

Respiratory Protection in Wildland and Wildland–Urban Interface Firefighting: Usability and Acceptance Findings from Operational Field Testing

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Abstract

Wildland and wildland–urban interface firefighters experience repeated, prolonged smoke exposure, yet respiratory protection devices (RPDs) are not widely used in this work activity, nor have RPDs been optimized for this task. This study evaluated constraints on usability, integration with other equipment and activities, and adoption for selected powered air-purifying respirators (PAPRs) and an elastomeric air-purifying respirator using a mixed-methods design. Across three field phases—pilot operational field test, expanded operational field test, and a natural terrain field test—California fire personnel completed realistic task evolutions and provided responses to questions about device experience and performance. Scaled ratings captured perceived performance across domains (e.g., donning, respiratory ease, comfort, interference), while qualitative responses identified specific friction points shaping adoption in practice. A central mixed-methods pattern was that favorable scaled ratings often co-occurred with critical qualitative feedback, reflecting trade-off-based decision-making rather than simple approval or disapproval of an RPD. Two usability drivers were consistent across methods: (a) airflow stability under exertion as a driver of perceived usability, and (b) system integration with gear, movement, and work practices as a determinant of acceptance. Findings indicate that some existing PAPRs provide stable airflow under exertion, while some cannot supply sufficient air to meet physical demands. Acceptance will depend on adaptations to the material design of existing RPDs to increase their durability and minimize interference with packs, helmets, eyewear, radios, and safety-critical protocols.

Keywords: WUI, respiratory protection, PAPR, usability, human factors, mixed methods, wildland firefighters

What's Important About This Paper?

This study contributes usability evidence from operational field testing of current air-purifying and powered air-purifying respirator configurations under realistic wildland and wildland–urban interface (W/WUI) task demands. The study found favorable device ratings can co-occur with specific criticisms of form factor and performance, indicating tradeoff-based adoption decisions. Airflow stability under exertion and integration with gear and operational practices are dominant adoption drivers. Findings translate firefighter feedback into actionable, configuration-specific design requirements and contribute data to inform policy decisions related to the supply of respiratory protection devices to W/WUI firefighters.

Introduction

Wildland and wildland–urban interface (W/WUI) firefighters undertake profoundly demanding physical work that results in repeated exposure to smoke and particulate matter, yet they lack respiratory protective devices (RPDs) optimized for their needs (Navarro 2020; Shahid et al. 2022). Although compressed-air equipment was introduced for structural firefighters in 1945, and self-contained breathing apparatuses (SCBAs) became mandatory for structural firefighting by 1980 (NIOSH 2019), the implementation of respiratory protection for W/WUI operations has been considerably delayed. Sustained attention to the hazards of wildfire smoke began when a mass illness incident in 1987 led to a request for exposure monitoring in Yellowstone National Park (Reh and Deitchman 1992), though respiratory protection for wildland operations has yet to be broadly implemented. Early surveys and field testing of air-purifying respirators (APRs) found interest in adoption but emphasized the need for discretionary use aligned with fire stage and integration with web gear; Driessen et al. 1992; Beason et al. 1996).

Interest in RPDs for W/WUI firefighting has been renewed. Not only have the number and intensity of W/WUI fires increased—increasing firefighters' exposures, but the adverse health effects experienced by firefighters are increasingly visible (International Agency for Research on Cancer 2023; Murray et al. 2026). The National Institute for Occupational Safety and Health (NIOSH) certifies respirators for occupational use, and they must be used in settings with OSHA mandated Respiratory Protection Plans (RPPs) (NIOSH 1995). Further, the National Fire Protection Association (NFPA), which develops consensus standards often incorporated by reference into law, has promulgated NFPA 1984, which outlines the design and operational requirements for three classes of air-purifying RPDs for use in W/WUI firefighting (NFPA 2022). Despite the recognized need, barriers to adoption of RPDs in W/WUI firefighting are numerous. Not only have no devices been certified to meet NFPA 1984, but limited exposure assessment sustains debate about the choice of respirator model, filters and cartridges. And, particularly for dedicated wildland firefighting activities in remote areas, there are concerns about the logistics of establishing comprehensive Respiratory Protection Programs in such complex operational environments (OSHA 2004; NASEM 2021). Firefighters, however, have made clear that they want to be engaged to decision-making around the adoption of

RPDs in W/WUI firefighting, and they have concerns about the function and performance of the devices related to reducing the inhalation of airborne contaminants without detriment to their physical safety or ability to perform job tasks (Driessen et al. 1992; Pelletier et al. 2022; Dawit et al. 2026).

The objective of this study was to evaluate usability and adoption constraints for candidate APR and powered air-purifying respirator (PAPR) configurations intended for W/WUI operations. The approach, guided by principles of user-centered human factors design, used mixed-methods to gather information about the experience of firefighters after using a RPD to perform simulated work activities across three phases. Elsewhere, results of physiological monitoring will be shared. The study was designed to develop the evidence-base for adoption of RPD in W/WUI firefighting in general, and specifically for regulatory efforts in California (Cal/OSHA, 2022).

Methods

Study design

The general approach to the study design was to provide firefighters opportunities to use candidate RPDs during simulated firefighting training and work activities and then gather their opinions about the devices. The study involved three field phases of training and work activities: (1) a pilot operational field test, (2) an expanded operational field (EOF) test, and (3) a natural terrain field (NTF) test. A mixed-methods design was used to gather information about the user experience that combined surveys with scaled and open-ended responses and semi-structured post-exercise debrief discussions. The study plan was reviewed and approved by the Institutional Review Board of the University of California, Los Angeles, protocol IRB-23-1146, and approval extended to San José State University through a reliance agreement. Data collection took place between March and July 2025.

Across field test phases, one half-mask elastomeric APR model (respirator A) was evaluated and four PAPRs (respirators B-C, B-D, E and F) (Table 1). Respirators B-C and B-D shared a blower model, but had different facepieces, and the same facepiece model was used in respirators A and B-C. Respirator E had demand-responsive airflow, while the other PAPRs each had 2-3 levels of fixed airflow that could be selected by the user. Respirator E is not commercially available and was provided at no-cost by the manufacturer for use in this study. All other respirators tested were purchased from vendors. Respirators A, B-C and B-D are NIOSH-certified. Respirator F incorporates a seal mechanism and material construction that does not fall under a current NIOSH classification.

To support the interpretation of configuration-level findings, each condition is described briefly here. Respirator A—the APR condition— used an elastomeric half-mask facepiece with a P100 filter cartridge attached directly to the facepiece. PAPR B was a belt-mounted blower with P100 filter and supplied airflow via dual hoses to a half-mask elastomeric facepiece referred to as configuration C (e.g., respirator B-C) or via a single hose to a full-face facepiece referred to as configuration D (e.g., respirator B-D). PAPR E combined a half-mask with a dedicated, clip-mounted blower unit with combination cartridge that provided demand-responsive air flow (device-specific). PAPR F combined a fabric half-mask with a dedicated blower unit with P100 filter worn with a shoulder/chest harness,

featuring front-mounted air controls for user access. PAPR F uniquely drew air into the mask from the back, at the nape of the neck.

In the Pilot phase, participants completed realistic task evolutions at a training ground, including a confidence course (confined space crawl), a sledgehammer station (20 blows on both dominant and non-dominant sides), and a six-story tower climb while carrying a 2.5-inch hose bundle weighing 54 lb. Exercise sequences were randomized within participants across respirator conditions. The EOF phase followed the same general protocol; however, the confidence course was replaced with a farmers' carry exercise (40 lb. in each hand over 500 meters). The NTF phase consisted of a progressive hose lay conducted in natural, hilly terrain at a local park on a warm sunny day to simulate field deployment conditions. The same survey instruments and semi-structured debrief guide were used across all phases; however, the natural terrain context introduced greater variability in movement, pacing, and equipment carry.

Within each phase, respirator order and a no-respirator control was randomized such that each participant was scheduled to test each configuration once. Although the design aimed for full rotation across conditions, some sessions were incomplete due to operational constraints, so some participants did not test all respirators. Each round consisted of donning the assigned respirator, completion of a pre-exercise survey, a 3-minute seated baseline measurement of physiological parameters, and a sequence of structured exercise evolutions. Individual exercise tasks lasted 10–20 minutes depending on task and participant pace. Following completion of the final exercise in each round, participants completed a standardized 7-minute seated recovery period followed by the post-exercise survey and de-brief.

Participants in this study were recruited from the Santa Rosa Fire Department (SRFD). Eligibility was based on having experience with wildland firefighting duties. Participants completed two surveys (Table S1): a brief survey administered immediately after donning each respirator, and a second survey after completing an activity. Surveys included Likert-scale ratings across usability domains, alongside open-ended items capturing constraints and recommendations. Each phase also included a semi-structured debrief to elicit narratives about usability, integration, safety, and adoption thresholds (Table S2).

Table 1. Respirators evaluated.

Label	Description	Study Phases Tested
A	NIOSH-certified half-mask elastomeric facepiece fitted with 1 class P3 filter cartridge. Weight ~ 4.7 oz (132 g) for size S, 4.8 oz (136 g) for size M, and 4.9 oz (138 g) for size L	EOS, NFT
B-C	NIOSH-certified PAPR with belt-mounted blower fitted with two P3 filters that supply air to a half-mask elastomeric respirator via two hoses. ¹ Air flow 175 l/min (normal operation) 240 l/min (boost operation). Weight 4.85 lbs. (blower) 4.85 lbs. Masks ~ 4.7 oz (132 g) for size S, 4.8 oz (136 g) for size M, and 4.9 oz (138 g) for size L	All

Label	Description	Study Phases Tested
B-D	NIOSH-certified PAPR with belt-mounted blower fitted with two P3 filters and particulate pre-filters that supply air to a full-face mask via one hose. ² Air flow: 175 l/min (normal operation) 240 l/min (boost operation) Weight: 4.85 lbs. (blower) Mask ~2.10lbs	All
E	Elastomeric half-mask PAPR prototype with a clip-mounted blower that delivers air on demand via a single hose (demand-responsive). ³ Airflow controls are on the top of the blower. Weight ~2 lbs. Filter is lab tested to provide protection against particulate matter comparable to P3.	EOS, NFT
F	Fabric half-mask PAPR fitted with a TH3 filter unit blower integrated into a shoulder harness and worn on the back or chest. Air flow 100-130 l/min. Weight 1.25 lbs. Airflow controls are front-mounted. ⁴	Pilot, NTF
Control	No respirator or face covering worn	All

¹ The half-mask facepiece was the same as respirator A

² Respirators B-C and B-D have the same model of belt-mounted blower

³ This device is not NIOSH-Certified and was provided by the manufacturer

⁴ This device is not NIOSH-Certified but passed equivalent filtration tests

Data Analysis.

Qualitative data were analyzed using a mixed deductive–inductive content analysis approach. An initial deductive codebook was developed a priori based on constructs embedded in the survey and semi-structured interview instruments and was organized around the concepts of Fit–Form–Function–Comfort (FFF+C). During the Pilot phase, the preliminary codebook was applied to survey responses and debrief transcripts independently by three investigators (S.G., M.H., and C.R.). Review of the data produced initial inductive codes and stabilized deductive code definitions.

Data from each phase (Pilot, EOF, and NTF) was first coded and reviewed individually to identify phase-specific patterns. After completion of data collection across all phases, qualitative data were pooled for final synthesis. The four higher-order analytic themes—Integration with Body; Integration with Gear and Occupational Equipment; Operational Tasks and Conditions; and User Acceptance and Design Recommendations—were developed inductively and applied across the complete dataset to reflect recurrent patterns observed across phases.

Two investigators (S.G. and M.H) reviewed the final coding pass, and intercoder reliability yielded a Cohen's kappa of 0.59 prior to reconciliation; discrepancies were resolved through investigator consensus. The finalized codebook is provided in the Supplementary Materials. (Supplementary Appendix: Final Analytic Themes and Usability Codes)

Quantitative survey responses were summarized descriptively (counts/percentages for binary items; means for 7-point scaled items) to characterize perceived performance patterns by respirator configuration and study phase. Survey summaries were used to identify patterns across domains (e.g., exertional breathing ease, comfort, interference, and communication), while qualitative findings were used to contextualize factors influencing usability and adoption. As a descriptive screening step, we also examined pooled Pearson correlations between overall experience and selected scaled items; we interpreted cautiously given unequal and sometimes small configuration-specific sample sizes.



Figure 1. Common integration issues observed during operational field testing. (A) Observed attachment instability, PAPR B. (B) Control placement, PAPR B-D (C) Slack hosing, Configuration B-C.

Alt text Figure 1: Illustrations of three observed integration issues (A) A participant with detached blower unit during hose lay, PAPR B. (B) A participant struggles to reach controls behind back, PAPR B-D (C) A figure working with slack hosing causing interference, Configuration B-C.



Figure 2: Illustrations of body placement and mounting strategies used across evaluated configurations. (a) Configuration E (front/clip-mounted placement) (b) Configuration E (rear-mounted placement) (c) APR (d) Configuration B-C (front-mounted placement). (e) Configuration B-D (front view; PAPR unit back mounted). (f) Configuration B-C (back-mounted placement) (g) PAPR F, front view (h) PAPR F, back view

Alt text Figure 2: Illustrations of eight device body placement and mounting strategies. (a) Configuration E on the waist front: clip-mounted (b) Configuration E strapped on the back to a pack (c) APR mask as worn (d) Configuration B-C mounted to waist front. (e) Configuration B-D front view; blower unit back mounted. (f) Configuration B-C waist-mounted at back (g) PAPR F, view of chest straps and controls (h) PAPR F, back view: showing airflow to rear of mask

1 Results

A total of 31 male firefighters participated in the study, with 2 individuals participating in multiple phases, for 33 total phase-level observations. The mean age of participants was 39.5 years ($SD = 8.1$), and mean years served in professional firefighting was 15.1 ($SD = 6.3$). On average, the participation time including the debriefing was four hours for each phase.

Firefighters' assessments of the respirators were consistently multi-dimensional

and context dependent. Scaled questions pointed to three central usability concerns: breathing ease, comfort, and interference, while open-ended responses and debrief narratives identified the specific friction points that shaped usability and adoption in practice.

Agreement with the yes/no statement, “Assuming the device is effective for chemical and particulate filtration, would you be willing to use it if the task or environment requires its use?” was generally high (mean values ≥ 5.67 on a scale of 1-7, for the different RPDs tested), as were scaled ratings of overall satisfaction. Configurations B-C and B-D received the highest mean ratings for overall experience (5.07 and 4.97, respectively) and for breathing ease during work tasks, including strenuous exertion (6.38 and 6.10). However, ratings for the statement “The PAPR and its components did not interfere with other equipment or gear during exercises,” were comparatively lower for B-C and B-D (3.76 and 3.43, respectively). In contrast, Configuration F received the lowest rating for breathing ease during strenuous exertion (3.44), and poor ratings for comfort, but higher agreement for gear integration, indicating gear integration and breathability under exertion as salient but often inversely related within specific devices. In pooled correlations, overall experience with the RPD aligned most strongly with comfort-for-duration of exertion and ease of breathing during strenuous work, andwork and also showed associations with equipment interference and radio audibility; we therefore interpreted sustained comfort and ease of breathing under exertion as probable drivers of operational usability (Supplementary Figure S1). A central pattern was that positive scaled ratings frequently co-occurred with critical qualitative feedback, particularly when participants weighed potential respiratory protection benefits against operational, integration, and safety costs.

The inductive usability codes applied to excerpted segments from survey open-ended responses and debrief transcripts are listed in Table 2. The codes were not mutually exclusive, and excerpts could receive multiple codes when they addressed more than one usability domain (e.g., body, gear, and tasks/conditions). Codes are presented here under the final analytic themes used for reporting. The quotes included are illustrative rather than exhaustive, and respirator-specific notes summarize common patterns associated with each subtheme (Table 2).

Table 2. Final Analytic Themes and Usability Codes.

Analytic Theme	Inductive Codes	Illustrative Quote	Specific Findings
Integration with Body	Airflow; Breathing Resistance; Sufficiency	“It was very comfortable but forced you to breathe through your mouth—once the air dropped, it just sucked the mask to my face.”	Configurations C and D (powered by PAPR B) were repeatedly described as providing consistent airflow during strenuous tasks despite added bulk; Configurations E and F were perceived as lighter but insufficient during high exertion. APR was described as breathable at rest but restrictive during sustained work.
Integration with Body	Facial pressure; Seal stability; Heat; Vision; Eyewear compatibility; Airflow controls; Movement restriction	“[...]it pinched the hell out of your nose.” “[...]” “I could not wear my sunglasses.”	Nose pressure; Full-face configuration B-D improved eye protection but introduced visual field distortion. High nose profiles of E and F interfered

Analytic Theme	Inductive Codes	Illustrative Quote	Specific Findings
		“[...]full face one [was] the best. Yeah, eye protection, respiratory protection, and just comfortability.” “I could not reach the button to adjust my airflow.”	with eyewear and downward peripheral vision. Hose routing restricted gaze by interfering with head movement in all PAPRs.
Integration with Gear & Equipment	Placement; Hose/tubing routing; Attachment points; Bulk; Straps;	“Air intake was blocked by my web gear back piece” “Air hose would flop around and get crushed.” “Some refining of straps and, you know, some clips that would be compatible with the web gear, they'd be way better off.”	Belt and strap mounted PAPRs were compressed by packs, obstructing intakes and controls. Hose packs and radios competed for space with tubing. Larger PAPRs delivered airflow but intended placements were incompatible with shelter deployment or pack carry.
Integration with Gear & Equipment	Helmet/chin strap interference; Shelter compatibility; Heat shroud conflicts	“Doffing the mask necessitates removing my helmet” “That's now on top of the shelter.” “I wasn't able to get the thermal barrier over that.”	Interference with helmet straps or shelter use was evaluated critically regardless of airflow performance. APRs were consistently described as easiest to integrate with existing gear.
Operational Tasks and Conditions	Donning/doffing; Battery management; Filter batteries; Filter life	“I can't spend a minute or two adjusting and fitting this [...]. So, if it was already on my pack, and I could just grab a mask and put it on, turn it on- mask on helmet on, and I'm gone.” “For those having, like, a rechargeable battery, like we have for BKs, yeah, and then just a clam shell.” “Can you change your filters? Are they easy to change? And have they been tested in that kind of environment?”	APRs were favored for rapid don/doff during dynamic tasks. PAPRs were viewed as advantageous for prolonged smoke exposure but participants raised concerns about battery swapping mid-shift and loss of airflow with ash-loaded filters
Operational Tasks and Conditions	Communication; noise	“Communication is always held to the highest standard - it's part of LCES. So not being able to communicate effectively with these masks is one of the things that I would say would keep us from utilizing them, even though, you know, they're designed to protect our lungs and, you know, allow us to work in these smoky environments. If I can't communicate with it, I'm going to toss it aside, because, you know, being able to communicate is more important.”	Blower noise and muffled speech were noted across respirators, with greatest noise related disruption reported for E during coordinated tasks requiring radio communication.
User Acceptance & Design Recommendations	Airflow controls; PAPR attachment	“[...]I was trying to, like, is it turning off and on, or what? I'm fiddling with the button. It's beeping at me. I'm like, I don't know what [...]is going on with this thing.” “I hated just because of the way it mounted. It broke off twice.”	Acceptance was conditional and task dependent. Firefighters favored designs allowing multiple mounting options, quick-release hoses, and accessible controls. Larger PAPRs were viewed as viable if attachment security, control access, and body placement issues were resolved.
User Acceptance & Design Recommendations	Occupational/operational; Integration; Interference	“This is getting in the way of my stuff that I, you know, already have and need to have on my web gear. So, it's really easy to do it wrong, is, I guess, the point that I'm saying- and if you do it wrong, it's gonna sour an entire group of individuals going, ‘What the hell do we spend all this money on?’ So, it's sensitive, right? Because there's	Participants emphasized that adoption depends on interoperable, modular systems rather than single fixed designs, enabling ease of use and appropriate protocols for fire stage, conditions and task.

Analytic Theme	Inductive Codes	Illustrative Quote	Specific Findings
		that cultural component. We gave guys free masks and everything else, and they went down to Los Angeles. I think no one brought them.”	

Integration with Body

Integration with the body refers to how the RPDs interface with body of participants, including the impact on the external body and body functions. In this regard, participants emphasized airflow stability of the tested PAPR configurations when under physical exertion, breathing resistance, facial pressure from facepieces, and vision. Other topics of significance included body placement and movement interference, as well as the impact of RPDs on hydration.

Across RPDs tested, scaled responses distinguished exertional breathability from other aspects of wearability. Ratings for ease of breathing during strenuous work were highest for configurations B-C and B-D (6.38 and 6.10 on a scale of 1-7), intermediate for E (5.04), and lower for A (4.84) and F (3.44). The lower score for F aligns with participant descriptions of airflow dropouts or “out-breathing” the device during high work rates. Comfort limits over sustained workload were reflected in comments about nose-bridge pressure and facepiece fit; though scaled responses to “comfortable to wear for the duration” was mid-range overall (A 4.96; B-C 5.00; B-D 5.23; E 4.67; F 4.00 on a scale of 1-7).

In the EOF survey responses, one participant linked unstable airflow of configuration E to panic under high work rates. Device-specific feedback highlighted the interaction between facepiece design and exertion. One NTF participant remarked that while the fabric construction of configuration F “felt good on your face,” it collapsed under exertion.

Participants also noted the tradeoff between bulk and airflow. Participants praised the airflow of configurations B-C, and B-D, but expressed that the blower unit would be difficult to integrate with full web gear in a wildland setting. Vision benefits and costs were also explicit. Participants valued the full-face protection and potential for reduced eye irritation of configuration C-D and explicitly linked its comfort to safety and sustained productivity, though participants also reported visual distortion from its curved lens. Physical interference from the air hoses in configurations B-C, B-D, and E was noted as restricting downward gaze, particularly in the hilly terrain of the NTF. Peripheral vision disruption from the high nose profile of configuration F was also noted (Supplementary Appendix: Final Analytic Themes and Usability Codes).

When worn in the intended rear waist position, the airflow controls of the B blower unit were nearly inaccessible. Participants were encouraged to innovate placement strategies, and several participants opted to strap the blower to their hydration packs. While this improved range of motion for activities that required bending at the waist, it placed the controls further out of reach, and participants described this frustration repeatedly (Figure 1B). In contrast, participants praised the ease with which they could reach the harness-mounted airflow controls of configuration F. The dilemma of finding body placements that did not interfere with movement was discussed frequently and linked to specific activities that require crouching, bending and the use of hand tools, such as cutting line and hose lays.

Participants frequently praised the low bulk and flexible placement of

configuration E, though the single clip attachment became dislodged by body movements that pushed it upwards, leading one participant to improvise a strap attachment (Figure 2b). In fact, all PAPR blower units experienced documented attachment failures during the NTF phase.

Participant discussion of hydration was nuanced. Some participants suggested integrating a hydration tube into the mask design. One participant explained that hydration was difficult to maintain during fire incidents and that adding the physical barrier of a mask could mean firefighters “drink less, and less frequently.” Several others suggested that it was important to have a head strap system that would allow them to drop the mask to hydrate, praising this feature in configurations A and B-C, suggesting this would support awareness of their own state as well as changes in conditions. One participant remarked, “I hope we’re not wearing these things in areas where we *couldn’t* breathe on our own. We should be able to pull [the mask] down and stop for a sip of water.”

Integration with Gear & Equipment

Participants and researchers frequently noted attachment instability (Figure 1a), control placement constraints (Figure 1b), and slack air hosing (Figure 1c) as integration challenges. Integration with packs, web gear, helmets, eyewear and radios decisively influenced participant evaluations. Participants frequently described air hose routing as a direct interference pathway. In the debriefs, participants described hose ridges snagging on their web gear, and interference between air hosing and fire hose bundles during the tower evolution. Several participants noted that the designs did not offer a quick release to allow air hoses to disconnect from masks easily, forcing rigid donning sequences and conflicts between air hoses and helmet straps.

During debrief discussions, participants also expressed that integration should take a systems design approach that considers the redesign of existing gear. A clear example was the redesign of skin protective heat shrouds, which would need to be redesigned to accommodate RPDs.

To contextualize these integration frictions with donning acceptability, multi-select survey responses about donning/adjustment difficulties were examined alongside agreement that “The time it takes to don the unit is acceptable.” Interference with web gear was the most frequently selected difficulty, and 70% of respondents who selected it still rated donning time as acceptable. However, when web gear interference co-occurred with difficulty adjusting belt size/shoulder straps (i.e., compounding fit-and-integration issues), agreement that donning time was acceptable dropped sharply.

One participant framed the importance of flexible placement in relation to hand dominance, stating, “Everything in fire service, [...], we do it based on muscle memory, or what side we work on. So, my radio, I wear on my left side. Like, I work my axe, my hose, the nozzle, all that stuff on the right side, the right side, so that’s why I put it on my left side.”

Participants framed poor integration as a barrier to function and also expressed concern that introducing designs prior to form factor and engineering refinements could result in compounded, widespread mistrust of RPDs.

Operational Tasks and Conditions

Across phases, participants framed acceptance as task and fire-stage-dependent, rather than absolute, noting that RPD use could align with specific smoke conditions

and activities, and must be integrated with other safety protocols.

Participants consistently linked usability requirements to operational realities, including energy management and supply logistics. A repeated point was that power systems must fit base-camp constraints. Participants referred to the radio model that is standard in the field and, in extended campaigns, commonly powered by a ‘clam shell’ supplementary power pack consisting of AA batteries loaded into a plastic shell. As one participant noted, “Every base camp’s got pallets of batteries.” Participants emphasized that battery and filter strategies must align with field contingencies such as low visibility and long shifts (Supplementary Materials: Final Analytic Themes and Usability Codes).

Survey ratings suggested that face-to-face audibility was generally rated favorably across devices with mean ratings of 5.4–6.2 on a scale of 1-7, depending on configuration, while PTT radio audibility was more variable and often lower (A 5.92; B-C 5.03; B-D 4.73; E 4.15; F 5.33). Ratings for “not needing to raise my voice” were also mixed (A 4.92; E 3.78; F 6.00), aligning with debrief emphasis that communication performance as a safety-critical requirement. One Pilot participant emphasized limitations relative to SCBA full-facepieces: “Yeah, there’s no speaking diaphragm like our SBCA mask [has] for close-range communication. So, it kind of sounds like you’re talking behind stuff...which I imagine would be even worse on a radio.” Another participant linked communication to operational safety: “Communication is always held to the highest standard—it’s part of LCES [lookouts, communications, escape routes, safety zones]. If I can’t communicate with it, I’m going to toss it aside, because being able to communicate is more important.”

User Acceptance & Design Recommendations

Across methods, acceptance was conditional and framed in terms of trade-offs. Participants articulated a clear preference for RPDs that reduce smoke exposure without introducing additional safety risks. This conditional framing was reflected in the surveys: willingness to use assuming filtration effectiveness was high overall (90% Yes; 88% device-normalized) but varied by configuration (93–97% Yes for A/B-C/B-D vs 78% for E and F). In the NTF phase, one participant summarized the need for form factor refinements “I don’t feel that a single one that we tried would be durable enough for me to trust on strike team [. . .] if we did all of them together and took a piece from this, yes, and this and this, maybe you can build the perfect one.”

Scaled ratings also showed consistent tradeoffs: configurations B-C and B-D scored highest for breathing ease during strenuous work (6.38 and 6.10 on a scale of 1-7) but lower for non-interference with equipment/gear (3.76 and 3.43), whereas the APR showed the opposite profile (4.84 for strenuous breathing; 6.04 for non-interference). Participants emphasized modularity and interoperability as adoption pathways and described procurement lock-in as a barrier to implementation in the field.

Design recommendations raised across debriefs and open-ended survey responses included:

- **Reduce burden while preserving airflow:** Participants described B-C and B-D as delivering the most effective airflow but noted that the approximately 4 lb weight and larger form factor of the air blower would be burdensome in extended operations; several emphasized that this tradeoff could be acceptable under specific conditions if placement, web-gear integration, and attachment security are improved.
- **Prioritize secure, modular systems:** Across devices, participants

emphasized the need for universally compatible, durable attachment hardware and stowage, and codesign of corresponding gear, pointing to existing modular standards (e.g., NATO STANAG, the NATO's military interoperability standard, and Firescope, the California incident command/operations interoperability requirements) as models for field-ready systems. Consistent with this concern, all blower units became dislodged and fell off during the NTF hose lay when participants were frequently bending and crouching, and some participants reported binding and pressure discomfort in these positions.

- **Improve placement and access to controls:** Participants suggested alternative attachment strategies (e.g., back mounting with front-accessible controls, pocket/pouch mounting, durable clip web gear mounting, and flexible/ambidextrous placement options) and design features to prevent air-intake blockage under hose packs (e.g., a rigid spacing hood or standoff).
- **Add quick-release and universal fittings:** Participants prioritized an air-hose quick release to reduce helmet-strap conflicts and rigid don/doff sequences. Several also noted that a universal 40 mm quick-release air hose interface could extend utility by allowing individually fit-tested masks to be used across SCBA/APR/PAPR configurations, including WUI operations and interjurisdictional deployments.
- **Simplify airflow control strategy:** Some participants recommended eliminating user-adjustable airflow controls in favor of a default higher airflow, while others preferred glove-friendly controls located on the mask or on a durable module that supports flexible mounting.
- **Preserve low-profile strengths while addressing performance limits:** Although configuration F was perceived as underpowered at high exertion, it was repeatedly valued for a snag-resistant, body-friendly shape, rear mask inlet, and accessible controls, suggesting that these form-factor features support acceptance when paired with sufficient airflow.

Additional illustrative quotes, organized by analytic theme and phase, are provided in Supplementary Materials: Final Analytic Themes and Usability Codes.

Discussion

This study evaluated wildland/WUI firefighter experiences with RPD using a mixed-methods approach that integrated post-exercise ratings with open-ended survey responses and structured debrief narratives. The results converge on two dominant adoption drivers: 1) stable airflow at high work rates and 2) practical integration with gear, movement, and safety-critical work practices. Importantly, favorable scaled ratings often co-occurred with critical qualitative feedback, suggesting that survey ratings in this context reflect tradeoff-based judgments rather than uniform approval of respirators worn.

Airflow stability under exertion emerged as a core usability threshold. Prior research has documented that breathing effort and CO₂ concentrations in the body increase with work rate and respirator resistance by the mechanisms of hypoventilation and rebreathing CO₂ (Louhevaara, 1984, Coyne et al. 2006), and that APRs can reduce the ability to sustain arduous wildland tasks at typical work rates (Beason et al. 1996; Driessen et al. 1992). PAPRs can theoretically reduce inspiratory

effort by delivering filtered air, but the airflow must match peak demand (Manninen et al., 1988; Popendorf et al., 1995). The results of this study emphasize the significance of this issue to firefighters: not only can airflow pulsing or inadequacy cause physiological distress (“... which induces slight panic”) but airflow can be impeded by poor respirator integration with other gear that can block air intake into the blower or pinch hoses. Participants consistently evaluated the air delivery of configurations B-C and B-D favorably, even at high levels of exertion, demonstrating it is feasible for PAPRs to meet the user demand for air supply. Furthermore, most participants perceived the breathing resistance contributed by configuration A—an APR—as tolerable, especially given that portability and quick deployment were valued by participants.

Gear integration constraints were equally influential. Across all study phases, it was observed by investigators and reported by participants that packs, radios, hose bundles, helmets, and web gear competed for the same physical space as the PAPR blower units and air hoses, and limited placement options interfered with access to controls. Participants’ narratives highlight the need for air hoses that can be detached and reattached quickly and routed to preserve head rotation and minimize catch points. Though not assessed in this research, others have found respirators can impair fine motor and visual performance when they add restriction or distraction (AlGhamri et al. 2013). In W/WUI contexts, integration challenges are intensified by long operational periods and rapid task transitions. Wildland firefighters move between short bursts of high exertion (e.g., cutting line, rescue efforts, tree felling), moderate sustained tasks (using hand tools), and prolonged lower-intensity work such as holding, often within the same operational period. Smoke exposure, ambient heat, and gear weight do not consistently co-occur with high workload. Because exertion, exposure, and thermal burden vary independently, a single fixed RPD configuration may be inadequate for the dynamic operational realities of W/WUI firefighting (Aisbett et al. 2012; Navarro 2020; Semmens et al. 2021).

Participants framed clear communication as operationally non-negotiable, and explicitly linked communication to critical safety protocols (e.g., LECS). It has long been recognized that RPDs can impede speech intelligibility, but speech diaphragms or amplification devices integrated into facepieces and the use of in-ear or other digital communication devices can improve speech intelligibility and reduce workload during RPD use (Nguyen et al. 2021; Caretti and Strickler 2003; Coyne and Barker 2014). Given the reliance of W/WUI firefighters on radio communication and the threats to life safety, RPDs intended for this application should have integrated technologies to enhance speech intelligibility.

These findings are timely in the context of evolving standards and policy discussions within fire service organizations and among regulators. Under OSHA and Cal/OSHA respiratory protection frameworks, required respirator use depends on hazard evaluation and Permissible Exposure Limits based on individual exposures within eight-hour periods in Wildland/WUI firefighting. However, exposures in excess of hazard thresholds have rarely been captured due to remote, high-exertion field conditions, and smoke and particulate profiles that are variable, mixed, and hard to characterize. This leaves respirator use in a gray area where it is often treated as voluntary rather than implemented as part of a comprehensive respiratory protection program (8 CCR § 5144; NASEM 2021; Navarro 2022). Cal/OSHA has drafted regulatory text that would require a written respiratory protection program aligned with the Respiratory Protection Standard, and it incorporates provisions intended to support operational discretion and exposure tracking under dynamic

conditions (Cal/OSHA 2022; Wilson 2024). At the federal level, proposed legislation would require the US Forest Service and Department of Interior to collaborate with OSHA and NIOSH to create suitable respiratory protection programs for wildland firefighters, and mandates RPD use when smoke exposure exceeds safety limits (Healthy Lungs for Heroes Act S.3183 2025). In parallel, OSHA has proposed an Emergency Response standard to update and replace 29 CFR § 1910.156 (Fire Brigades), so as to explicitly address W/WUI operations as part of the updated scope and incorporate NFPA 1984 by reference (OSHA 1980; OSHA 2024).

The selection of the RPD model, filters and cartridges for W/WUI firefighting has posed several challenges. While NIOSH has not certified an RPD explicitly for this application, many NIOSH-certified RPDs could be used in specific W/WUI settings, including some of the configurations examined herein (NIOSH 1995; NUSTL 2022). Typical respirator selection logics, however, are difficult to apply for W/WUI firefighting exposures because measured exposures are generally below OSHA Permissible Exposure Limits, which may not accurately capture dynamic and long-term exposures, and the disparate toxicological profiles of the exposure prevent utilization of standard methods for assessment of exposures to mixtures (Navarro 2020, Navarro et al. 2021). Though all current draft regulation under discussion incorporates all or most of NFPA 1984, the standard itself continues to evolve, as some elements have been found to be impracticable and no RPD has been certified to meet its specifications to date. Much of the recorded input during regulatory and standards development processes highlights the need to consider the human experience of RPD use in W/WUI firefighting settings (OSHA 2024; NFPA 2026).

The present study adds usability evidence to help align future RPD requirements with end-user constraints. Implications for material design and evaluation follow directly from the integrated themes. First, airflow delivery and facepiece behavior must be validated at high work rates typical of wildland/WUI tasks, not only at low-to-moderate exertion. Second, designs should prioritize multiple mounting options and accessible controls, enabling users to adapt placement to web gear configurations, hand dominance, and task sequences. Third, hose and attachment designs should minimize snag hazards and preserve head mobility. Fourth, communication solutions (e.g., speaking diaphragms, integrated microphones) should be treated as safety requirements rather than optional enhancements. Finally, participants' repeated emphasis on interoperability and modular systems suggests that procurement and standards efforts should incentivize compatibility across components and reduce vendor lock-in where feasible. Participants noted that even bulkier PAPR forms would be acceptable if donning and attachment were flexible and secure and body placements did not interfere with task required movement. This suggests that PAPRs could be applied in a number of W/WUI settings if integration is thoughtfully considered.

Even with improved respiratory options, sustained high-exertion work in smoke will depend on implementation of engineering and administrative controls (e.g., spacing, rotation, condition monitoring, and the use of CO sensors) because respiratory safety often requires exiting exposure rather than relying on respirators alone (Austin, 2008; Henn et al., 2019). For those conditions where APRs and PAPRs represent a substantial improvement in air filtration over improvised coverings such as bandannas and heat shrouds, it should be understood that they are not a complete solution and cannot protect against all toxic products of combustion or inhalation hazards in the W/WUI environment.

A key strength of this study is the use of operationally realistic task evolutions

and natural-terrain testing combined with rich narrative evidence. The mixed-methods approach enabled triangulation between scaled ratings and explanatory narratives. Limitations include phase-to-phase variation in configurations and contexts, which constrains direct statistical comparison across all conditions; the purposive nature of participant selection; and the fact that quotations reflect a specific sample of experienced career firefighters and may not generalize to all agencies or regions. Further, the studies were performed in conditions without smoke, which means participants may be more likely to provide negative feedback about the RPDs since they cannot experience the potential benefits of RPDs in a smokey environment, like reduced irritation to the nose and throat, that may be trade-offs to some discomfort associated with wearing an RPD.

Future human factors research should continue to involve firefighters in evaluating RPDs at the level of task performance, in prolonged deployments, and across fire stages. Standards-aligned testing should explicitly assess airflow stability and respiratory comfort at high work rates, donning speed, modularity and interoperability of components, material durability, accessibility of controls when in full gear, radio intelligibility, and compatibility with shelter deployment and ambidextrous tool use. Manufacturers, W/WUI Firefighters and those developing standards and policy should take an iterative approach to the development and adoption of RPDs.

Conclusions

This study indicates that respiratory protection can be adopted in W/WUI firefighting when powered devices deliver stable airflow under exertion and all devices integrate cleanly with existing gear and safety practices. Adoption is likely to remain conditional and discretionary unless RPD designs reduce interference with packs, helmets, radios, and tools, and preserve communication as a safety-critical function. Evidence from operational field testing can help align design innovation, procurement choices, and emerging standards and regulations with the realities of W/WUI work.

Data availability

De-identified data included coded excerpts of interviews and survey summaries are available from the authors upon reasonable request, subject to institutional and participant-protection constraints.

Conflict of interest

The authors declare no conflicts of interest related to the material presented in this article. Respirator E was provided at no cost by the manufacturer because it is not commercially available, but the manufacturer had no input into the study design, data analysis or the dissemination of the study findings.

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Supplementary material

Supplementary material is available at:
Supplementary Figures

Supplementary Figure S1. Summary of post-exercise survey drivers of overall experience

Note: Items most closely correlated with the question “Assuming the device is effective for chemical and particulate filtration, would you be willing to use it if the task or environment requires its use?”

Alt text, Supplementary Figure S1: A bar chart summarizing post-exercise drivers of overall experience



Supplementary Figure S2. Full wildland turnout with hose pack context illustration for PAPR E configuration (representative). The PAPR E blower is the cylinder worn on

the belt, next to the radio, under the left arm.

Alt text Supplementary Figure S2: A participant stands slightly bent forward wearing a heavy hose pack and other gear.

Supplementary Table S1. Pre-exercise and post-exercise survey. Questions answered with an Agreement Scale used a seven-level scale (Strongly Disagree, Disagree, Somewhat Disagree, Neutral, Somewhat Agree, Agree, Strongly Agree) when not otherwise specified.

Pre-Exercise Instrument (PAPR Usability)

Instructions: Please indicate your level of agreement with the following statements based on your experience.

Q1 I have previous experience using a powered air purifying respirator (PAPR). Agreement Scale

Q2 I have previous experience using a SCBA (Self-Contained Breathing Apparatus) or APR (Air-Purifying Respirators). Agreement Scale

Q3 I was able to don the PAPR and facepiece without extra instructions.
Agreement Scale: Strongly Disagree (Could not put it on without significant assistance), Disagree (Needed some instructions or minimal assistance), Neutral (Some uncertainty but mostly independent), Agree (Managed independently with minor difficulty), Strongly Agree (No assistance needed, very easy to put on)

Q4 The time it takes to don the unit is acceptable. Agreement Scale

Q5 The PAPR could be adjusted to fit securely without bunching clothing. Agreement Scale

Q6 The facepiece fit properly. Agreement Scale

Q7 The PAPR allows for a tight facial seal. Agreement Scale

Q8 The head or helmet straps and neck straps could be adjusted to fit comfortably.
Agreement Scale

Q9 Please select any difficulties you had with putting on or adjusting the respirator. (question absent in pilot) [Multiselect]:

- Difficulty with tubing
- Interference with web gear
- Difficulty adjusting belt size or shoulder straps to fit

Q10 Briefly describe any difficulties you had with the facepiece fit and seal. [Short answer]

Supplementary Table S1. Survey: Pre-Exercise; Post-Exercise (Page 2 of 3)

Post-Exercise Survey Instrument (PAPR Usability)

Instructions:

Please indicate your level of agreement with the following statements based on your experience using the respirator during the exercise. Unless otherwise noted, responses were recorded on a 7-point Likert scale.

Overall Experience & Acceptance

Q1. How would you rate your overall experience with this device? Very Poor, Poor, Adequate, Somewhat Good, Good, Very Good, Excellent

Q2. Assuming the device is effective for chemical and particulate filtration, would you be willing to use it if the task or environment requires its use? [Yes/No]

Comfort & Fit

Q3. The PAPR was comfortable to wear for the duration of the exercise. Agreement Scale

Q4. The PAPR did not cause excessive facial irritation. Agreement Scale

Q5. The overall comfort (feel) of the device was excellent. Agreement Scale

Q6. Please describe any discomfort or pressure points you experienced while wearing the respirator. [short answer]

Breathing & Airflow

Q7. It was easy to breathe through the respirator while resting. Agreement Scale

Q8. It was easy to breathe through the respirator while walking. Agreement Scale

Q9. It was easy to breathe through the respirator while working strenuously. Agreement Scale

Q10. It was easy to adjust the airflow as needed. Agreement Scale

Q11. The facepiece did not have to be readjusted to ensure a tight seal during vigorous tasks. Agreement Scale

Q12. There were no apparent leaks in the facepiece while moving vigorously. Agreement Scale

Q13. The respirator could be worn throughout the exercises without affecting the ease of breathing. Agreement Scale

Q14. Please describe any difficulties or limitations you encountered with breathing while using the respirator. [short answer]

Q15. I was able to hear others clearly through the facepiece during face-to-face communication. Agreement Scale

Supplementary Table S1. Survey: Pre-Exercise; Post-Exercise (Page 3 of 3)

Integration with Gear & Equipment

Q16. The PAPR and its components did not interfere with other equipment or gear during exercises. Agreement Scale

Q17. I was able to comfortably wear my preferred corrective and/or protective eyewear with the PAPR. Agreement Scale

Q18. Please describe any difficulty you encountered in wearing the PAPR with your personal gear. [short answer]

Communication

Q19. I was able to hear others clearly through the facepiece when using push-to-talk (PTT) radios. Agreement Scale

Q20. I did not need to raise my voice to an unacceptable level to be heard clearly by others. Agreement Scale

Vision & Mobility

Q21. The mask or shield did not obstruct my line of sight at near to intermediate range (within 6 feet). Agreement Scale

Q22. The mask or shield did not obstruct my line of sight at far range (beyond 6 feet). Agreement Scale

Q23. The PAPR did not inhibit my range of motion. Agreement Scale

Task Performance

Q24. The PAPR did not interfere with job performance, including: (a) Use of hand tools (b) Navigation of confined or enclosed spaces. Agreement Scale

Durability & Adjustability

Q25. The facepiece and its straps and components seemed durable. Agreement Scale

Q26. The PAPR assembly and its straps and components seemed durable. Agreement Scale

Q27. The straps were easy to adjust and did not loosen during strenuous tasks. Agreement Scale

Supplementary Table S2. Semi-Structured Debrief Guide

- Is there anything you'd like to add or clarify from your survey responses?
- Is there anything we haven't asked that you think we should know?
- Were there any tasks where you felt the respirator was particularly helpful or particularly challenging?
- Was there anything about using this respirator that stood out to you, either positively or negatively, that wasn't covered in the survey?
- Did you notice any pressure points or discomfort over time?
- How did the respirator affect your mobility and range of motion?
- Modify movements?
- Did you make a different mounting choice on first v/s second pass (for PAPR B)?
- Did the respirator impact your communication? Do you think it might impact communication with your crew? If so, in what way?
- Were there any issues with fogging, visibility, or airflow that we haven't covered?
- If you were designing a respirator for wildland firefighters, what's the most important thing you'd focus on? (encourage input from each participant).
- If you were to design an ideal PAPR for WUI, assuming it functioned well and was rugged enough to withstand conditions, what would it be? What would you want manufacturers/designers to know?

- Is there anything we haven't asked that you think we should know?

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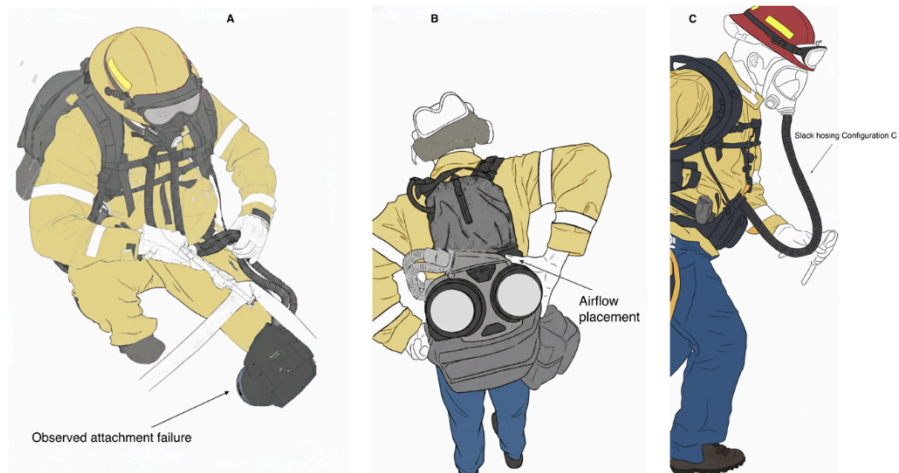


Figure 1: Common integration issues observed during operational field testing. (A) Observed attachment instability, PAPR B. (B) Control placement, PAPR B-D. (C) Slack hosing, Configuration B-C.



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Supplementary Figure S1. Summary of post-exercise survey driver items of experience

Note: Items most closely correlated with the question “Assuming the device is effective for chemical and particulate filtration, would you be willing to use it if the task or environment requires its use?”



Supplementary Figure S2. Full wildland turnout context illustration for PAPR E configuration (representative).

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