TWO WATERSHED EVENTS OCCURRED IN 1963 that effectively spelled the end of America’s post-war period of national innocence: the assassination of President John F. Kennedy and the destruction of the nuclear submarine Thresher, commanded by Lieutenant-Commander John Harvey.

Just as the context for both these events were markedly different, so too would be the fallout from each. In the case of JFK’s assassination, it would mark the end of the moral rectitude of U.S. politics and the sanctity of the office of the president. Robert MacNeil of the MacNeil/Lehrer Newshour summed this up by stating, “…perhaps we lived in a fool’s paradise before the Kennedy assassination” (Proctor, 1993).

In the case of the Thresher accident, the result would be scrutiny of submarine design and the implementation of assurance systems. It marked the beginning of SUBSAFE, a quality assurance program of the U.S. Navy designed to maintain the safety of the nuclear submarine fleet. Specifically, it provides maximum reasonable assurance that sub hulls will stay watertight and that they can recover from unanticipated flooding.

Interestingly, and by a twist of fate, both Kennedy and Harvey share more than just a tragic place in U.S. history. Both had apparently received a gift from enigmatic Admiral Hyman Rickover, director of the U.S. Navy’s Naval Reactors Branch. The gift was a plaque inscribed with an old French fishing prayer: “O God the sea is so great and my boat is so small.” Rickover had made a habit of presenting these plaques to new submarine captains, which was intended to be a reminder of their vulnerabilities. Kennedy, a World War II U.S. Naval Reserve officer, had also received the plaque (which now resides in his presidential library).

While the Thresher’s demise did not put the brakes on the U.S. nuclear submarine program, it underscored the fact that these ever-increasingly complex platforms were still susceptible to their environment, a dark, frigid world of extreme pressures occupied by adversaries, both above and below the surface.

These weaknesses have been reasonably well appreciated since the earliest of submarines, as the accident record will attest. Since the 18th century, more than 1,800 submarines have been sunk and roughly 60,000 submariners have perished worldwide in peace and in war (Gray, 2003).

While these figures may seem relatively high, consider them in the following context:

• Early submarines were notoriously unsafe. However, when coupled with the drive to maintain a technological edge, these early losses resulted in improved design and operation.

• Major overt conflicts naturally increase the risks to submarines. Losses in these scenarios will continue to occur despite improvements in design and operation.

The question remains: Have improvements in design and operations realized benefits in terms of reducing losses or has the increasingly complex submarine coupled with the ebb and flow of the geopolitical situation introduced even greater risk resulting in relatively more losses?

To determine this, the author analyzed submarine accident data that has been collated since 2001. The scope of the data covers the 60-year period, 1946 to 2005. These data were selected as they ensured elimination of accidents attributable to poor design during the early part of the 20th century as well as

Abstract: An analysis of submarine accidents from 1946 to 2005 was conducted to determine whether improvements in design and management systems have reduced the probability of an incident. The analysis showed that from 1946 to 1974, 0.92 sunk per 500 available submarines per year; and 38 fatalities per 30,000 available submariners per year, while from 1975 to 2005: 0.31 sunk per 500 available submarines per year, and 12 fatalities per 30,000 available submariners per year.

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the significant number of submarine losses due to the two major wars at that same time. The data also include submersible accidents. While submarines and submersibles have entirely different design intents—the former as a strategic deterrent and the latter for research and recreation—both operate under the same physical constraints, providing an inextricable link in terms of risk management.

The data are an aid to assessing whether the situation has improved as well as an aid to identifying areas for further improvement in terms of the magnitude and nature of the incidents that occur. The information also provides probabilistic accident data for industrial mishaps for risk assessment tools such as event and fault trees.

The Accident Data

Over the course of several years, data regarding submarine and submersible accidents (for reasons of brevity, future discussion regarding submarine accidents includes submersibles) for the period 1946 to 2005 have been gathered from various sources including the following:

- **Literature.** Several books have been written on the subject of submarine accidents. These include Gray (2003) for submarine accidents in general, Busby (1976) for submersibles accidents, Sontag, Drew and Drew (1998) for U.S./USSR cold war submarine activity, Kévorkian (2005) for French submarine accidents and Jane's Fighting Ships (JFS), which describes fleet compositions and from time to time records submarine losses.

- **Databases.** Several official databases are available online, notably the U.S. Coast Guard’s accident database and U.S. Navy’s Naval Sea Systems Command (NAVSEA) ship casualty reports, as well as unofficial databases such as globalsecurity.org, fas.org, deepstorm.ru, navsource.org and bellona.org. It should be noted that online sources can be unreliable with respect to sustained availability. Readers wishing to seek out these sources are cautioned that they may no longer exist in their quoted state.


- **Investigations and inquiries.** Signatories to the International Maritime Organization (IMO) conventions must investigate significant accidents in their territory or accidents involving their flag state vessels. An example of this type of investigative report includes the Canadian Transportation Accident Investigation and Safety Board report (1994) concerning the collision between sailing vessel Moonglow and the Chilean submarine Thomson. In addition, governmental subcommittees often seek additional information regarding expenditures and losses, as evidenced by the congressional Armed Services Investigative Subcommittee that probed the foundering of Guitarro in 1969 (U.S. House of Representatives, 1969).

- **News and journal articles.** In addition to news stories, more in-depth journal articles stand out, including Pritzlaff (1972) for submersible accidents, and Kosritchenco and Eizenberg (1997) for a compendium of Soviet and Russian submarine catastrophes. The latter is typical of the wellspring of newly available foreign language information made accessible through online translation engines.

- **Oral histories.** The Internet and the proliferation of forums and blogs related to submarines make it easier to tap into the oral history that currently exists.

For each incident, data attributes such as date, name, class, fate, cause, location and owner have been gathered. The fate and immediate cause categories and their corresponding definitions are described in the definitions sidebar at left. To provide some relative context for these incidents, an exposure basis detailing the total number of submarines and submariners (seagoing or otherwise) by nation has been determined using JFS, an annually updated almanac that currently exists. From 1898, that details the composition of the world’s navies.

Coupling submarine accident data with the number of submarines and submariners from JFS not only permits some normalization of the data but also allows benchmarking against accidents in other similarly hazardous industries. The JFS data also provide details regarding the change in nations that operate submarines, since the average size of submarine fleets adds an interesting dimension to the analysis. Figure 1 depicts this change.

### Definitions

#### Fate Categories

- **Damage:** An accident yielding damage but without fatality.
- **Decommissioned:** As a result of the mishap, the vessel is decommissioned from further service.
- **Significant damage:** An accident yielding at least one fatality.
- **Sunk:** Vessel unintentionally sunk.
- **Sunk vessel:** Collision or action resulting in the demise of another vessel.
- **Unknown:** The fate is unknown.

#### Immediate Causes

- **Collision:** Submarine hits another vessel or man-made infrastructure.
- **Disease:** Personnel succumb to a disease.
- **Explosion:** Vapor explodes (not necessarily leading to fire).
- **Fire:** Material and/or personnel is/are damaged/injured by fire.
- **Flood:** Submarine’s watertight integrity is compromised reducing the reserve of buoyancy.
- **Grounding:** Submarine hits the bottom, shoreline or ice.
- **Man overboard:** Person falls over the side and is not recovered alive.
- **Murder:** Murder is committed aboard.
- **Nuclear:** Incident mostly nuclear related.
- **Occupational death:** Fatalities due to causes other than disease, man overboard, murder or toxic substance exposure.
- **Suicide:** Person commits suicide aboard.
- **Systems failure:** Material failures leading to consequences other than flood, explosion, fire, collision or grounding.
- **Toxic substance exposure:** Personnel are exposed to a toxic substance other than radioactive material.
- **Unknown:** Type of incident is unknown.
Figures 3 and 4 (p. 36) are control charts depicting the normalized SUBSUNK and normalized submarine fatalities, respectively. Nelson (1986) developed control chart analysis rules that center on identifying special causes from the following eight tests:

1) One point is more than three sigma from the mean, also known as a *freak*.
2) Nine or more points are in a row on the same side of the mean, suggesting *bias*.
3) Six or more points in a row continuously increasing or decreasing, indicating a *trend*.
4) Fourteen or more points in a row oscillate or alternate in direction.
5) Two or more points out of three points are more than two sigma from the mean.
6) Four or more points out of five points are more than one sigma from the mean.
7) Fifteen points in a row are all within one sigma of the mean on either side.
8) Eight points in a row exist with none within one sigma of the mean.

Using these tests, both control charts for SUBSUNK and submariner fatalities were observed to have a *freak* at 1968 and *bias* at 1980 to 1989 for SUBSUNK, and 1972 to 1992 for submarine fatalities.

**A Bad Year: 1968**

The freak at 1968 was indicative of the worst year for submarine losses to date and accounted for the loss of five operational submarines (*Alvin*, *K-129*, *Scorpion*, *Dakar*, *Minerve*) and 362 deaths. Each accident is described in more detail in the following discussion.

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Interestingly, while the number of submarines peaked at around 950 in the mid-1990s, it is now fewer than post-World War II levels, while the number of nations operating submarines has steadily increased to more than double what it was in 1946. This has ultimately resulted in more nations with smaller submarine fleets.

It should be stressed that the submarine accident database has gaps. Aside from the fact that some countries do not admit to incidents or do not provide incident details, one attribute, cause, has been tricky to assign for several reasons:

- the root cause for a sunken submarine at sea generally goes down with the boat (although forensic engineering of recovered wreckage can be enlightening regarding potential causes);
- as the gravity of the incident diminishes, data quality and availability degrade.

To date, this database contains more than 560 entries and another 90 to 100 entries remain under investigation.

**Register of Sunken Submarines**

Table 1 (p. 34) presents a small excerpt of data on incidents that resulted in a submarine being sunk between 1946 and 2005. Twenty-two of these accidents occurred with submarines that had already been decommissioned and were awaiting disposal. While these represent losses, the damage they incurred largely affected the vessel itself (which still retains some value) and the environment but did not normally affect personnel.

The remaining 55 operational submarines that sunk, otherwise referred to as SUBSUNK (standard North Atlantic Treaty Organization terminology used to report a sunken submarine), were the subject of further study since they typically incurred more losses due to the fact that they were crewed and the fact that the platforms represented a significant capital expenditure for their owners.

**SUBSUNK & Submarine Fatalities Analysis**

Figure 2 (p. 35) depicts a bar chart of the normalized SUBSUNK and submarine fatalities that occurred between 1946 and 2005. To interrogate this data, advanced statistical process control (SPC) techniques were employed. Run and control charts can identify unusual variations in data (special causes) over and above the normal variation expected (common causes). Identifying when these special causes occur is important insofar as analyzing their origins with a view to risk mitigation, hazard elimination or risk acceptance.

While run charts can provide a valuable overview of a process, control charts focus more on acceptable limits in the process and can provide even more valuable information regarding special causes. This is done by depicting runs of data against time, with the mean and three standard deviations superimposed.

The number of operating submarines peaked at around 950 in the mid-1990s. It is now fewer than post-World War II levels, while the number of nations operating submarines has steadily increased to more than double what it was in 1946.
The battery explosion theory is plausible (at least six other battery explosion accidents occurred between 1946 and 2005, accounting for 15 fatalities) and GOLF-II submarines are diesel-powered vessels with large batteries. However, it should be noted that most with only minor injuries sustained before the vessel plunged 5,000 ft to the bottom. Alvin was later salvaged on Aug. 28, 1969 (Photo 1) and continues to operate today. As a result of this incident, Alvin’s subsequent launches and recoveries were made with the hatch shut.

The other four accidents are shrouded in mystery and, therefore, subject to conjecture regarding the causes.

The reasons for K-129’s demise point to one of the following:

• an explosion (ammunition or battery);

• a faulty snort (diesel-powered submarines, when dived and charging, induct combustion air through a mast with a float valve designed to prevent ingress of water in the event that the vessel plunges due to heavy weather or poor trimming) with subsequent carbon monoxide poisoning (similar to what is believed to have occurred with Chinese submarine 361 in 2003);

• a collision with a U.S. Navy submarine.

The list of accidents continues:

### Table 1

<table>
<thead>
<tr>
<th>Date</th>
<th>Vessel</th>
<th>Owner</th>
<th>Accident</th>
<th>Fatalities</th>
<th>Condition*</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 Jan 46</td>
<td>SAFARI</td>
<td>UK</td>
<td>Flood</td>
<td>0</td>
<td>Decommissioned</td>
<td>English Channel</td>
</tr>
<tr>
<td>27 Jun 46</td>
<td>C-4</td>
<td>Spain</td>
<td>Collision</td>
<td>44</td>
<td></td>
<td>Mediterranean</td>
</tr>
<tr>
<td>5 Dec 46</td>
<td>U-2326</td>
<td>France</td>
<td>Flood</td>
<td>26</td>
<td></td>
<td>Mediterranean</td>
</tr>
<tr>
<td>15 Dec 52</td>
<td>S-117</td>
<td>USSR</td>
<td>Collision</td>
<td>52</td>
<td></td>
<td>Sea of Okhotsk</td>
</tr>
<tr>
<td>31 Jan 53</td>
<td>SIRDAR</td>
<td>UK</td>
<td>Flood</td>
<td>0</td>
<td>Alongside</td>
<td>Sheerness</td>
</tr>
<tr>
<td>2 Apr 53</td>
<td>DUMULPINAR</td>
<td>Turkey</td>
<td>Collision</td>
<td>81</td>
<td>At Sea</td>
<td>Black Sea</td>
</tr>
<tr>
<td>Dec 53</td>
<td>M-117</td>
<td>USSR</td>
<td>Flood</td>
<td>0</td>
<td>Decommissioned</td>
<td>Sevastopol</td>
</tr>
<tr>
<td>10 Apr 63</td>
<td>THRESHER</td>
<td>US</td>
<td>Flood</td>
<td>129</td>
<td></td>
<td>Atlantic</td>
</tr>
<tr>
<td>25 Jan 68</td>
<td>DAKAR</td>
<td>Israel</td>
<td>Flood</td>
<td>69</td>
<td></td>
<td>Mediterranean</td>
</tr>
<tr>
<td>27 Jan 68</td>
<td>MINERVE</td>
<td>France</td>
<td>Flood</td>
<td>52</td>
<td></td>
<td>Mediterranean</td>
</tr>
<tr>
<td>11 Apr 68</td>
<td>K-129</td>
<td>USSR</td>
<td>Explosion</td>
<td>97</td>
<td>At Sea</td>
<td>Pacific</td>
</tr>
<tr>
<td>22 May 68</td>
<td>SCORPION</td>
<td>US</td>
<td>Explosion</td>
<td>99</td>
<td>At Sea</td>
<td>Atlantic</td>
</tr>
<tr>
<td>16 Oct 68</td>
<td>ALVIN</td>
<td>US</td>
<td>Flood</td>
<td>0</td>
<td>At Sea</td>
<td>Atlantic</td>
</tr>
<tr>
<td>15 May 69</td>
<td>GUITARRO</td>
<td>US</td>
<td>Flood</td>
<td>0</td>
<td>Alongside</td>
<td>Mare Island</td>
</tr>
<tr>
<td>4 Mar 70</td>
<td>EURYDICE</td>
<td>France</td>
<td>Explosion</td>
<td>57</td>
<td>At Sea</td>
<td>Mediterranean</td>
</tr>
<tr>
<td>8 Apr 70</td>
<td>K-8</td>
<td>USSR</td>
<td>Fire</td>
<td>52</td>
<td>At Sea</td>
<td>Bay of Biscay</td>
</tr>
<tr>
<td>25 Oct 76</td>
<td>TIGRONE</td>
<td>US</td>
<td>Flood</td>
<td>0</td>
<td>Decommissioned</td>
<td>Unknown</td>
</tr>
<tr>
<td>21 Oct 81</td>
<td>S-178</td>
<td>USSR</td>
<td>Collision</td>
<td>32</td>
<td>At Sea</td>
<td>Pacific</td>
</tr>
<tr>
<td>24 Jun 83</td>
<td>K-429</td>
<td>USSR</td>
<td>Flood</td>
<td>16</td>
<td>At Sea</td>
<td>North Pacific</td>
</tr>
<tr>
<td>29 May 97</td>
<td>K-313</td>
<td>Russia</td>
<td>Collision</td>
<td>0</td>
<td>Decommissioned</td>
<td>Kamchatka</td>
</tr>
<tr>
<td>6 Oct 97</td>
<td>K-313</td>
<td>Russia</td>
<td>Flood</td>
<td>0</td>
<td>Decommissioned</td>
<td>Kamchatka</td>
</tr>
<tr>
<td>10 Oct 97</td>
<td>K-313</td>
<td>Russia</td>
<td>Flood</td>
<td>0</td>
<td>Decommissioned</td>
<td>Kamchatka</td>
</tr>
<tr>
<td>23 Jun 98</td>
<td>UNKNOWN</td>
<td>North Korea</td>
<td>Flood</td>
<td>9</td>
<td>At Sea</td>
<td>South Korean Coast</td>
</tr>
<tr>
<td>5 May 00</td>
<td>BENTOS 300-1</td>
<td>Ukraine</td>
<td>Flood</td>
<td>0</td>
<td>Decommissioned</td>
<td>Sevastopol</td>
</tr>
<tr>
<td>12 Aug 00</td>
<td>KURSK</td>
<td>Russia</td>
<td>Explosion</td>
<td>118</td>
<td>At Sea</td>
<td>Barents Sea</td>
</tr>
<tr>
<td>30 Aug 03</td>
<td>K-159</td>
<td>Russia</td>
<td>Flood</td>
<td>9</td>
<td>Decommissioned</td>
<td>Barents Sea</td>
</tr>
</tbody>
</table>

Note: *The term at sea refers to a vessel that has deployed to open water as opposed to being alongside in harbor, at anchor, etc. Decommissioned infers a vessel that is no longer operational and is destined for disposal or some alternative use.

PHOTO COURTESY WHOI ARCHIVE

This table presents only a sampling of the data reviewed. To view the complete table and data, visit [www.asse.org/psextras](http://www.asse.org/psextras).
submarines which catastrophically flood are prone to suffer subsequent battery explosions when they ultimately come into contact with seawater.

The theory that the vessel collided with another submarine was given some credence when the Swordfish showed up in Japan shortly after K-129’s accident with collision damage to her fin and periscope, damage that was worked on only by U.S. personnel. Years later, Swordfish’s captain at the time stated that the damage was caused by striking ice. Adding to the intrigue was the Central Intelligence Agency’s efforts to clandestinely recover K-129 using one of the largest single-purpose ships ever designed and constructed, Glomar Explorer. Despite spending billions of dollars, only a partial recovery was reportedly achieved.

Several theories surround Scorpion’s accident, ranging from payback for K-129’s demise to being hit by a friendly torpedo to the more plausible theory postulated by Sontag, et al. (1998) that the vessel was sunk after a known but largely ignored defective torpedo battery cooked-off, detonating the torpedo’s warhead (Photo 2).

Dakar was a 25-year-old T-Class submarine purchased from the Royal Navy (ex-HMS Totem). Unlike K-129 and Scorpion, it has not been prone to cold war conspiracies over the years, yet it remains an incident about which little is known.

It is surmised that while snorting, the vessel suffered an incident either caused by or exacerbated by the cluthing arrangement that existed between the diesel engines and the propellers, which was a faster means of snorting. The direct-drive mode was not recommended for long durations because it was resource-intensive, and more importantly because the loss of hydraulic pressure (due to the four clutches) could cause the after planes to jam hard to dive (Baumgartner, 1999).

The most conceivable circumstance is that Dakar was snort transiting in the direct-drive mode and suffered an after planes jam that caused a depth excursion to collapse depth. In addition to the loss of Dakar, the Israeli Navy suffered another accident just 8 months earlier during a T-Boat procurement program when Leviathan lost two sailors over the side in the Irish Sea.

Minerve was a DAPHNÉ-Class submarine believed to have sunk due to a faulty snort system, a failure possibly exacerbated by the prevailing heavy weather. Unlike the other submarines that sank in 1968, her wreckage has never been located. Interestingly, two other DAPHNÉ-Class submarines suffered similar fates: Eurydice sank at sea in 1970 due to either an explosion or collision (Photo 3); and in 1972, La Sirene sank while alongside due to the failure of a temporary watertight bulkhead. Other DAPHNÉ-Class incidents have included the collision of Galatee in 1970 with a surface ship. The captain ran the vessel aground to save all but six crew members.
To understand whether improvements in design, operation or other reasons have resulted in reduced accidents, it is worth considering the change in mean values during the 60-year period. A simple plot of the accumulated SUBSUNK and fatality rates (Figure 5) demonstrates a dramatic change in slope occurring at 1974 (subsequently verified by a correlation analysis), suggesting that the mean values should logically be calculated using that as a midpoint.

Table 2 summarizes these statistics, including a strong correlation in the accumulative data in each time period that was examined (1946 to 1974 and 1975 to 2005). Hypothesis testing similarly confirmed that a statistically significant difference exists between these two periods. Both analysis of variation (ANOVA) and the Mann-Whitney test were used to determine whether a statistically significant difference existed between the means (in the former case) and medians (in the latter case). While it should be noted that ANOVA should only be used for a normal distribution (unlike the Mann-Whitney test), which was not the case here (both distributions are positively skewed), the two tests confirmed that a statistically significant difference existed between the two distributions.

Figure 3

Control Chart: Normalized SUBSUNK, 1946 to 2005

Safer Submarines
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Figure 4

Control Chart: Normalized Submarine Fatalities, 1946 to 2005

Finally, in 1983, Doris sustained a battery explosion that killed two and injured five, including the captain. Of the 11 DAPHNE-Class submarines in the French Navy, four suffered catastrophic accidents.

The worst submarine collision on record involved the Turkish submarine Dumlupinar in 1950, which foundered, taking the lives of 81 crewmembers. The worst collision on record in terms of fatalities where
neither vessel involved sank was between Soviet submarine K-56 and the Soviet research vessel Berg in 1973, in which 27 submariners were killed by the subsequent flood. K-56’s captain purposely ran her aground to save the remainder of the crew and the submarine (Kostrichenko & Eizenberg, 1997).

Unlike floods, the causes behind collisions involve human factors (operator error and/or an aggressive party) or a less-than-adequate capability to effectively detect (or be detected as the situation warrants) and quickly maneuver to avoid striking. Indeed, sensor and navigational capability for submarines and their surface counterparts have improved considerably during the period of study. That coupled with the fall of the Iron Curtain and the introduction of regulatory instruments such as IMO’s collision regulations have likely contributed to the 40% to 50% reduction in the number of catastrophic submarine collisions observed since 1988.

A correlation analysis of the collision rates was undertaken to determine when reduction, if any, has occurred. The analysis determined that for comparison purposes, the maximum correlation occurred using the periods 1946 to 1987 (mean = 2.0 collisions per 500 submarines available) and 1988 to 2005 (mean = 1.1 collisions per 500 submarines available). Photo 4 (p. 38) shows a rare moment when a submarine broached the surface after colliding with a destroyer.

Finally, it is interesting to note that nuclear accidents have not dominated the accident record, a testament to the scale of safe design, built-in redundancy, and operational effectiveness stemming from a near-zero tolerance of such incidents. It is also interesting, given the relatively high levels of stress incurred by serving submariners, that murders and suicides have not figured more prominently in this accident record.

**Submarine Reliability**

An interesting trend emerges when the date of sinking is compared with the date of launch. Figure 7 (p. 38) suggests that during the period studied, the majority of sinking incidents occurred either within the first 10 years of a submarine’s operation or at roughly the 27- to 29-year mark. The minimum rate period is at roughly the 15- to 20-year mark. The bar chart mirrors a reliability effect called the bathtub curve, which suggests that product failures occur most often at the beginning and end of service life. Dividing the period into two reveals that fewer new submarines have sunk during the period 1975 to 2005 when compared with 1946 to 1974, reinforcing the view that enhanced designs, design techniques and commissioning processes have realized tangible benefits.

**Table 2**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Period</th>
<th>Mean</th>
<th>Correlation*</th>
<th>Ratio of means*</th>
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<td>0.92</td>
<td>0.99</td>
<td>3.0</td>
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<td></td>
<td>1975-2005</td>
<td>0.31</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>Submarine</td>
<td>1946-1974</td>
<td>38</td>
<td>0.98</td>
<td>3.1</td>
</tr>
<tr>
<td>Fatalities</td>
<td>1975-2005</td>
<td>12</td>
<td>0.91</td>
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</tr>
</tbody>
</table>

**Note.** *Correlation (or R2) is a term describing the degree of variation in the data; as R2 approaches unity, a regression approaches a perfect fit. Ratio = Mean(1946-1974)/Mean(1975-2005)*

To understand whether improvements in design, operation or other reasons reduced accidents, the change in mean values during the 60-year period was examined. This simple plot demonstrates that a dramatic change in slope occurred at 1974.
The highest loss rate of all occupations surveyed, is the maximum threshold used before which any legislative intervention to mitigate risk would be considered (HSE, 2001).

The MAIB data for fishing vessels was plotted with its equivalent submarine data to produce Figure 8. The benchmarking indicates that on average submarine losses are less than for U.K. fishing vessels by roughly a factor of two for fatalities and five for sinking accidents (Table 3). This would also suggest that from a worldwide perspective and in line with HSE’s approach, no further regulation of submarine activities at the present incident rate would be deemed cost effective.

**Conclusion**

The study of submarine accidents from 1946 to 2005 has shown that the number of these incidents has declined roughly three-fold between the 1946 to 1974 period and the 1975 to 2005 period, where 1974 represented the beginning of a period with fewer accidents. Indeed, when compared with a similarly hazardous activity such as the U.K. fishing industry from 1992 to 2000, submarines were deemed safer by a factor of two in terms of fatalities. Indeed, when compared with a similarly hazardous activity such as the U.K. fishing industry from 1992 to 2000, submarines were deemed safer by a factor of two in terms of fatalities.

The use of advanced statistical process tools such as control charts has been demonstrated and proven useful for identifying periods where special causes dominated. Concentrating efforts on root-cause analysis for these periods can aid in the mitigation of significant risks and improvement in performance.

Undoubtedly, the impact of catastrophic accidents such as Thresher in 1963 has brought about improvements in submarine safety. A testament to the effectiveness of engineering management programs such as SUBSAFE is that the U.S. Navy, for instance, has not suffered a SUBSUNK in almost 40 years, although one cannot ignore significant blips caused by operator error in cases such as the Greeneville in 2001 and the San Francisco in 2005.

Submarine designs and design practices continue to improve. The RN ASTUTE Class is one of the first submarine designs to follow the safety-case approach from inception. By comprehensively and systematically front-end loading safety
into the design process, builders are minimizing risks and costs later in the running period. Along these same lines, new innovations such as unmanned underwater vehicles eliminate the risks to humans by removing them from the equation.

What's next with this study? With approximately 100 accidents requiring more information, the submarine accident database will inevitably be expanded and refined. Filling gaps left by the demise of online resources is necessary to ensure the free distribution of submarine accident data as well as to recognize the sacrifice of the submariners who have served and continue to serve in this hazardous line of work.

An interesting recent development in submarines worldwide has been the expansion of tourist and personal submarines. While the effect of this development remains to be seen, it will likely account for an increased exposure basis with the probability for more incidents and accidents, necessitating more regulatory control similar to that in the aviation sector.

References

The benchmarking indicates that on average submarine losses are less than for U.K. fishing vessels by roughly a factor of two for fatalities and five for sinking accidents.

### Table 3
Benchmarking Accident Data—F/V & Submarines, 1992 to 2000

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Period</th>
<th>Mean</th>
<th>Ratio of means (F/V/submarine)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUNK</td>
<td>1992 to 2000</td>
<td>1.8 F/V SUNK/500 available</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.34 SUBSUNK/500 available</td>
<td></td>
</tr>
<tr>
<td>Fatalities</td>
<td></td>
<td>44 F/V fatalities/30,000 available</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20 Submariner fatalities/30,000 available</td>
<td></td>
</tr>
</tbody>
</table>