualitative and anecdotal. This is not surprising given that rural households—often without access to clinics that record injury statistics—are the primary users of solid fuels for cooking and heating (IEA, 2010). Existing studies identify injuries such as burns to the hands from contact with open flames, burns to the legs from clothing fires, morbidity related to procuring and carrying wood, and scalds from heated liquid spilling from the cooking vessel (Alam et al., 2006; Forjuoh et al., 1995; Han et al., 2005; Mock et al., 2008; Wickramasinghe, 2003; WHO, 2011b). These are just a few types of injuries related to collecting fuel, cooking, and cleaning up after cooking. Yet most of these hazards pertain to the local cooking environment or kitchen. Consider the wood cooking fire placed on the floor of a small kitchen as shown in Fig. 2. Several hazards are apparent:

- Long clothing can catch fire resulting in severe burns to the legs (Fig. 3a).
- Long hair can catch fire while cooking and working around the cookstove.
- Children can fall into the fire and be severely burnt on the hands and arms (Fig. 3b).
- Children can grab pots and overturn heated contents onto themselves (Fig. 3c).
- The surrounding wood and straw can catch fire from a stray ember.

Fig. 2. Cooking on an open fire in Mali.

Fig. 3. Injuries from open fire cooking (from left to right): burn from skirt fire, scald from overturned pot, and loss of fingers from contact with burning embers. Photos courtesy of Don O'Neal.

It is apparent from this illustration and the studies mentioned above that cooking hazards are, in part, a product of the local cooking environment. Stated differently, user safety is influenced by the cookstove, fuel type, cooking method, cooking utensils, food type and quantity of food cooked, the cookstove operator, cooking behavior, and kitchen layout. From these, cookstove design and user education are perhaps the easiest points of intervention for reducing cooking-related injuries when compared to altering the kitchen layout or changing cultural cooking practices.

The design process for cookstoves is similar to the design process for any product—design is a compromise of meeting consumer need and optimizing a set of desired outcomes (e.g., efficiency, cost, ease of use, aspirational value) with respect to a set of constraints. Common design considerations for cookstoves include fuel type, cookstove portability, use of a vented chimney or open fire, number of cooking hobs, fuel loading method, form factor, height of the cookstove working surface, available materials and manufacturing methods, and cooking practices. Yet in spite of the many hazards associated to cooking, safety is often not explicitly considered and evaluated in the design of household cookstoves. In a large part this is due to the lack of quantifiable risk data associated with cookstove injuries and the lack of easily implemented stove safety guidelines and protocols. Cooking risks are challenging to quantify because of the many local factors that can lead to harm and the very limited data on injury incidence as a result of those local factors. There is simply not enough data to quantify risk as "the chance of a negative outcome" (Ayyub, 2003). However, it is possible to mitigate or remove cooking hazards that would cause injury, and by necessity reduce risk, even if that reduction cannot be quantified on a probabilistic basis.

This article identifies cooking and cookstove hazards, offers safety guidelines to reduce or remove hazards, and proposes test protocols and metrics to rate cookstove safety against each hazard. This article consolidates earlier work by the authors that began in 2004 (Johnson, 2005; Johnson et al., 2005). This earlier work introduced ten guidelines with safety tests and target metrics to reduce cooking hazards leading to burns, scalds, cuts, and loss of property. Today that work has been applied to rate the safety of over 100 stove designs across more than 20 countries and has been adopted into an International Workshop Agreement on stove testing by the International Standards Organization. International Workshop Agreements generally serve as precursors to international standards. This is a fundamental step towards adding safety as a consideration alongside other design criteria such as performance and emissions.

Reviewing stove safety

For engineered products and systems, the concept of a "safe" stove does not mean zero chance of harm, but rather represents a personal judgment corresponding to an acceptable level of hazard or risk. A hazard is an "act or phenomenon posing potential harm to some person or thing" (Ayyub, 2003). To better understand hazard mitigation, it is first helpful to understand the related topic of risk assessment. A comprehensive risk assessment answers three questions known as a risk triplet: "What can go wrong?" "How likely is it?" and "What is the outcome or consequence?" (Kaplan and Garrick, 1981). In practice this includes identifying hazards and then assessing the likelihood and severity of injury that can be caused by the hazard. Ayyub (2003) defines thirteen distinct methods based on the type of information and analytical procedure used to answer the triplet of risk questions. Methodologies for risk assessment are varied though can be broadly separated into two groups—inductive reasoning and deductive reasoning (Blanchard and Fabrycky, 2010; Ericson, 2005; Kayis et al., 2006; MIL-STD-1629A, 1980; Otto and Wood, 2000; Ulrich and Eppinger, 2011). Inductive reasoning is used to assess risk by asking "What types of outcomes would result from a particular scenario?" whereas deductive reasoning asks "How can a particular outcome occur?" Popular deductive methods include fault trees and success trees used to create flow charts of events. Event interactions are explored using probabilities to determine the likelihood of a particular outcome, such as harm to an individual or property. Deductive methods are particularly useful for assessing the risk of complex engineering systems with many interacting components and subsystems. Common inductive methods for risk assessment include hazard analysis and failure mode and effects analysis (FMEA). Inductive methods seek to provide a general description of risk from individual case examples, as in hazard analysis, which involves an inspection of operation conditions rather than a statistical study of quantitative accident conditions (Reunanen, 1993). This methodology is useful for listing potential hazards of a new product category or drafting a preliminary risk management plan at the onset of product design. Noting this, two approaches were taken to develop an understanding of the risks associated with household cookstoves and to develop safety guidelines that are appropriate to mitigating these risks. These are hazard analysis and a review of existing safety standards.

Hazard analysis

Hazard analysis is well suited for cookstove safety rating because of the limited quantitative data available on injury severity and frequency. Hazard analysis is used here to (a) identify potential causes of harm and then (b) use that information to identify preventative measures. Potential causes of harm were identified through a review of prior studies on cooking safety (Bizzo et al., 2004; Forjuoh et al., 1995; Han et al., 2005; Peck et al., 2008; Johnson, 2005; Kruger, 2005; Lloyd and Truran, 2008; Barradas, 1995; WHO, 2011a,b) and cooking practices (Johnson and Bryden, 2012b; Mahat, 2003; Mandibog, 1984; Sinha, 2002; Wickramasinghe, 2003), a review of cookstove design literature (Bryden et al., 2005; Still et al., 2007; MacCarty et al., 2010), a review of existing standards on gas and electric cooking ranges in industrialized nations (ANSI, 2012a,b; UL, 2011), discussions with industry professionals, and the authors' personal experiences working directly with women in developing nations (Johnson and Bryden, 2012b). These findings are categorized in Table 1 as they relate to solid fuel cookstoves. Addressing mechanical, thermal, and structural design

Table 1
Solid fuel cookstove hazards and potential injuries.

Category	Hazard	Injury
Mechanical	Sharp edges and points	Cut or abrasion
	Pinch points	Pinched fingers, skin
Thermal	Open flames	Clothing fire
	Hot surfaces	Skin burn
	Hot operating handles	Skin burn
	Hot chimney	Skin burn
	Radiative heat to surroundings	Fire with property loss
Structural design	Stove instability, tipping	Scald, burn, property loss
	Obstructions near cooking surface	Scald, burn
	Poor containment of burning fuel	Burn or property loss
	Deformation	Scald, burn, fire with property loss
Materials	Toxic materials	Human exposure, poisoning
Operational guidelines	Lack of operating instructions or training leading to improper use	Exacerbates other hazards
Fuel	Unsafe collection area	Animal or human attacks
	Carrying heavy loads	Back or neck injury
Electric	Exposed wiring	Electric shock, fire

hazard categories is the primary focus of this work. These hazards are mainly a product of the cookstove design type and fabrication method, with material hazards introducing risk of injury from low-quality stove construction—deformation, stove stability, hot surfaces—and exposure to toxic substances. Fuel collection and carrying hazards are outside the scope of this study, which is focused on the cookstove only. Further, cookstove operational guidelines and electrical components—as in forced-air stoves—are left out of this work to facilitate development of a more generalizable core set of tests that can be applied to many stove design types. Considerations for durability and degradation should also be addressed separately.

Existing safety standards and guidelines

A review of existing standards for cooking appliances (Table 2) and articles on safety concerns (Bizzo et al., 2004; Kruger, 2005; Lloyd and Truran, 2008) were used to inform methodological development of tests appropriate to solid fuel cookstove designs. Contents considered in the review included the type of fuel and stove, risks or hazards identified, test procedures and metrics, test location, equipment, expertise required to complete the tests, and certification agencies and policies. Findings from this review are summarized below:

- Each stove standard is written for a single type of fuel, and commonly for a specific design type (e.g., non-pressurized paraffin vs. pressurized paraffin).
- Protocols and metrics may differ based on the intended end-use location (e.g., indoor vs. outdoor) or relative size of the stove (stationary vs. portable).
- No two safety standards provide an identical set of testing procedures or metrics.
- Safety standards for small household cookstoves are underrepresented when compared to larger stationary cooking ranges.
- Compulsory standards based on determining whether a product is safe or unsafe are common in industrialized countries with strict enforcement agencies and testing procedures.
- Expensive equipment and trained technical expertise are needed to complete the safety evaluations.
- No national standards or industrial standards were created for field use—i.e., outside of a laboratory setting.
- Hazards not related to the stove design were discussed in journal articles and discussion papers (e.g., hazards of wood collection) but do not appear in national standards.

Table 2
Product standards with applications to cookstove safety.

Fuel type	Institution	Year	Standard no.	Standard title
Solid	CEN	2003	EN 1860-1	Appliances, solid fuels and firelighters for barbecuing — barbecues burning solid fuels
	CEN	2004	EN 1860-4	Appliances, solid fuels and firelighters for barbecuing — single use barbecues burning solid fuels
	CEN	2001	EN 12815	Residential cookers fired by solid fuel
	CEN	2001	EN 13229	Inset appliances including open fires fired by solid fuels
	BIS	1991	IS 1315Z	Solid biomass chulha
	SABS	2008	SANS 1111	Coal-burning appliances (reduced smoke emission type)
	SABS	1982	VC 8034	Coal-burning stoves and heaters for use in a dwelling
	UL	2007	ANSI/UL 737	Fireplace stoves
	UL	1999	UL 1101	Standard for solidified fuel cooking appliances for marine use
Liquid	ISO	2000	ISO 14895	Small craft—liquid-fueled galley stoves
	SABS	2007	SANS 1243	Pressurized paraffin-fueled appliances
	SABS	2009	SANS 1906	Non-pressure paraffin stoves and heaters
	UL	1999	UL 1100	Standard for alcohol and kerosene cooking appliances for marine use
Oil	JSA	2009	JIS S 2016	Oil burning cooking stoves
	JSA	2009	JIS S 2019	Open type natural ventilating oil burning space heaters
	JSA	2007	JIS S 2038	Wicks for oil burning appliances
	UL	1993	ANSI/UL 896	Standard for oil-burning stoves
Gel	SABS	2010	SANS 448	Ethanol gel for cooking and other gel burning appliances
	SABS	2008	SANS 666	Ethanol-gel fueled appliances
Gas	ANSI	2005	ANSI Z21.1	Household cooking gas appliances
	ANSI	2005	ANSI Z21.58	Outdoor cooking gas appliances
	ANSI	2000	ANSI Z21.72	Portable type gas camp stove
	CEN	2008	EN 30-1-1	Domestic cooking appliances burning gas
Electric	CEN	2002	EN 60335-2-6	Household and similar electrical appliances; particular requirements for stationary cooking ranges, hobs, ovens, and similar appliances
	CEN	2002	EN 60335-2-36	Household and similar electrical appliances; particular requirements for commercial electric cooking ranges, ovens, hobs, and hob elements
	CEN	2002	EN 60335-2-37	Household and similar electrical appliances; particular requirements for commercial electric deep fat fryers
	IEC	2010	IEC 61558-1	Safety of power transformers, power supplies, reactors, and similar products
	SABS	2006	SANS 153	Electric stoves, cooking tops, ovens, grills, and similar appliances
	UL	2010	ANSI/UL 197	Standard for commercial electric cooking appliances
	UL	2005	ANSI/UL 858	Standard for household electric ranges

• The national standards in Table 2 are based on the premise that stoves are produced in high volumes at close tolerances using industrial equipment.

From this it is clear that existing product standards in use in the industrialized world cannot be used directly in small shops in developing nations. First, although the standards in Table 2 are appropriate for industry in industrialized economies with advanced testing laboratories, the protocols and approval processes are poorly suited for application to small-scale stove production processes in developing nations. Cookstove designers and manufacturers in developing countries face significant financial and logistical barriers that preclude routine laboratory evaluation of stove safety. Because of this, safety protocols are needed that can be completed in the field at low cost with limited equipment. This would enable small-scale stove producers that lack money, have little equipment, and little laboratory training to directly incorporate safety into their household cookstoves. Second, the lack of regulatory bodies in developing countries makes it difficult to enforce compulsory standards that require stoves to meet a minimum level of safety in an all-or-none approval. An incremental safety metric is more suitable to encourage voluntary use of safety protocols, provide a mechanism to track safety improvements, and facilitate the consideration of safety alongside thermal performance, emissions, and cost during cookstove design or purchasing. A third consideration is that the methods and metrics from existing national standards were developed to evaluate a complete and constructed product, and provided little design advice or guidelines to encourage cookstove design decisions along a safer path. Yet after acknowledging these challenges, many of the safety standards available include general themes that can be mapped into a set of guidelines and protocols for cookstove safety in the developing world. For example, standards that limit the rise in cookstove surface temperatures can be implemented with a small set of tools and minimal training.

Summary of hazards

From this review a set of 10 household cookstove hazards were selected from the list in Table 1. These hazards are enumerated in Table 3. As noted earlier, the work presented here does not seek to address issues associated with fuel collection and storage, electrical wiring hazards, chemical starters, or toxic fumes. Rather, the target of these safety guidelines is to reduce the incidence of burns, scalds, cuts, and property loss from household free convection cookstoves utilizing traditional solid biofuels for cooking and heating water. These hazards are pervasive in locally designed and manufactured cookstoves around the world, and without low-cost and easy to use guidelines, it is unlikely that a transformative shift in safety will occur.

Safety principles, protocols, and metrics

Having identified a set of hazards associated with household solid fuel cookstoves, a set of safety principles is needed to conceptualize how to address these hazards, followed by testing protocols and metrics to rate stove safety against each principle. Each test result is compared against a performance rubric to rate the safety of the cookstove on a specific safety principle (van Weperen, 1992; van Weperen, 1993). Each rubric includes an incremental rating system that allows test results to be combined into an overall safety rating that facilitates comparison between stoves.

Incremental safety rating metric

As discussed earlier, an incremental rating system is used to facilitate developing safer designs. To address differing injury severity and likelihood of minor and major injuries, four levels of safety (i.e., Poor, Fair, Good, and Best) are identified (Table 4). A similar generalizable schema was used by van Aken to assess risk across various product categories of childhood toys (van Aken, 1997). With cookstoves, hazards associated with sharp edges and points could result in minor injuries, whereas a tipping hazard could result in major injuries from scalds to burning embers spilled onto bare feet. In some circumstances the two severity levels in Table 4 may both be applicable to a single hazard if that hazard can result in multiple forms of injury—e.g., open flames may cause minor burns to the hands or major burns resulting from a clothing fire. In these dual-severity cases, safety is assessed on the likelihood to cause minor injuries because it has a greater restriction on the likelihood of injury. This greater restriction is preferred to prevent all forms of injuries, no matter the severity. Where possible, boundaries between levels of safety were chosen such that stoves meeting the target metric of existing standards receive a Good rating. The Best rating identifies stove safety levels beyond the existing target metrics in the referenced standards from industrialized nations. This does not suggest that existing standards are insufficient but is used to encourage cookstove designers and manufacturers to exceed the minimum. Also, some hazards may not be present in certain design types. In these cases, the cookstove receives a Best rating for those hazards that are not applicable. For example, a cookstove that is built into the ground or wall receives a Best rating for the tipping guideline.

Equipment needed

The testing equipment in Table 5 is low-cost and easy to use to facilitate application in the field. The equipment can be assembled into kits at an expense of approximately US$100–150, significantly less than laboratory testing equipment. Performing a test will also require a cookstove, cooking pots, and fuel.

Guidelines and tests

Ten safety guidelines have been developed for the hazards in Table 3. Each guideline includes four pieces of information—a name of the test, a short description of the underlying safety principle, a protocol for conducting the test, and a metric for rating stove safety using a corresponding rubric. Five of the protocols were adapted from existing national standards (i.e., ANSI, 2011, 2012a,b), and five additional protocols were developed to address safety concerns specific to solid fuel household cookstoves.

No set number of duplicate tests is specified. Rather it is the responsibility of the safety evaluator to select the number of tests and the

Table 3
Cookstove hazards for safety guideline development and evaluation.

1. Sharp edges and points
2. Cookstove tipping
3. Poor fuel containment
4. Obstructions near the cooking surface
5. Elevated cookstove surface temperatures
6. Elevated environmental surface temperatures
7. Elevated temperature of operational construction
8. Limited or no chimney shielding
9. Flames surrounding the cookpot
10. Flames or burning fuel exiting the fuel chamber

Table 4
Rubric of safety levels.

Rating	Description	Likelihood of injury: Minor injury	Major injury
4	Best	Low to unlikely	Unlikely
3	Good	Moderate	Low
2	Fair	High	Moderate
1	Poor	Very high	Moderate to high

Table 5
Cookstove safety test kit.

- Tape measure or ruler
- Calculator for division (hand calculation can be used)
- Cloth, rag, or loose clothing
- Stick chalk to make sketches on stove, floor, and wall
- Thermometer to measure air temperature
- Infrared thermocouple to measure cookstove and environment surface temperatures

desired confidence of their findings, such as measuring improvement in a single stove, comparing two stoves, or selecting the safest of multiple stoves. Approximately 90–150 min is needed to complete all tests of one stove, with the total time depending largely on the stove size. A subset of tests can be completed if the safety evaluator is focusing on a specific safety concern. If some equipment cannot be acquired, such as an infrared thermocouple, many of the tests can still be completed. Testing begins with the stove unlit for the first four tests. The stove is then lit for the remaining six tests. Preparations for Test 5 and Test 6 should be completed before igniting the stove to make efficient use of time. Test 6 requires that the fire be extinguished in portable stoves before the stove is moved; however, this requirement is not applicable to fixed or stationary stoves due to their immobility.

Test 1: sharp edges and points

Principle: exterior surfaces of a cookstove should not catch or tear any article of clothing or cut hands during normal use. Sharp edges and points can cut flesh or entangle clothes and overturn a stove.

Equipment includes a piece of cloth, rag, or loose clothing. Gently rub the cloth over the entire exterior surface of the cookstove. Note areas that catch or tear the cloth. These areas represent parts of the stove that could cut flesh or overturn the stove when clothing become entangled. Stone or clay stoves with rough surfaces that resist material should not be counted unless the stove moves or the cloth becomes snagged. Compare the total number of times the cloth is snagged to Table 6 to identify the safety rating. This metric is derived from ANSI 2011 and 2012b, which stipulate that no sharp edges or points be present to receive a Best rating. Ratings below Best have been formulated to show that one, two, or even three sharp edges or points are somewhat hazardous, with four or more considered the result of poor design or construction.

Test 2: cookstove tipping

Principle: cookstoves should remain in a stable upright position. Cookstoves that easily overturn pose scald and burn hazards from the spillage of heated liquid and flaming fuel, respectively.

All cookstove covers and/or utensils should be placed in their normal positions during the test. Fuel is placed in the loading area but is not ignited. The stove is tipped in multiple directions because the center of gravity may not be equivalent to the geometric center. Cookstoves with square, rectangular, or circular bases need to be tested in four tipping directions (one-quarter turn or 90°). Stoves with three legs or a triangular shape need to be tested in three directions (one-third turn or 120°), presuming the legs are spaced equally apart.

Fig. 4 illustrates the test for a stove with four legs. The cookstove is tilted in directions facing outward and perpendicular to adjacent legs.

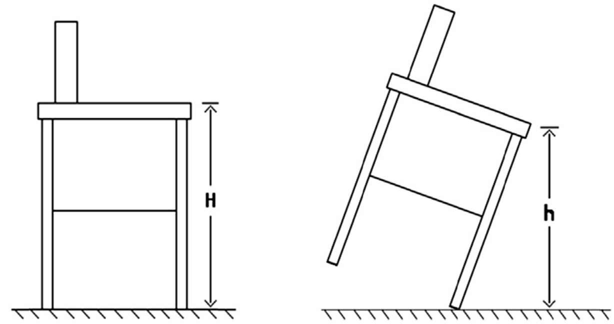

Fig. 4. Schematic of height measurements for the tip test.

A height measurement is taken from the tallest point (typically the cooking surface) on the side towards which the stove is being tipped. This measurement is recorded as the starting height (H). Next, the cookstove is tilted to the chosen side until the stove is able to tip over of its own accord (when the center of gravity is directly above the point of contact with the ground). The new height of the chosen point is measured and recorded as the tipping height (h). Measurement differences may be small. The tipping ratio (R) of the tipping height to that of the starting height is calculated as $R = h/H$.

Table 6 includes tipping ratios and the corresponding safety ratings. The tipping ratio specified in ANSI, 2011 represents the middle of the Good range. Stove weight measurements and horizontal force calculations (as in UL, 2011) are not utilized because they are ill-suited to test small and light outdoor cooking appliances. Stoves that are fixed to the ground, fixed to the wall, or otherwise immobile are given a Best rating and can proceed to Test 3. A stove with a chimney attached to a solid structure, such as a ceiling, may be immobile and hence receive a Best rating.

Test 3: fuel containment

Principle: fuel should rarely fall from the stove if overturned, and embers and burning fuel should have little chance of being expelled from the combustion chamber. Burning fuel and embers that exit the stove can start house fires, clothing fires, or burn the skin and eyes.

All cookstove covers and/or utensils should be placed in normal operating positions during the test. Fuel is placed in the loading area but is not ignited. Visual inspection is used to identify areas through which fuel can be seen (e.g., along the sides of the pot or through the fuel loading chamber). Fuel spillage may occur through these gaps when the stove is overturned. All gaps should be measured, the areas calculated, and then summed for the entire stove. Gaps commonly resemble a rectangular, circular, triangular, or ring shape, allowing the gap area to be approximated using area formulas for those shapes. The total gap area for the stove is applied to the metric given in Table 6. Stoves with smaller gap areas receive better ratings because they are less likely to allow burning fuel to pass outside of the combustion area. Stoves without a bottom—fire is resting on the floor—receive a Poor rating on this test due to lack of fuel containment. The Best reference point for this metric was established using the loading chamber size of a single-pot rocket stove, a common portable cookstove design.

Table 6
Metrics for tests 1–4.

Rating	Test 1	Test 2	Test 3	Test 4
	Number of clothing snags	Tipping ratio, R	Area exposed, A (cm^2)	Height, h (cm)
Best	None	$R < 0.940$	$A < 50$	$h < 1$
Good	One or two	$0.940 \le R < 0.961$	$50 \le A < 150$	$1 \le h < 2.5$
Fair	Three	$0.961 \le R < 0.978$	$150 \le A < 250$	$2.5 \le h < 4$
Poor	Four or more	$R \ge 0.978$	$A \ge 250$	$h \ge 4$

Test 4: obstructions near the cooking surface

Principle: the area surrounding the cooking surface should be free of obstructions. Handles or protrusions along the cooking surface create obstructions for pots being moved to and from the stove, and can result in the spillage of scalding liquid on hands or nearby children.

A ruler or tape measure is used to find the difference in height of the cooking surface to the height of nearby vertical handles or protrusions. The greatest height of all obstructions is applied to the metric in Table 6 to identify the safety rating. Stoves with a pot skirt (i.e., a sheet of material focusing hot flue gases along the sides of the pot) receive a Good rating; pots may collide with the pot skirt even if no protrusions occur above the pot skirt.

Test 5: cookstove surface temperature

Principle: Exterior surfaces of a cookstove should not cause burns if touched for a short duration of time.

Contact with high temperature surfaces may cause minor or significant burns to the skin. The severity of the burn depends upon several factors, including the stove surface material, temperature difference between the stove and skin, skin thickness, skin moisture content, touching force, the contact area between the stove and skin, and the duration of contact. Product standards simplify the complexity of describing risk by specifying a temperature; the burn threshold, below which a superficial burn should not occur from a short period of contact, is often defined as less than one second (British Standards Institution, 2006). Burn thresholds are different for metallic and non-metallic materials (British Standards Institution, 2006; ANSI, 2011, 2012a,b; UL, 2011), and are more stringent at smaller stove heights (≤0.9 m) because children have thinner skin than adults and are hence more susceptible to burns (ANSI, 2012b).

Uncontrolled environmental conditions such as the ambient air temperature, wind, and solar radiation can create spurious results. Testing within a shaded and windbreak space removes the effects of wind and solar radiation. Temperature-controlled testing facilities are rare in remote areas of the developing world and therefore the naturally occurring ambient air temperature is used instead.

Preparation for the test begins by using chalk to draw a grid of 8 cm × 8 cm squares along the external surface of the cookstove (see Fig. 5); temperatures at grid intersections will be later recorded. A square grid is often adequate; however, cookstove geometry may dictate whether a different grid shape or smaller grid sections can be more accurately or easily referenced. Extra thick chalk lines are marked at heights of 0.9 m and 1.5 m on the cookstove to denote regions with greater temperature restrictions for children (≤0.9 m), standard temperature restrictions for adults (>0.9 m and ≤ 1.5 m), and no restrictions for out of reach regions (>1.5 m) (ANSI, 2012b). Grid lines can be differentiated with numbers and letters, and then repeated on sketches of the stove for data recording and future reference. Horizontal cooking surfaces, such as burners or griddles, are excluded from the analysis because they must be hot to cook food. Chimneys are excluded from this test (see Test 8 for testing chimneys). Preparations may be made for Test 6 before lighting the cookstove to reduce the evaluation time of all tests.

Fig. 5. Chalk grid marked along the exterior of the cookstove for the surface temperature test. Photo courtesy of Laboratory of Evaluation of Stoves SENCICO.

The cookstove is loaded with fuel and ignited for this test. More fuel is added as necessary until the cookstove reaches its normal operating temperature (at least 30 min run-time). When the cookstove reaches its normal operating temperature, measure the ambient air temperature. Next, use a thermocouple to measure the cookstove surface temperature at each grid intersection and record the following: data point location or identifier, temperature, and material type (metallic or non-metallic). An infrared thermocouple is recommended for temperature measurement because it is much faster compared to its wired counterpart.

Maximum surface temperatures are determined above and below the child-line and on both metallic and nonmetallic materials when applicable. Differences between ambient air temperature and cookstove temperature correspond to the safety ratings given in Table 7. This method is also used in ANSI, 2012b if the temperature of the testing environment is greater than or less than the desired 25 °C written into the standard (ANSI, 2012b). The recorded ambient air temperature can be added to values in Table 7 to equate the range of surface temperatures for each safety level. For example, a Good rating for metallic components below the child-line would be 69.5 °C ≤ T < 75.5 °C for an air temperature of 31.5 °C. The ANSI/UL reference point of 65 °C was placed in the middle of the Good range and indicates one second of contact without burn in an ambient testing environment of 25 °C (ANSI, 2012b; British Standards Institution, 2006). The Best range is based on two seconds of contact, and the Fair and Poor ranges are based on less than one second of contact, as determined from the burn threshold curve for temperature and contact time (British Standards Institution, 2006). The lowest safety rating based on material, temperature, and location is used as the result for this test.

Test 6: environment surface temperatures

Principle: heat transmission from the cookstove should not significantly elevate temperatures of the surrounding environment. High cookstove surface temperatures and hot flue gases can ignite combustible materials near the cookstove. Product standards commonly limit the temperature rise in nearby walls and floor (ANSI, 2012a; ANSI 2012b; UL, 2011).

The test procedures differ for stationary and portable cookstoves:

- For stationary cookstoves that are attached to the floor or wall, use an IR thermocouple to record the highest surface temperatures on the ground and wall at the point of connection with the cookstove and apply those temperatures to Table 7 to identify the safety rating. This simplified method is used to test stoves that are constructed on-site, built into the kitchen, or too heavy to be moved. If the stove is not lit, begin this test by igniting the stove and adding fuel when necessary until the cookstove reaches its normal operating temperature (at least 30 min run-time), then record surface temperatures.
- For portable stoves, a grid will be drawn on the floor and walls near the stove to indicate temperature measurement points. The grid should be completed when the stove is cold (at ambient temperature) to negate hazards associated with moving a hot, burning stove. This can be done prior to igniting the stove in Test 5 or after sufficient time has past between tests for the stove to cool to ambient temperature. Position the stove in the corner of a room with 10 cm of space between the cookstove and each wall. Orient the stove so that the combustion chamber and/or chimney is parallel to either wall. Sketch the outline of the stove on each wall. Also, sketch the outline of the stove on the ground if the stove's lower surface is within 5 cm of the ground. Pull the stove away and sketch a grid of 8 cm × 8 cm squares inside the outlines on the floor and wall. Sketch two additional squares in height on each wall to assess temperature increases from

Table 7
Metrics for Tests 5–7.

Rating	Test 5				Test 6		Test 7	
	Below child-line		Above child-line		Floor	Wall	Metallic	Nonmetallic
	Metallic	Nonmetallic	Metallic	Nonmetallic				
Best	$T_s < 38$	$T_s < 46$	$T_s < 54$	$T_s < 62$	$T_e < 45$	$T_e < 60$	$T_o < 20$	$T_o < 32$
Good	$38 \le T_s < 44$	$46 \le T_s < 52$	$54 \le T_s < 60$	$62 \le T_s < 68$	$45 \le T_e < 55$	$60 \le T_e < 70$	$20 \le T_o < 26$	$32 \le T_o < 38$
Fair	$44 \le T_s < 50$	$52 \le T_s < 58$	$60 \le T_s < 66$	$68 \le T_s < 74$	$55 \le T_e < 65$	$70 \le T_e < 80$	$26 \le T_o < 32$	$38 \le T_o < 44$
Poor	$T_s \ge 50$	$T_s \ge 58$	$T_s \ge 66$	$T_s \ge 74$	$T_e \ge 65$	$T_e \ge 80$	$T_o \ge 32$	$T_o \ge 44$

T_s: temperature difference between cookstove surface and ambient air temperature (°C).
T_e: temperature difference between environmental surface and ambient air temperature (°C).
T_o: temperature difference between cookstove operational construction and ambient air temperature (°C).

flue gases. If the stove is not lit, ignite the stove and add fuel when necessary until the cookstove reaches its normal operating temperature (at least 30 min run-time). The fire should be extinguished and any flaming embers secured before moving the stove to record temperatures—thermal hand protection may be required when touching the stove. Use a thermocouple to measure the surface temperature at each grid intersection and record the data point location, and temperature. The cookstove should be moved for temperature measurements—an IR thermocouple field of view may otherwise be obstructed and affect reading accuracy.

Measure the ambient air temperature. Differences between ambient air temperature and floor or wall temperatures correspond to the safety ratings given in Table 7. As in Test 5, the recorded ambient air temperature can be added to values in Table 7 to equate the range of surface temperatures for each safety level. The maximum temperature on the floor and wall is used to determine the cookstove rating. The ANSI reference points of 50 °C and 65 °C for the rise in temperature above ambient temperature for the floor and wall, respectively, were placed in the middle of the Good range to encourage improvement (ANSI, 2011; ANSI, 2012a; ANSI, 2012b; UL, 2011).

Test 7: temperature of operational construction

Principle: the temperature of cookstove handles and other operational construction should not cause discomfort or burns. Examples of cookstove components touched during regular use include handles on the combustion chamber door, handles to regulate airflow, and the pot skirt.

This test can be completed directly after Tests 5 and 6 when the stove is at its normal operating temperature (at least 30 min run-time). Stoves that do not have operational construction receive a rating of Best on this test. Use a thermocouple to measure the surface temperature of handles and record the following: data point location, temperature, and material type (metallic or nonmetallic). Temperature differences between ambient air and operational construction are given in Table 7. Allowable ranges for both metallic and nonmetallic handles can be computed in the same manner as in Tests 5 and 6, with ANSI and UL limits placed within the middle of the Good range (ANSI, 2011; ANSI, 2012a; UL, 2011). Safety for this guideline is determined by the most deficient rating.

Test 8: chimney shielding

*Principle: chimneys with elevated temperatures should have shielding to prevent contact by children and adults. Uninsulated chimneys can become extremely hot during use and can easily cause burns. Shielding (*e.g., *a protective wire cage) can be placed around the chimney to prevent accidental contact.*

The safety of a chimney without shielding is rated using the temperature, location, and material type in Test 5 and Table 7. If shielding is used, the exposed area to the chimney provides a measurable quantity to determine the risk of contact (see Fig. 6). Shielding is commonly made from a uniform pattern and therefore only one gap in the shielding needs to be measured and applied against Table 8 to identify the safety rating. For shielding with various sized gaps, however, the largest gap is measured and applied to Table 8. The Best rating of 10 cm^2 prevents accidental contact by fingers. Larger areas of 100 cm^2 and 300 cm^2 serve as reference points between Good–Fair and Fair–Poor to prevent accidental contact with the hand or arm, respectively.

Test 9: flames surrounding cookpot

Principle: flames should not engulf the cookpot or cookpot handles. Large amounts of flames around the cookpot can ignite clothes or produce severe burns to the hands and other parts of the body.

The cookstove is loaded with fuel and fully ablaze from prior tests. A cookpot is placed on the stove and monitored in a high burn for five minutes. The amount of flames on the cookpot—single largest height observed reaching up the cookpot—is recorded and applied to the metric given in Table 8. A Best rating was established for this hazard with no risk present for fully concealed flames. The Poor rating was created from the worst possible scenario—flames along cookpot sides reach to the rim of the pot and/or cover the handles of the cookpot. Good and Fair ratings were established as intermediate levels between these two extremes. In noting that shorter cookstoves with open flames expose children to greater risk, subtract one rating level if the cooking surface is below 0.3 m in height and unconcealed flames are present. This addresses the greater likelihood for children to burn themselves or clothes to catch fire with flames nearer to the ground.

Fig. 6. Shielding surrounding the chimney to reduce the chance of contact with skin.

Table 8
Metrics for tests 8–10.

Rating	Test 8	Test 9	Test 10
	Hole size (cm^2)	Amount of uncovered flames on cookpot	Flames visible?
Best	$A < 10$	None	No
Good	$10 \leq A < 100$	Less than 4 cm up the sides, not handles	N/A
Fair	$100 \leq A < 300$	More than 4 cm up the sides, not handles	N/A
Poor	$A \geq 300$	Entire cookpot to rim and/or covering handles	Yes

A: area of one open segment in the shielding pattern.

Test 10: flames or burning fuel exiting the fuel chamber

Principle: flames or burning fuel should not protrude from the fuel loading area. Uncontrolled flames that exit the fuel chamber can ignite clothes and burn nearby children and adults.

Evaluation for this test occurs while the cookstove is fully ablaze. A Best rating is given if no flames exit the fuel loading area, otherwise a Poor rating is given if any flames are visible (Table 8). No incremented rating system is implemented for this hazard. The fire can be extinguished after completing this test.

Overall safety rating

The overall safety rating is calculated as a weighted sum of the individual ratings. Each individual rating is first transformed into a numerical score: Poor—1, Fair—2, Good—3, Best—4. Individual ratings are then multiplied by the weights given in Table 9 to achieve the overall safety rating that falls between the minimum of 25 and maximum of 100 (Table 10). The choice of weighting is based on a qualitative understanding and agreement on the quantification of risk that was developed over two years of discussion between professionals in the cookstove community, and this weighting has been accepted in conferences and workshops including the International Workshop Agreement arranged by the International Standards Organization. Greater weight is given to hazards that can result in greater harm. For example, Test 1 has a weight of 1.5 because a cut or abrasion is a minor injury when compared to a second- or third-degree burn which could result from open flames around the cookpot, as in Test 9 with a weight of 3. In addition, this weighting schema was adopted in Review 10: Burns and poisoning, evidence review for the recently released WHO Indoor Air Quality Guidelines: Household Fuel Combustion (Diekman et al., 2014).

The overall cookstove safety rating can be used alongside other criteria such as efficiency and emissions to facilitate the cookstove design process, consumer purchasing decisions, and investment considerations by funding agencies.

Test results of solid fuel cookstoves

Fifty solid fuel cookstoves were evaluated using the safety protocols and metrics introduced earlier. These tests included five categories of stove designs: open fires, single-pot traditional cookstoves, single-pot improved cookstoves, multi-pot improved cookstoves, and griddle cookstoves. Tests were completed by three centers in the United States (Iowa State University, the Engines and Energy Conversion Laboratory at Colorado State University, and Aprovecho Research Center), one center in Uganda (Centre for Research in Energy and Energy Conservation), and one center in Bolivia (Laboratory of Evaluation of Stoves SENCICO). It is clear from Fig. 7 that the safety ratings of cookstoves are not uniform across all design types or product categories. The safety concerns of each of these stove categories are reviewed below:

Table 9
Weighting of individual test results used to obtain overall cookstove safety rating.

Test	1	2	3	4	5	6	7	8	9	10
Weights	1.5	3.0	2.5	2.0	2.0	2.5	2.0	2.5	3.0	4.0

Table 10
Metric for overall safety rating.

Rating	Point score
Best	$93 \leq S \leq 100$
Good	$84 \leq S \leq 92$
Fair	$76 \leq S \leq 83$
Poor	$25 \leq S \leq 75$

S: sum of points from weighted individual safety tests.

- Open fires: traditional open fire cooking methods commonly use three stones to hold cooking pots above the fire. This cooking arrangement scored well below any type of enclosed fire from the other four design categories. The lack of fire and ember enclosure (Tests 3, 5–7), flames surrounding the cooking vessel (Test 9), and flames exiting the fuel chamber (Test 10) produce an unsafe cooking environment for women and children.
- Single-pot traditional cookstoves: these stoves are hand-crafted by artisans or household members to enclose the fire yet lack an improved combustion chamber or chimney. These stove designs reduce the risk of clothing and hair fires by enclosing the fire and reduce the risk of burned hands or feet of children near the fire (Tests 3, 10). However, many designs are built by hand with minimal tools that create sharp edges and points (Test 1), are small and prone to tipping (Test 2), or have thin metal walls that reach excessive temperatures (Tests 5–7).
- Single-pot improved cookstoves: improved cookstoves are a general description for stoves with an improved firebox and/or chimney to increase efficiency and reduce emissions. Single-pot designs are generally smaller and portable, whereas multi-pot designs are generally larger and stationary. Common design types include rocket stoves and gasifiers. Several of these stove designs are similar to single-pot traditional cookstoves in size and wall construction and therefore receive similar safety ratings for sharp edges (Test 1) and tipping potential (Test 2). Yet several other designs within this product category have achieved higher safety ratings by adding insulation around the combustion chamber and increasing the wall thickness. This in turn

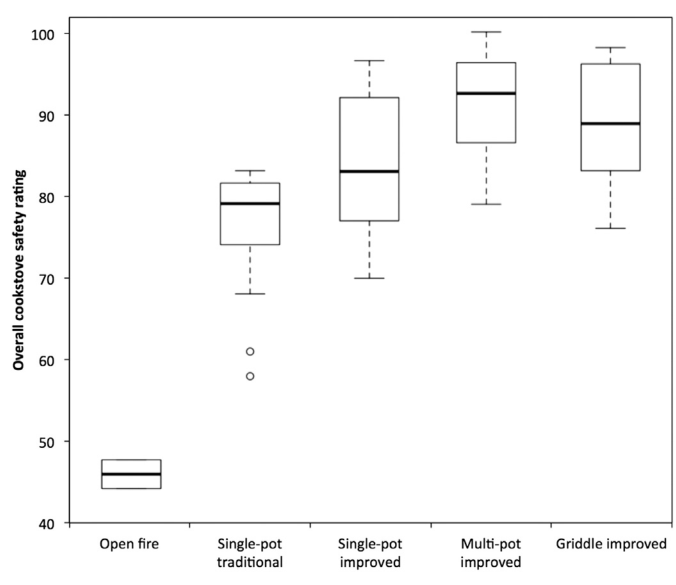

Fig. 7. Safety ratings for solid fuel cookstoves. Tests completed at Iowa State University, the Engines and Energy Conversion Laboratory at Colorado State University, and Aprovecho Research Center.

decreases the exterior wall surface temperature—a hazard assessed by three of the ten tests (Tests 5–7).

- Multi-pot improved cookstoves: these stoves offer multiple cooking hobs (or burners) to cook several dishes simultaneously while still providing the increased efficiency and reduced emissions of their single-pot counterparts. Multi-pot stoves are commonly fixed to the ground or have a broad base that prevents tipping. In general, multi-pot cookstoves reduce the risk of burns by maintaining low exterior surface temperatures, and they reduce the risk of scalds from their inability to tip. Yet these stoves often include a chimney, and the temperature of the chimney must be within safe limits (Test 5) or be shielded to prevent human contact (Test 8).
- Griddle cookstoves: griddle cookstoves are described here as improved cookstoves with a flat cooking surface used for making flat breads. Griddle cookstoves with the safest rated cookstoves have thick clay or earthen walls that insulate the combustion chamber to maintain very low exterior wall surface temperatures; lower rated griddle designs generally have metal walls that have higher surface temperatures. As with all improved cookstoves, griddle cookstoves are manufactured with improved tools and have a greater degree of workmanship and reduced risk of cuts due to sharp edges (Test 1). However, drop-in griddles commonly have handles that protrude from the cooking surface and create obstructions for pots moving from the griddle (Test 4), thereby increasing the risk of scalding.

These data on cookstove safety represent a cross-section of stove designs developed around the world between 2004 and 2012. It is clear that improved cookstoves provide greater safety than traditional cookstoves and offer a significant improvement over open fires. It is also clear that cookstove innovators are directly, or indirectly, improving stove safety while targeting other design objectives such as increased performance, reduced emissions, and delivering product at an affordable cost. Yet there is still work to do. Single-pot traditional and single-pot improved stoves face challenges to mitigating hazards associated with stability, elevated surface temperatures, and open flames. Stationary multi-pot and griddle stoves, while tending to be safer than single-pot portable stoves, face other challenges such as elevated chimney temperatures, limited chimney shielding, and obstructions near the cooking surface that could case scalds.

Discussion

The field-based approach to safety evaluation in this study provides a mechanism to evaluate, rank, and improve the safety of hand-crafted cookstoves. Protocols can also be applied to manufactured stoves: however, that market is not the primary use case or motivation for this work. Ten safety guidelines provide stove designers and manufacturers with a set of safety principles, testing protocols, and metrics to identify, measure, and reduce cookstove hazards. Results from each safety test can be used for targeted improvements of a product (e.g., reducing exterior surface temperature), or combined into an overall safety rating that offers a metric for consumers and funders to compare stove safety alongside other metrics such as efficiency, emissions, and durability. A tiered rating system has been developed to encourage improvements in stove safety and facilitate greater granularity in progress tracking. Although the protocols are voluntary, adoption thus far is encouraging. To date, the protocols have been used to evaluate the safety of over 100 stoves in more than twenty countries since being first introduced in 2005. The results in Fig. 7 provide a sample of cookstove testing laboratories and stove developers that have adopted the protocols in North America, South America, Asia, and Africa. This trend is expected to increase with the recent founding of regional cookstove testing and knowledge centers supported by the Global Alliance for Clean Cookstoves. Translated copies of the protocols are available in Spanish and French.

It is clear that improved cookstoves offer a substantial improvement in safety when compared to the traditional open fire. Design aspects of improved cookstoves such as enclosing the fire, adding a wide base to prevent tipping, and limiting the fuel chamber size provide several safety advantages to an open fire. Even single-pot traditional cookstoves can provide a safer environment by adding a partial or full enclosure of the combustion chamber. Yet it is also clear that there is room for improvement. Further outreach, education, and testing initiatives are needed to benefit the many organizations with rapid stove development and deployment programs. This global challenge is being made easier through the use of an editable safety datasheet with calculations and instructions that is available freely through the Global Alliance for Clean Cookstoves (GACC, 2014). Looking ahead, laboratory-based safety and durability protocols must be developed to provide evaluation capabilities that address technical innovation as the stove industry evolves. In closing, it is important to reflect that improving stove safety does not necessarily have to increase cost or impair stove performance—modifications such as rounding a sharp edge to reduce the occurrence of cuts or widening the stove base to prevent tipping can increase safety without adversely affecting desirable traits of the stove. This realization is important to advancing stove safety by demonstrating that we have the ability to improve stove safety while preserving—and growing—the other unique capabilities of a cookstove to reduce deforestation, pollution, and human disease.

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