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Technical Report 200

Constructing a Predator Exclusionary Fence to Protect Hawaiian Petrels (*Pterodroma sandwichensis*) at Hawaiʽi Volcanoes National Park

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Abstract

Remnant nesting colonies of endangered Hawaiian Petrels, or 'Ua'u (*Pterodroma sandwichensis*), on Mauna Loa, Hawai'i Island, are primarily threatened by feral cats. At Hawaiʽi Volcanoes National Park, trapping success has been variable due several challenges, including the difficulty of accessing remote, subalpine (9,000') sites. To create a core area free from cat predation, the park, with support from multiple partners, constructed a five mile barrier fence encircling 640 acres of the richest known concentration of subalpine Hawaiian Petrel nests on Mauna Loa. We report on key fence design elements, pilot studies, step by step construction details, concurrent and subsequent monitoring, and lessons learned throughout the project for the benefit of other managers considering exclusionary fencing.

Introduction

The Hawaiian Petrel, or 'Ua'u (*Pterodroma sandwichensis*), was once one of the most numerous seabirds in the main Hawaiian Islands. Due to sheer numbers, this and other seabird species likely were ecologically significant as a source of marine nutrients for generally impoverished tropical soils (Loope 1998). Hawaiian Petrels also had an important place in native culture: Hawaiians harvested chicks and adults as a food source. These endangered birds still persist in remnant colonies at the margins of their former range—generally at high elevations or on steep slopes where nesting birds are best able to evade introduced mammalian predators. Here, they nest in underground burrows, coming and going after dark. The female lays a single egg in early June. Both parents take turns incubating for approximately 60 days and then feed the chick until it fledges in November (Simons et. al. 1998).

Figure 1 Hawaiian Petrel chick exercises wings outside of burrow

On Hawai'i Island, the subalpine regions of Mauna Loa within Hawaiʻi Volcanoes National Park (HAVO) harbor the only known surviving Hawaiian Petrel nesting colonies (Figure 1). The primary threat to this species is predation by introduced small mammals. Since their discovery in 1990, these subcolonies have been depredated by feral cats (Hu et al. 2001), and this threat remains the most serious impediment to survival of the park's population (Figure 2). The problem is particularly severe because Hawaiian Petrels have a K-selected life history (late maturity, low annual reproductive output - a single egg clutch - and long lifespan) (Judge 2012), and, while chicks are taken (Figure 3), predation appears to be focused primarily on adult birds (HAVO unpublished data).

Figure 2 Adult Hawaiian Petrel depredated at burrow by cat

Figure 3 Cat emerges from burrow with Hawaiian Petrel chick

The NPS and the University of Hawaiʻi's Pacific Cooperative Studies Unit (PCSU) conducted petrel inventories in subalpine habitat in 2006-2007. Although field crews found no significant new subcolonies, scattered nests do persist across an elevational band within HAVO, and available nesting sites are plentiful. All total, the park has identified approximately 95 nests that are currently active, and about 60 of these are in areas that the park manages and regularly monitors. Thus, there is opportunity for this species to recover within the park.

Although the park has trapped for predators in known petrel areas with varying intensities and durations for approximately 15 years as funding permitted, live traps cannot fully protect these colonies. In some years, feral cats have continued to enter these remote colonies, evading traps for some or most of the protracted breeding season. A single cat can kill multiple seabirds and devastate a subcolony. In addition, most subcolonies on Mauna Loa are in extremely remote areas where the terrain is precarious (due to the unstable lava substrates), and access is typically limited to helicopter, limiting the feasibility of trapping. While predator control remains an important tool to protect breeding Hawaiian Petrels, it still can permit unacceptable levels of adult mortality that push the population into decline (Simmons 1984). To ensure the species' survival within HAVO, the park decided to create a core area free from predation, using recent advances in predator fencing. The objective was two-fold: to secure and bolster the colony with the highest density of nests and to eventually increase recruitment in other areas of Mauna Loa from which the species has been extirpated.

Choosing the Fence Design

Two designs were considered: the Xcluder® and the Arid Recovery designs. Xcluder® (https://www.xcluder.co.nz/) is a New Zealand based company that designs fences to exclude a full range of predators including all mammalian predators residing in Hawaiʻi. Their design consists of a fence base built to support predator proof mesh with a buried skirt and a rolled metal hood. Arid Recovery (http://www.aridrecovery.org.au/) is a conservation and research initiative in South Australia that designed a fence to exclude feral cats, foxes and rabbits to protect a suite of unique, endangered small mammals. Their design consists of a 1.8 meter mesh fence with mesh skirting and a floppy mesh overhang.

The Xcluder® was ruled out based on the following concerns: 1) the successful construction of this design was unlikely primarily due to the extremely uneven terrain 2) the solid metal hood was expected to deteriorate rapidly due to wind and volcanic emissions 3) the primary threat to the Hawaiian Petrel is feral cats, therefore the level of construction required to exclude mice was not worth the additional cost. At the time of consideration, the cost estimates were $90 per meter for the Xcluder® and $45 per meter for the Arid Recovery design.

We chose the design developed by Arid Recovery Project because of the potential to construct it on the park's challenging terrain and the successful results of field trails with feral cats (Moseby 2006). This fence is 1.8 meters high, with a 60 cm arc extending up and out from the top to prevent climbing or jumping over and a 30 cm buried skirt to prevent digging under (Figure 4). Their design consisted of a base fence of posts with seven horizontal strands of smooth wire covered with hexagonal mesh. They affixed a heavy gauge, galvanized mesh to the base fence, with a smaller mesh opening (30mm) for the bottom section to prevent ingress by small rabbits and a larger mesh (50cm) above rabbit height. The mesh was buried to prevent digging underneath and formed a floppy, outward arc at the top.

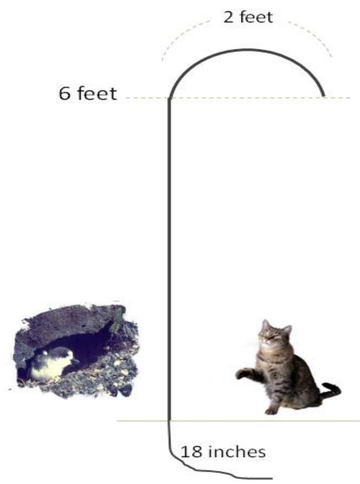

Figure 4 Key components of Arid Recovery fence

While the Arid Recovery program found an electrified version of this design contained all feral cats in field trials, they also used a non-electrified version for an exclosure of 28 km^2 and found it to be cat free after 3.5 years (Moseby 2006). Follow up conversations with Arid Recovery staff indicated that the expanded exclosure, now totaling 60 km^2, sustained only a single breech (as of 2009) resulting from high drifting sand which notably reduced fence height (K. Moseby pers. comm.).

Refining the Design

Once the design was selected, the park conducted preliminary trials to address concerns regarding the feasibility of predator exclusionary fencing for endangered species protection. The first task was to develop mitigations to reduce the potential for bird strike. Additionally, the park developed modifications to the design and materials to accommodate the rough, uneven substrate and the corrosive volcanic environment. To test these design modifications, the feasibility of construction, and the effectiveness of the design, a small scale, pilot fence was built in an accessible area to protect breeding Nēnē.

Developing Bird Strike Avoidance

In 2003, the park developed strategies to increase the visibility of the fence to the night-flying Hawaiian Petrels. HAVO and PCSU collaborated on a project evaluating the ability of Hawaiian Petrels to avoid a novel fence and the efficacy of fence markings in alerting birds to the fence (Figure 5). Findings indicated that Hawaiian Petrels were able to make adjustments to flight when presented with new fences, however, a single strike on a simulated fence (netting that resembled hog wire) during foggy weather suggested that avoidance may be more difficult during poor visibility. The addition of white linear flagging to mock fences showed a suggestive difference in avoidance behaviors between flagged and unflagged fences, indicating that birds undertook avoidance measures earlier when approaching a marked fence (Swift 2004). Based on these findings, white linear markings are now used on all exposed park fences that may be transited by Hawaiian Petrels. The park has used several different types of linear white marking to date including cable pulling tape, vinyl under sill and modified polytape. We are currently using the latter, commonly referred to as cool tape, which is a modified version of electrified polytape used for horse fencing, without the wire.

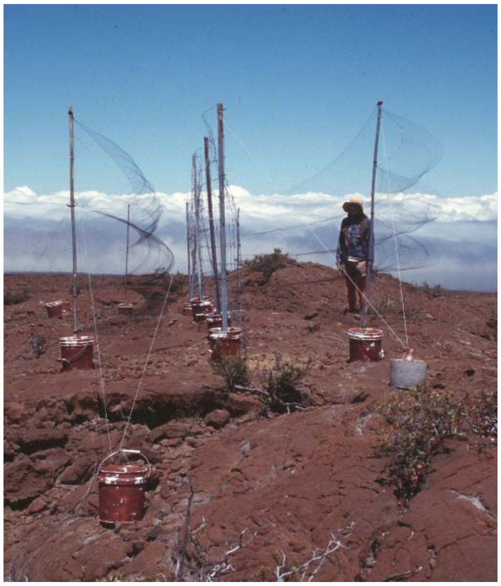

Figure 5 Testing fence markings on Mauna Loa

Pilot Fence - 'Āinahou

In 2004, a 13 acre (900 meter perimeter) pilot fence was constructed as a replacement for a deteriorated predator resistant fence protecting Nēnē nesting habitat. In addition to protecting key breeding habitat, this fence allowed NPS staff to assess the feasibility of constructing this design on the rough volcanic substrate and to monitor the longevity of the materials in our corrosive environment. Techniques for securing the skirting to the pāhoehoe substrate and forming a base for the arc using hog wire were developed during this project.

Key Modifications

While maintaining the primary design specifications, HAVO staff made several key modifications to suit the rough, undulating substrate and the corrosive, volcanic environment.

Key modifications included:

1) Two rolls of hog wire were used for the base fence, rather than seven strands of smooth wire, to add stability and strength on the uneven terrain (Figure 6).

Figure 6 Modified fence design at HAVO

2) The hog wire was extended up to a 6 foot height then bent out slightly (1-2 eyes) to form a support base for the floppy arc (Figure 6). This reduced the number of smooth wire arc stays required.

3) PVC coated hexagonal mesh was used rather than galvanized mesh to increase the longevity of the fence exposed to the park's corrosive volcanic environment (Figure 7).

Figure 7 PVC coated hexagonal mesh

4) In areas where the skirting could not be buried, it was affixed directly to the substrate (Figure 8).

Figure 8 HAVO design modification; skirted affixed to surface

A key lesson learned during this pilot project was to use hog rings with a coating, such as Bezinal or Galfan, to affix the mesh to the hog wire to reduce corrosion at contact points. Initial hog rings were not coated, and required replacement at 1-2 years (Figure 9). Understanding the reactions between different types of metals is key to selecting the best hog rings, anchor wires, arc supports and any other metal items that will be in contact with the hog wire. The park now uses Bezinal coated materials to eliminate corrosive reactions.

Figure 9 Non-galvanized hog rings after one year

The fence successfully excluded cats, pigs and mongooses until 2016 (12 years) when breaks in the mesh were discovered near the ground. At that time, mongooses were detected inside, however cats had not breached the pen. The mesh stood up well until this breach, and the only sections that have failed are low to the ground, and may have resulted from weed-eater damage.

While this fence is experiencing some level of deterioration after 14 years, it remains largely intact and with patching will continue to exclude predators until it is replaced. As it is located in proximity to two volcanic vents (six miles from Halemaʽumaʽu crater and eight miles from Puʽu ʽŌʽō), it has been exposed to high levels of volcanic emissions which notably increase the rate of deterioration and rust formation.

Pilot Fence - Ohaikea

A second fence was constructed in 2012-2013 for the protection of Nēnē due to the success of the ʽĀinahou fence (Figure 10). In preparation for the large scale Mauna Loa fence, a cost saving modification was included in this fence design as a trial. The top roll of hog wire was replaced with a custom manufactured product, referred to at the park as "sheep wire", which has a wider spacing between vertical wires (18-24") and comes at a significant cost savings. This wire was originally used to increase the height of the park's existing 4' fences to 6' to stop ingress from encroaching sheep. This modification proved unsuccessful as the wider spacing meant the wire was less rigid and therefore did not sustain the weight of the floppy arc (Figure 11). As a result, additional wire arc supports had to be added which required a notable increase in labor and a decrease in floppiness of the arc. It was determined, however, that the sheep wire could be used for the lower roll as it was sturdy enough to support the mesh and allowed added flexibility to form fit the lower roll to the undulating landscape.

Figure 10 Nēnē family within corrected Ohaikea exclosure

Figure 11 Sheep wire did not support arc

Lessons learned from pilot fences:

1. By forming the beginning of the floppy arc with hog wire, few smooth wire stays are needed, allowing the arc to remain floppy.
2. Sheep wire is not sufficient for the base of the arc, but may be substituted for the lower portion of hog wire, particularly in areas where pig pressure is not expected.
3. The hog rings should be coated (Bezinal or Galfan) to avoid corrosion at contact points with the hog wire.
4. The PVC coating on the hexagonal mesh is durable, however, if this coating gets scratched off or nicked the wire is more susceptible to rust. To minimize exposing the inner wire, we bent the mesh to conform to hills and valleys along the line, rather than cutting and piecing.
5. Mongooses were successfully excluded until damage to the mesh near the ground occurred, allowing access. Workers should use caution to avoid damage to the PVC coating when clearing vegetation along the fence.

Mauna Loa Fence

Construction Sequence

From March 2013 to May 2016, Hawai'i Volcanoes National Park constructed a 5 mile (8 km) long cat barrier fence around the primary ‘Ua’u (Hawaiian Petrel) colony. The completed fence encircles over 600 acres (250 ha) of the richest known concentration of subalpine Hawaiian Petrel nests on Mauna Loa, and spans from approximately 8200’ to 9600’ (2500m to 2925 m) in elevation.

1. Fence line routing and survey

An initial route was mapped based on known nesting habitat and borders with a’a flows. A three person team surveyed the route for petrel nests, rare plant and archaeological sites. The survey corridor was 50 meters wide, to allow for adjustments to the exact line based on survey findings and/or terrain. After the survey was complete, the fence leads flagged the actual route, making adjustments within the corridor as needed to accommodate the fence. The line was routed to include a minimum 50 foot buffer from nests and to avoid high ridges to reduce the potential for bird collisions. The routing was placed along low areas to the degree possible; efforts were made to avoid higher ground outside, but in proximity to, the fence.

2. Preparing the route

The majority of the route was across unstable a’a flows. To stabilize the line for construction the a’a had to be pulverized to facilitate walking and post pounding. A crew of 10 spent 7 days preparing a 1.5 x 8,000 meter construction corridor. The crew used sledge hammers to pound the a’a into a workable condition (Figure 12). The first sledge hammers had fiberglass handles however, they were promptly replaced with wooden handles to reduce the excessive vibration associated with the fiberglass. Personal protective equipment for this portion of work included: knee pads, shin guards, protective cups, leather boots, leather gloves, long pants, eye protection.

Figure 12 Fence crew pulverizing the route

3. *Installing the posts*

Over 3,900 posts were installed along the route using gas drills and post pounders (Figure 13). Crew worked in groups of 5-6 with people assigned to lining up the posts, drilling (Figure 14) and setting and pounding posts rotating assignments throughout the day to avoid fatigue. Personal protective equipment included leather boots, long pants, leather gloves, eye protection and hard hats.

Figure 13 Lining up and setting the posts

Figure 14 Drilling holes to sink the posts

4. Attaching bird visibility tape

In an effort to alert birds to the new posts during the upcoming breeding season, and to pre-condition them to the coming fence, linear white tape was installed upon completion of post installation (Figure 15). Two strands of cool tape (polytape) were attached to each post at the top (6') and midway down (3'), via 3" plastic T-post insulators (Figure 16). The insulators were used to hold the tape away from the mesh to reduce wear from rubbing on the fence. This type of insulator attaches to the back of the T-post and was selected so that the cool tape could be attached in advance of the fencing. Tape was twisted between each insulator to promote movement to increase visibility. Over twisting may result in too much slack; 1-2 twists between insulators is sufficient.

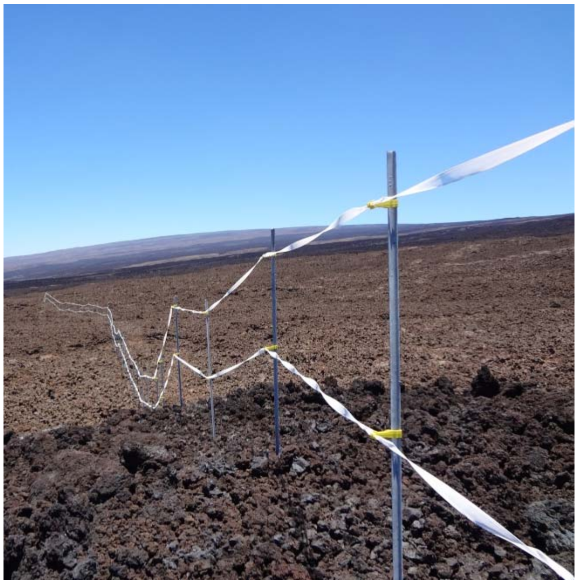

Figure 15 White cool tape at two heights

Figure 16 T-post insulator to reduce friction

5. Attaching hog wire

Hog wire was used as the base for attaching the hex mesh. Two rolls were attached, one above the other, to a height of roughly seven feet (Figure 17). The top foot (roughly) was bent out to form the base of the floppy arc. A gap was left between the two rolls to provide the flexibility to adhere to the ground undulations while allowing for a consistent overhang at the top to provide the base of the arc. The mesh sufficiently covered the gap and was notably overlapped to avert potential breaches. Hog wire was attached to the T-posts using Bezinal coated fence clips. On the aʻa sections, the bottom roll of hog wire was not anchored to the substrate; on pāhoehoe sections anchors were installed to stabilize the skirting.

Figure 17 Two heights of hog wire for stability

6. Attaching mesh to hog wire

Hexagonal mesh was attached to the hog wire using hog rings. Bezinal coated hog rings were applied using both manual and pneumatic tools powered by CO2 (Figure 18). To keep from tipping, the CO2 cylinders were secured to the fence at each worksite using a bungee cord (Figure 19). Two heights, 5 foot and 6 foot, were attached one above the other. Mesh was overlapped a minimum of 8 inches and securely attached at multiple levels along the join. The bottom roll was attached leaving 1.5 – 2 feet of mesh along the ground to form the skirt. The upper roll was attached with roughly 2 feet of mesh available at the top to form the arc.

Figure 18 Attaching mesh to hog wire using hog rings

Figure 19 Using the CO2 powered hog ring tool

7. Constructing the mesh skirt

The fence route was largely on rough, aʿa lava, however, some segments crossed over varying pāhoehoe flows. The fence crew developed strategies for securing the skirting to the different types of flows to ensure that it provided adequate barrier against predators. On the aʿa, the crew removed loose rock and pulverized remaining rock to solidify the spaces underneath the skirt. Then they laid the skirt down, angled outward away from the fence, and covered it with additional pulverized and some heavier pieces of aʿa (Figure 20). Care was taken to angle the skirt downward, and to avoid piling rocks too high atop the skirt, and/or out beyond the edge of the top arc, to avoid shortening the overall height of the fence. On the pāhoehoe sections, the skirt was pressed down to conform to the lava and then attached to the surface using a nail gun (Figure 21) using .27 caliber charges (red or yellow, rated 4-5, depending on substrate) and loaded with 4” nail and 11/2” washers. Nails were driven in as needed to ensure the mesh stayed tight to the lava surface.

Figure 20 Stacking rocks to secure the mesh skirt

Figure 21 Attaching mesh skirt to surface using nail gun

8. Constructing the floppy arc

The top two eyes of hog wire were used to form the base of the floppy arc. The hex mesh was attached to the bent out hog wire using hog rings (Figure 22). A formed arc, made of smooth wire, was inserted as needed to form the outer edge of the arc. It is critical to the design that the arc remains flexible; in the event a cat attempted to jump and grab the arc, it would flex down and discourage the animal from getting a secure hold to climb. The arc should be stable enough to hold its form and maintain the distance from the fence (not droop down) but should remain flexible enough to bend down and spring back up into position when batted at with one’s hand (with roughly 6 inches of play). It was difficult to maintain exact heights and arc lengths given the significant undulations of the substrate in this area, therefore, modifications were made as needed. For example, in some areas, more hog wire was available for the arc than needed. In order to maintain the floppy edge, the mesh was only attached to the hog wire at the base, and the outer section was left to hang loose at the edges, below excess hog wire.   In other cases, slight bends of the fence line required the splicing in of additional mesh to complete the arc and while maintaining the flexibility (Figure 23).

Figure 22 Forming the floppy arc

Figure 23 Splicing in mesh as needed

9. Attaching deterrent devices

In addition to the double strands of white linear tape, we attached various commercial bird deterrents to the hoop at roughly 15 meter intervals. Products included the Firefly II, Bird Mark and Fence Flags and included a combination of white, reflective and glow-in-the-dark materials (Figure 24). All devices were installed to allow for flapping movements, as well to increase visibility. Initial methods were modified due to challenges in attachment. The Firefly II came with a stainless steel S-hook that was looped through the mesh and clamped shut with pliers. The S-hook was particularly thick, however, and crimping it tightly was difficult, therefore within the first few years we found several Firefly II deterrents on the ground, likely due to the mesh sliding through the gap in the S-hook. The Bird Mark was attached using a stainless steel O-ring; however, the long overlap was cumbersome and in some cases, the mesh may have been lodged in the overlap of the ring, rather than fed all the way through, resulting in a portion of Bird Marks falling to the ground within the first three years. Currently we are reattaching devices using heavy duty, UV resistant cable ties applied through the mesh to the hog wire to avoid excessive rubbing on the PVC coating of the mesh (Figure 25). Bird strike surveys are conducted along key sections of fence on all monitoring trips and around the entire fence on annual inspections. No bird strike has been detected.

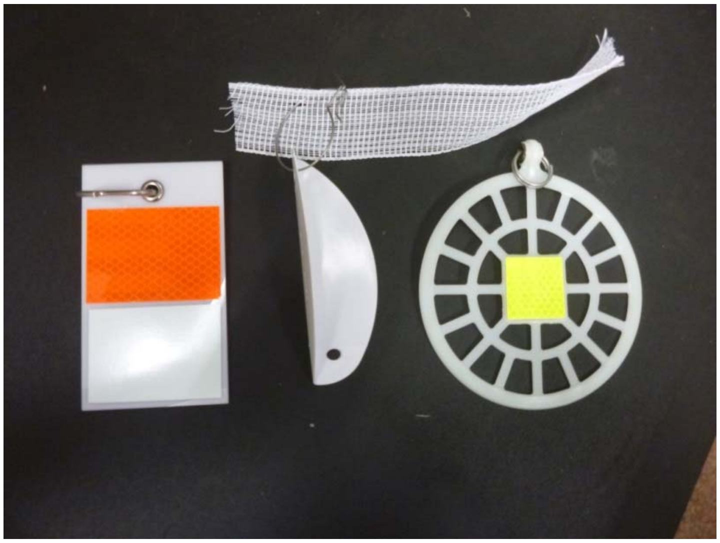

Figure 24 Firefly II, Fence Flag and Bird Mark; Cool tape on top

Figure 25 Attaching the deterrents

10. Installing the gates

Eight gates were installed at intervals around the perimeter, to allow staff to pass in and out of the fence freely for fence inspections, maintenance and other purposes. Gate locations were determined ahead of construction. During post installation, a set of T posts was placed four feet apart at each of the eight locations to support the gate frames. The hog wire was wrapped onto each of these posts, leaving a gap in the middle. The PVC mesh was attached right across the opening so that the floppy arc and skirt were contiguous. The gates and frames were constructed with galvanized pipe and covered with 2” x 4” hog panels and PVC hex mesh. The frames were installed from behind the existing mesh and secured to the T posts (Figure 26). The gates are two feet wide by four feet high and sit flush within the frames (Figure 27). The bottom of the gates sits 20” above the ground and the top is roughly 6” below the height of the fence so that the upper and lower portions of PVC hex mesh (including the skirt and floppy arc) are contiguous.

Figure 26 Attaching the gate frame to the T posts

Figure 27 Alternate view of the gate

11. Removing high spots

While careful routing was implemented at the beginning of the project, not all high spots could be avoided outside of the fence. Upon completion, survey was conducted around the outside of the fence to identify high spots within 8 feet of the perimeter. Once identified, these high spots were either (1) removed by pounding/pulverizing or (2) covered in coiled smooth wire to prevent a cat from using the higher area to launch onto the top of the arc (Figure 28).

Figure 28 Smooth wire coiled on high spot

12. Fence inspections

Key portions of the fence were checked for bird strikes multiple times per season during monitoring and predator control trips; no strikes or evidence thereof were observed. Complete fence inspections were conducted annually; thus far the only required maintenance has been to replace fallen bird deterrent devices and reconnect occasional broken strands of white marking tape. Due to the potential for high amounts of water running through the lower corner of the fence during extreme rain events, this site was checked as needed following major storms. A debris trap that was installed to stop rocks and other items from washing down and piling up again fence has successfully protected fence and skirting below from impacts during heavy rain events (Figure 29). The fence remains in good condition at this time (2.5 years after completion, 5.5 years after the start of construction). Routine fence inspection and repair trips will continue annually, at a minimum, and more frequently if potentially damaging situations arise.

Figure 29 Debris in trap in a wash out area

13. Materials used

- T posts, galvanized, 8.5 – 9 feet
- Hog wire, Bezinal coated
- Anchors (construction pins)
- Fence clips, Bezinal coated
- Hexagonal mesh, 1”, PVC coated (CE Shepherd)
- Hog rings, #16GF110, Galfan coated (King Hughes Fasteners)
- Smooth wire, 9 gauge, Bezinal coated
- Cool tape (Polytape), 1.5” width (special order from Northwest Fence)
- Plastic insulators, 3”, back of T-post mount
- Bird deterrent devices (Firefly II, Bird Mark, Fence Flag)
- UV resistant cable ties, 8” long

14. Specialized tools used

- Wooden handled and B.A.S.H.® unbreakable sledge hammers
- Rock drill, gas powered, Cobra Combi
- Post pounder, 35 pounds
  Pneumatic hog ring pliers, CO2 powered. Two models used: KCT-C1-48 (www.agwholesalers.com.au) and HC716 (King Hughes Fasteners; www.hogrings.com)
- 20 pound refillable CO2 tanks with bungie cords for stability
- Manual hog ring pliers: model = Ring-It, 9/16 compatible (www.hogrings.com)
- Nail gun, Ramset (4” nails and 1 ½” washers)

Lessons learned from Mauna Loa fence construction:

1. Different substrates require customized skirting techniques, and projects should allow time to develop or refine and trial these.
2. For remote projects, allowing the fence construction crew to practice together on a smaller project or a short demonstration section, if time and funds permit, may result in faster and smoother project start-up.
3. Work is most efficient with a larger crew that can be split into two teams so personnel can alternate jobs to decrease fatigue.
4. When the fencing work is very demanding, as in this case--high elevation, extreme weather and temperature conditions (rain, cold, high winds, and/or very hot and dry), and physically demanding work (e.g. pounding posts into rough, volcanic substrate)—consider alternating bouts of fence work with less demanding jobs to prevent injuries and time lost.
5. Provide the construction crew with the best available tools for the job. Initially, fiberglass handled sledge hammers were used, however, the vibrations caused discomfort and increased potential for injury, therefore alternate hammers (wooden handle or anti-vibration necks) were purchased.
6. Actions to minimize the threat of bird strike appear to be effective, based on monitoring to date. These include judicious fence routing (avoiding high spots and giving known nests wide berth when possible), adjusting the sequence of construction (erect and mark all posts first; finish marking all completed sections as they go up), and using a variety of commercial diverters to increase visibility.

Construction Logistics

Timing of work

In order to minimize disturbance to the petrels, construction was limited the non-breeding season (mid-December through May). All pulverizing, rock drilling and post pounding was completed by March, before the birds were back in the area. Less disruptive work occurred as late as May in some years, with specific mitigations incorporated into camp protocols (minimal use of lights) to ensure the nocturnal bird behaviors were not disrupted. Due to timing restrictions, the construction spanned four non-breeding seasons (2013-2016). Construction was completed during 23 week-long camp trips, with crews of 6-12, over the four year period. The construction of this fence design was extremely labor intensive; this combined with the high elevation, temperature extremes and inordinately difficult terrain made for an extremely challenging project. During construction periods, care was taken to avoid scheduling work trips in back to back weeks to reduce crew fatigue, injury and burnout.

Material and personnel transport

All personnel, camp gear, materials and field equipment were flown to and from the work site by helicopter. Helicopter operations were conducted at the beginning of each work period to bring in materials and supplies needed for the current phase of construction (Figure 30); additional flights occurred throughout the work period to shuttle work crews and gear in and out and to haul in additional material as needed. Fence materials were delivered via sling load to marked points along the route (Figure 31).

Figure 30 Transport of camp gear from helispot

Figure 31 Sling loading fence materials to the site

Safety and Personnel Protective Equipment (PPE)

This project posed significant challenges to work crews on all levels. The fence construction was both arduous and tedious, with a notable attention to detail required. The terrain was uneven and rough; substrate was mostly loose. The weather ranged from hot and dry to cold and wet, often in the same day. All work was conducted between 8,000 and 10,000 feet in elevation. The site required helicopter access for all personnel, gear and fence materials and all construction work was conducted during camp trips. Because of all of these challenges, special attention was made to ensure crew safety, reduce fatigue and minimize the risk of injury.

It was critical to ensure that crew members had the appropriate equipment and PPE available. Some items, such as gloves and boots, were destroyed quickly in the harsh environment (Figure 32); extra supplies needed to be stored at camp. Very few trees exist in the project area; crew carried umbrellas for shade and took breaks as needed during the heat of the day (Figure 33). Due to the extreme physical challenges of working in this environment, camp trips were scheduled to allow at least one week of alternate work in between trips when possible. These and other safety measures contributed to overall project success.

Figure 32 Damaged boots and gloves

Figure 33 Seeking shelter from the sun

Project Costs

The project was funded over several of years by multiple partners including the National Park Service, National Fish and Wildlife Foundation, U. S. Fish and Wildlife Service, American Bird Conservancy and Hawaiʿi Pacific Parks Association. Cost related breakdowns were as follows:

Table 1 Cost Breakdown by Category

Total	$1,033,995
Personnel	$712,539
Materials	$181,069
Helicopter	$108,098
Other	$32,298

Table 2 Cost Breakdown per Unit

Unit	Cost / Unit
Mile	$206,800
Kilometer	$123,500
Foot	$39
Meter	$129

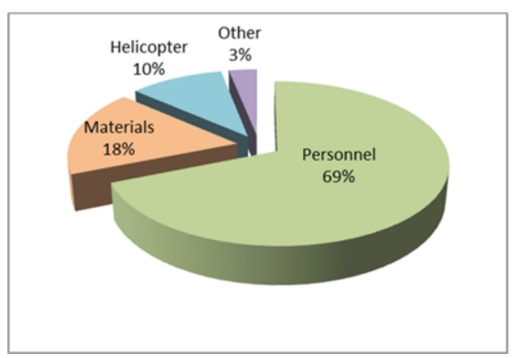

Figure 34 Percentage of total cost by category

The majority of fencing was purchased in 2012 and 2013; costs are expected to be higher at present due to factors such as increased steel prices and the potential for tariffs. Additionally, the park purchases fencing in high volume, often for multiple projects at a time. Labor was conducted by skilled NPS and PCSU employees that were shared across other projects; labor costs would be significantly higher if contracted. Based on these factors, labor and material costs for future fences should not be estimated on a project by project basis and not solely based on costs detailed in this report.

Survey and Monitoring

Hawaiian Petrel

The Hawaiian Petrel Monitoring Protocol (Hu *et. al.* 2015) was the primary method of evaluating activity within the colony. This protocol was designed to determine trends in nest density and reproductive outcomes over time by gridding the colony into 50x50 m plots and sampling a subset of plots annually. The number of grids surveyed (24) remained consistent across sampling years and was based on the total size of the area. A set number of random and legacy (based on prior known nests) grids were canvassed each sampling year. Plots were searched for whitewash defecations on the surface and crevices; small tubes and tumuli were further inspected for additional signs of petrel presence (footprints, body feathers, down). Grid surveys were conducted from 2012 through 2014, 2016 and 2017. Surveys were not conducted in 2015 due to multiple weather events cancelling trips to the site.

After active nests were identified during grid surveys, follow up monitoring was conducted to determine reproductive outcomes. Nests were categorized using the following set of standards: 1) Nest sites with fresh petrel sign (*e.g.* droppings) in the vicinity are considered "active" 2) A nest deemed "active" early in the season but with no signs of activity after October 1, is considered an "early failure or non-breeder" 3) Fledged nests were identified by the presence of chick down at the nest site or a fledgling captured on camera 4) Failed nests were defined by direct signs of failure such as an adult or chick carcass or an abandoned, depredated or scavenged egg and 5) A nest outcome was deemed unknown if it is not possible to determine if the nest fledged, failed, or if it was actually inhabited by a non-breeding pair. The latter was common in seasons when frequent rain occurred as signs of activity were typically washed away.

Monitoring occurred two to three times post survey and involved searching for signs of activity that indicated entry or disturbance. Indirect sign of petrel activity included footprints, feathers, smell, natal down and droppings. Direct signs of disturbance included adult or chick carcasses, eggs, or associated scents. Due to the inaccessibility of most chambers, direct sightings of eggs or live birds were extremely rare and therefore not typically available to indicate nesting activity. In addition to assessing on-the-ground cues, game cameras were used at a subset of nests for all or a portion of each nesting season. Cameras were directed at nest site entrances (Figure 37) to monitor adult and chick activity (Figure 38) and the presence of predators at nest sites.

Figure 35 Camera aimed at a nest entrance

Figure 36 Chick exercising wings at same nest site

Grid survey and subsequent reproductive results are shown below (Table 3.). Data analyses and density calculations for the five years of grid survey data are currently in progress and will be available in a detailed report at the end of 2019.

Table 3 Hawaiian Petrel Grid Monitoring Summary

Year	Total nests located in grids	Active nests	Fledged nests	Fledging success
2012	16	11	7	64%
2013	14	10	3	30%
2014	15	14	3	21%
2015	x	x	x	x
2016	25	19	4	21%
2017	19	12	6	50%

*Survey did not occur in 2015 due to weather. Fence was completed at the beginning of the 2016 nesting season.

Remote cameras (Bushnell Trophy-cams, various models) were used to improve nesting data within the fenced area. Videos provided detailed information on timing of adult visits, emergence of chicks and suggested which nests were either early failures or non-breeders (based on timing of adult activity). Monitoring conducted and refined during the project, both on the ground and using remote cameras, will serve as a baseline to assess the future response of this colony.

Feral Cat

Ground survey for signs of predator presence occurred throughout the project period during nest monitoring, predator control and fence construction activities (Table 4). Four depredated petrel carcasses (1 Hawaiian Petrel, 3 Band-rumped Storm Petrels) were observed during from 2012 through 2014; none have been identified since. Scat and/or cat tracks were observed annually through 2015, however no cat sign was observed in 2016-2017.

Figure 37 Cat captured on remote camera entering nest

Table 4 Cat Activity Summary

Year	Predation	Cat(s) on camera?	Comments
2012	1 BRSP	Y	
2013	0	Y	Construction began prior to this nesting season
2014	1 HAPE, 2 BRSP	Y	Two individual cats documented at nests in April; petrel feathers documented in cat scat
2015	0	Y	Only one cat in one image on one night
2016	0	N	Fence completed prior to this nesting season No cat tracks or scat observed
2017	0	N	No cat tracks or scat observed

Trapping and camera survey for feral cats continued for two years following fence completion. A total of 32 cameras were deployed for the duration of the breeding season in both 2016 and 2017, a subset of cameras spanned the interim period between seasons (January through March

2017). Cameras were placed at nest sites, traps and along then fence. While the majority of cameras were standard remote game cameras, requiring SD card retrieval, texting cameras were also utilized during both years (4 in 2016 and 8 in 2017) to collect instant information should a cat remain within the fence. From May 2016 through December 2017, over 125,000 images (both videos and stills) were collected in the colony; no cats were observed. Based on this monitoring we believe the exclosure to be cat free at this time.

Lessons learned from use of cameras:

1. Based on cats seen on camera, we now realize feral cats enter the colony more often than is suggested by the number of cat kills at monitored petrel nests.
2. Nest monitoring by cameras can clarify the status of nests that would have been scored "unknown outcome" based solely on indirect cues.
3. The sheer volume of information obtained via camera monitoring poses its own challenges: Users need to develop means to efficiently identify and record key information necessary to ascertain reproductive status and outcomes.
4. Because cameras yield so much additional information, we suggest retaining the complete videographic and photographic records for potential additional analyses in future.
5. Texting cameras were tested in the field and will be useful in providing rapid information on cat presence within the fence.

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