Via email to: Tom Huetteman
Steven Linder
Omer Shalev, and
Bob Pallarino,

Email cc to: Jinky Callado

Catastrophic Release Potential at Red Hill Fuel Storage Facility

Introduction

The Navy is conducting facility studies and preparing engineering plans for improvements at the Red Hill Bulk Fuel Storage Facility to establish a continuing operating plan extending at least several decades. The US EPA Region 9 asked PEMY Consulting LLC (PEMY) to evaluate the potential for a catastrophic release of liquid petroleum from the Red Hill facility.

Qualifications

PEMY is an engineering consultancy specializing in the design, operation, construction, and risk assessment of petroleum storage tank facilities. PEMY's core expertise in risk mitigation and failure analysis of petroleum storage infrastructure uniquely qualifies it to address the catastrophic release concern. Specifically, PEMY has extensive experience in risk assessment methods as applied to the potential for leaks, spills, and fire related incidents at petroleum storage facilities.

Risk Scenario Definition

This memo addresses the potential for a catastrophic release from the Red Hill facility. There is not a universally accepted definition of "catastrophe," but the term carries implications of (a) suddenness and (b) widespread damage. The risk scenarios discussed in the balance of this document focus on events capable of creating a large breach in the tanks, several inches in diameter, through which the tank contents could escape uncontrolled in sufficient volume and rate to create unsafe conditions inside the facility and/or impact the groundwater resource near and beneath the site.

Limitations and Guidelines for Use

Because detailed and complete information normally used in risk assessments is not currently available it is important to understand the limitations of statements made in this memo or conclusions reached resulting from this memo. PEMY does not have access to detailed facility information and operational procedures that are required to conduct a risk assessment. This memo is not a risk assessment even though it does discuss one limited aspect of risk at the Facility. Rather, this discussion should be considered an opinion subject to refinement as more details become available about the design, engineering, construction, maintenance, installation, and operation of not only the tank system but also the integral accessory facilities such as the piping, the terminal, the loading and unloading areas, the control systems, the emergency response systems, and other infrastructure and procedures.

Red Hill Facility Description

The Red Hill Bulk Fuel Storage Facility (Red Hill) is a deeply embedded system of 20 vertical cylindrical storage tanks constructed in cavities mined into a basalt ridge on the southwest flank of the Koolau Mountains. Access tunnels, surge tanks, and pump stations connect the tanks. Figure 1 (below) shows a simple overview of the facility relative to surrounding roads and topographic features.

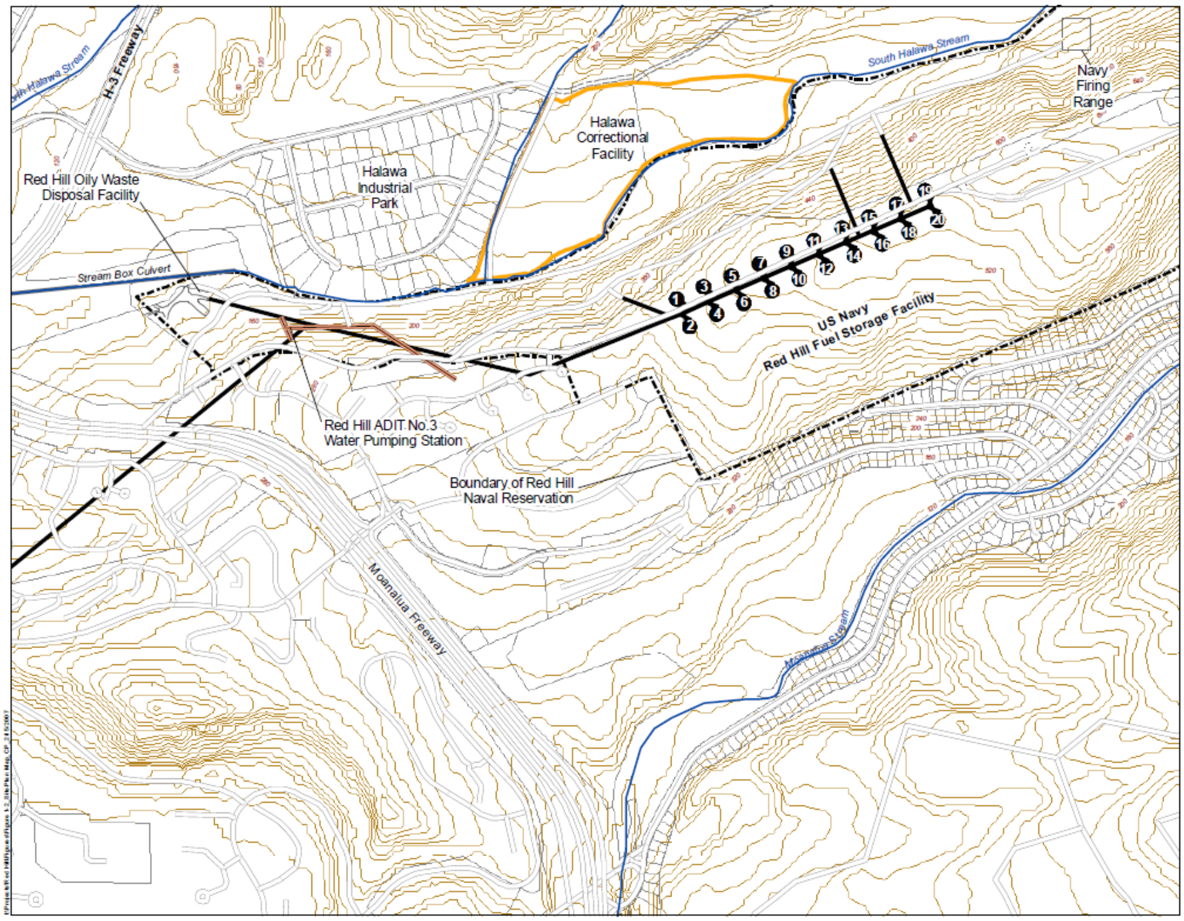

Figure 1 - Red Hill Bulk Fuel Storage Facility

Tank Construction

The 20 tanks are configured in two parallel rows. Each tank measures approximately 245 feet high and 100 feet in diameter for a storage volume of about 12.5 million gallons per tank. The upper domes of the tanks lie at depths varying between approximately 100 feet and 200 feet below the existing ground surface. The tank bottoms are about 100 feet above the local basal aquifer.

Tanks 1 to 20 were constructed by mining vertical shafts into the basalt bedrock of Red Hill to create a vault for each tank. The tank shape includes a cylindrical central barrel with dome structures at the top and bottom. The reinforced concrete liner is 2.5 feet thick on the barrel sides and up to 4 feet thick under the bottom dome. After the concrete was affixed to the bedrock, a ¼" thick steel liner was installed and any gaps between the concrete and steel were sealed with grout. The overall structure transfers hydrostatic pressures from the fuel directly through the tank body and into competent bedrock.

Tank Contents

Fuel stored in the tanks is classified as NFPA Class 2 liquids, commonly called combustible liquids. These liquids have flash points above 100 degrees F, which means that they do not generate enough vapor at the liquid surface to ignite if an ignition source is located at the surface of the liquid. The combustible liquids stored at Red Hill have a very different risk profile from common flammable liquids like motor and aviation gasoline and paint thinner.

Facility Risk Evaluation

It is a fair question to ask "what is the potential for a catastrophic release of fuel from the Red Hill facility?" Typically in formal risk assessments this question is framed in terms of annual failure probabilities or exceedance intervals, which can be incomprehensible to the layperson. A working knowledge of probability as well as a frame of reference based in experience for comparison to other kinds of risk events is necessary to engage in a detailed risk evaluation. Here we will provide an informal approach that should lead to a better understanding of the risks sufficient for the layperson to judge the vulnerability of the region near Red Hill to events that would cause a threat to public safety and environmental resources.

In order to accomplish this we must first understand what risk is. While there are many definitions, the most common and robust definition of risk is based on the work of Kaplan and Garrick (1981), defining risk as the answer to three questions:

1. What can happen?
2. How likely is it?
3. If it does happen, what are the consequences?

We will take this approach in attempting to provide insight about the risks associated with a "catastrophic release". We will ignore the thousands of minor types of incidents that can occur.

What Has Happened

Past incidents are often a good indicator of the future in terms of understanding potential failure modes. Red Hill has not experienced a catastrophic failure event over the facility's 70-year operating history. Moreover, no receptor exposure like groundwater contamination has been documented that could have resulted in illness, injury, or environmental impairment[1].

This is not say that the future can't bring about a catastrophic event. Aging equipment is known to have a failure rate that increases with time. But upgrading, inspection and testing compensate to an extent for age related deterioration. An effective operating plan, including the plan that the Navy has undertaken to develop, allocates effort and resources to maintaining an acceptable risk profile as equipment ages.

[1]Injuries and fatalities have occurred in the construction, testing and inspection of the facility that are excluded from this assessment. Those types of losses are common to all large construction projects, especially when considering the era of construction.

What Can Happen?

The approach to asking questions about risk starts with "What can happen?" Immediately, natural catastrophes such as earthquakes, storms, tsunamis and the like come to mind. As discussed in a subsequent section, earthquake risk is the natural hazard that requires detailed consideration. Many of the other hazards can be considered briefly and dismissed because of the facility's site selection and construction methods.

Flooding from torrential rainfall is not a problem since the Red Hill tanks are buried at elevations well above sea level and the access tunnels provide excellent gravity drainage if any stormwater were to infiltrate down to the tanks.

Erosion is similarly not a hazard because of the depth that the tanks are embedded in bedrock and the erosion resistance of the hard basalt into which the tanks were built.

Landslides are not a credible hazard at the site because the tanks were built into cylindrical caverns excavated into basalt bedrock. Damaging landslides do occur on Oahu, most commonly in residual soils that formed by basalt weathering over geologic time since Koolau volcano became inactive. Where landslides occur, though, the slide plane is near the boundary between surficial weathered soil (red dirt) and the underlying bedrock. The tops of the Red Hill tanks are well below the surficial soil layer and not susceptible to landslide.

Volcanic slump is a credible hazard on the flanks of active volcanoes. The Koolau Mountains, though, have been inactive for about 2 million years[2] and have no potential for slumping.

Tsunami inundation is not a hazard because the site is several hundred feet above sea level and far enough inland to be well outside the inundation zone.

Earthquake Shaking

Perhaps the most common *ad hoc* concern is the issue of earthquakes. Oahu has experienced ground shaking from several small and medium-sized earthquakes and is considered to have moderate seismicity. There are a number of different aspects to earthquake risk that bear evaluation. The two most important are (a) the record of past shaking and (b) the potential for future shaking by an earthquake that might occur on a source that has not had an event during recorded history.

Historical Damaging Earthquakes

The last earthquake that damaged property on Oahu was the October 15, 2006 Hawaii earthquake on the Kona side of the Big Island. Almost all damaging earthquakes in Hawaii, in fact, occur on or near the Big Island. The 2006 event caused a 14-hour blackout on Oahu. Prior earthquakes have caused minor damage like broken windows. Attenuation with distance is the reason that damaging earthquakes on the Big Island do not cause problems on Oahu. The 2006 epicenter is more than 150 miles away from Red Hill. The risk at Red Hill is small because the seismogenic potential of the Big Island source is limited to magnitude 7 or 7.5 events, too small to damage the Facility located more than 150 miles away.

[2] Cinder cone development on the east side of the Koolau range that formed Diamond Head and Koko Head is a different process from shield-building and is not associated with earthquakes or slumps.

There are no records of damaging earthquakes occurring close to the site. The largest earthquake recorded within 50 miles of the site was a Magnitude 4.48 event on May 25, 1969. The most recent event of Magnitude 4.0 or larger was on August 22, 2014. Neither caused damage on Oahu or at the Red Hill facility.

Unprecedented Earthquakes

Seismicity in Hawaii is correlated with active volcanism. Since the Koolau volcano has been inactive for about 2 million years, there is not a credible nearby seismic source. There are no seismogenic faults in Hawaii like there are in California.

The Hawaiian Islands are located in the interior of the Pacific Plate far from the edges where it interacts with other tectonic plates. Earthquakes along plate margins can, in some locations, have long recurrence intervals. The Cascadia Subduction Zone near Oregon and Washington is an example of areas where large earthquakes are possible but infrequent. While tsunamis caused by these distant earthquakes do sometimes reach the Oahu shoreline, ground shaking does not.

Separate from a seismogenic fault or a tectonic plate interface, an unexpected shift in Pacific Plate interior may be capable of generating small earthquakes at an essentially random location. This type of seismicity may be the cause of the 1969 and 2014 events discussed in Historical Seismicity above. Shaking from such an event could damage poorly built or old structures, but not structures that are buried in bedrock like the Red Hill tanks.

Seismic Hazard

A more formal method of quantifying seismic hazard at Red Hill is with the probabilistic seismic hazard maps that the United States Geological Survey publishes, and which are the basis for the seismic design provisions in the International Building Code[3]. The details of developing and using probabilistic seismic hazard maps are beyond the purpose of this memo, but there is some useful basic information available that will help to explain the risk of earthquake damage at Red Hill.

First, an understanding of relative seismic hazard may be useful. The USGS reports that one pertinent aspect of the design-level[4] ground shaking at Red Hill is a peak ground acceleration of PGA = 0.265 g. On its own this parameter is not adequate for a complete understanding of seismic risk, but it does allow correlation with other areas with a range of seismic hazard.

[3] http://earthquake.usgs.gov/designmaps/us/application.php

[4] "Design level" is a generic term that, for this evaluation, means the level of ground shaking on bedrock that has a 2% chance of being exceeded in 50 years. This level of risk roughly correlates to a 2,475-year recurrence interval.

Figure 2 (right) shows the design PGA for Red Hill compared to five Mainland locations. The comparisons illustrate how:

1. Almost all locations in the US have at least some seismic hazard, including Denver and New York City, which are not considered prone to earthquakes.
2. Knoxville is the population center with seismic hazard most comparable to Red Hill. Similar to Oahu, Knoxville is an area affected by moderate and infrequent earthquakes that are not particularly hazardous.
3. The design-level ground motion at Red Hill is less than half of that for downtown San Francisco, an area of well-known high seismicity.

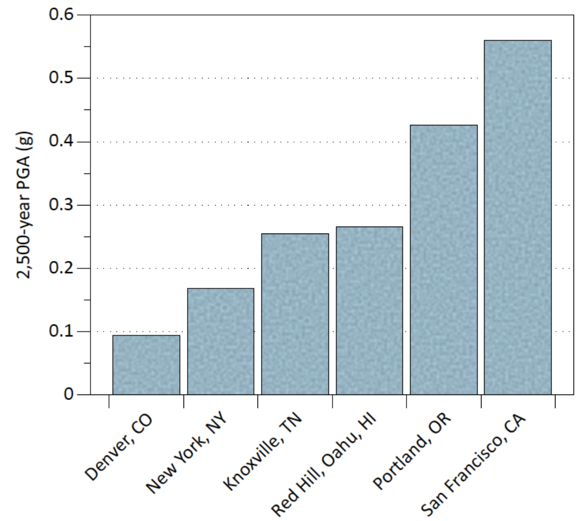

Figure 2 - Red Hill Seismicity Comparison

Seismic Vulnerability

The catastrophic release risk at Red Hill is comprised of both seismic hazard and also the vulnerability of the tank structures. The seismic hazard is moderate, so noticeable shaking has about a 2% chance of occurring in a 50-year period. The tank structures, though, are very tolerant of shaking because:

1. The tank walls are surrounded by and connected to bedrock. This type of shaking is very different from shaking that affects a building, for instance.
2. The steel tank shells are flexible and able to accommodate any small-magnitude temporary deformations during shaking.
3. The tanks are 2.5 times narrower than they are tall, significantly limiting the sloshing loads that can be generated in the stored liquid during shaking.

Considering these factors, it is not feasible that moderate earthquake shaking from a distant source would breach the tank liners to cause a catastrophic release. While the additional detail in this report is probably appropriate, the result is the same: earthquake is not a credible source of catastrophic failure risk.

Other Facilities

Piping

As indicated in the first figure, there are several miles of large diameter piping that allow fuel to be pumped into and out of the tanks. Piping, if correctly designed, is flexible and able to withstand severe ground shaking. Today, sophisticated finite element analyses can be used to compute stresses, flexibility and deformation in pipes and fittings. Any "hard spots" that might exist in the system may be vulnerable to stress concentration during deformation, which can cause cracking or tearing and could result in uncontrolled release. As part of the risk assessment for the facilities, a complete piping flexibility analysis can be conducted.

Fittings

In addition to the piping flexibility issue, screwed or flanged connections can be vulnerable to deformation that would allow an uncontrolled release. A review of the proper kinds of fittings and joints, their metallurgical properties, and their present condition can ensure that the joints are as good as the piping in terms of mechanical integrity.

Pumps and Appurtenances

There are other system vulnerabilities such as those associated with pump seals, sampling lines, tubing and other sources of releases. A potential release on one of these sources would not generally be considered large enough to create a catastrophe. Nonetheless, ensuring adequate mechanical integrity through various risk assessment tools is appropriate.

Communications and Control

Day-to-day operations are managed by communication systems, control systems, alarms, and interlocks. The network of such controls can lead to failures that result in releases or loss of containment. A thorough review of these systems will allow for the determination of:

- How closely these systems align with current best practices,
- How reliable and robust the alarm systems are that will provide early warnings and minimization of release size,
- The human-machine interface and design considerations related to human factors,
- The use of modern alarm management philosophy as capture by standards such as ISA 18.2.

Emergency Response

Emergency response procedures are based on the assumption that uncontrolled releases sometimes occur. Reasonable and likely scenarios are then analyzed to ensure that the response to the assumed release is thoroughly and adequately addressed through communication with the emergency response personnel, the facility owners, the medical facilities, the pre-arranged clean up contractors, and the public and its leadership.

Part of the assessment certainly involves emergency response. It is uncertain to PEMY how robust the entire emergency response system is, the incident command system, and the quality of equipment and training provided to the operators responsible for emergency response. This assessment typically is best done by an independent third party reviewer that has experience in these areas and with the types of release involved.

Summary and Conclusions

The Red Hill tanks have very low potential for a catastrophic release. The tanks are embedded in bedrock 100 to 200 feet deep that makes them well protected from geologic and natural hazards. There are no credible mechanisms that could rapidly cause a large breach in a tank wall and allow a damaging release of stored liquids.

A catastrophic failure would require more than one type of failure occurring on more than one system comprising the facility, and could involve elements of management, controls, and operations as well as mechanical integrity of tank liner, pipes, and valves. These types of risk are complex and are best evaluated using broad, multidisciplinary methods that consider all elements of the facility and its operation.

That the tanks alone have little catastrophic risk is not unexpected. Rather it is the totality of the system and subsystems that require investigation and analysis. A preliminary review by an independent 3rd party qualified to analyze systemic and operations issues is necessary to thoroughly understand the Red Hill Facility's risk profile. Further information combined with neutral independent investigation taking into account all aspects of the facility including but not limited to materials, fabrication methods, construction, operation, maintenance, and safeguards is needed to understand what risks the Navy facility poses to population and environmental resources.