Submarine Accidents

A 60-year statistical assessment

By Christopher Tingle

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.*

TWO WATERSHED EVENTS OCCURRED IN 1963 that effectively spelled the end of America's postwar 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

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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 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 submersible 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.
- **Reports.** Two reports provide a compendium of submarine accidents: the Australian Department of Defense's 1992 audit review of submarine safety major accidents since 1945, and the Arkin and Handler (1989) report of ship and submarine accidents.
- **Investigations and inquiries.** Signatories to the International Maritime Organization (IMO) conventions must investigate significant accidents in their territorial waters 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 Investigating 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 Kostrichenko 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 in print since 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.

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.

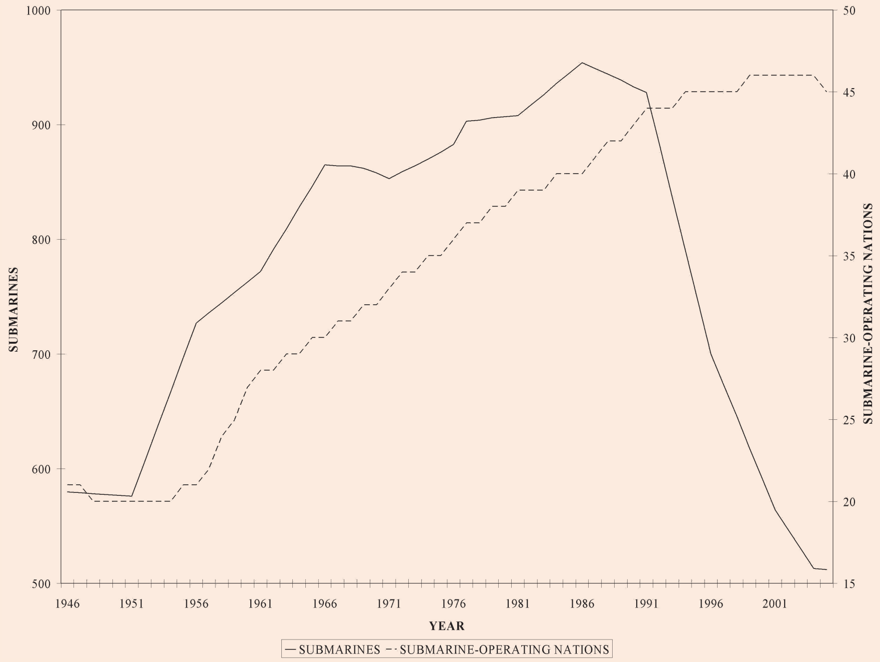
It should be stressed that the submarine accident database has gaps. Aside from the fact that some countries do not admit to incidents or do not provide incident details, one attribute, cause, has been tricky to assign for several reasons:

- 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.

Figure 1

Submarines & Submarine Operating Nations, 1946 to 2005



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. 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.

Alvin sank after two cables snapped during a recovery operation and water entered the sphere through an open hatch (Ballard, 2000; Kahral, 1990). The two occupants managed to scramble to safety

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.

Table 1

Excerpt of Data on Submarines Sunk Between 1945 & 2005

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

Note: [a]*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.*

This table presents only a sampling of the data reviewed. To view the complete table and data, visit www.asse.org/psextras.

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 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

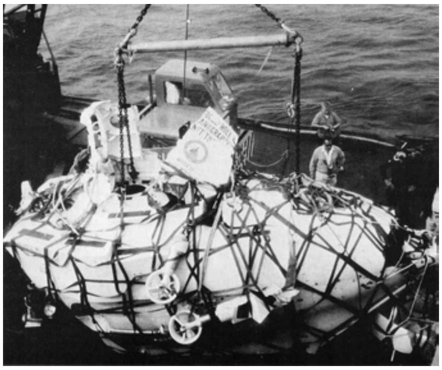


Photo 1: *Alvin* recovered from 5,000 ft after sitting for 1 year on the bottom.

PHOTO COURTESY WHOI ARCHIVE

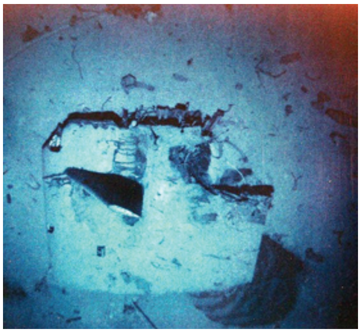


Photo 2: ***Scorpion's*** **stern section at 10,000 ft.**

(USN PHOTO NH 97221-KN)

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 clutching 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.

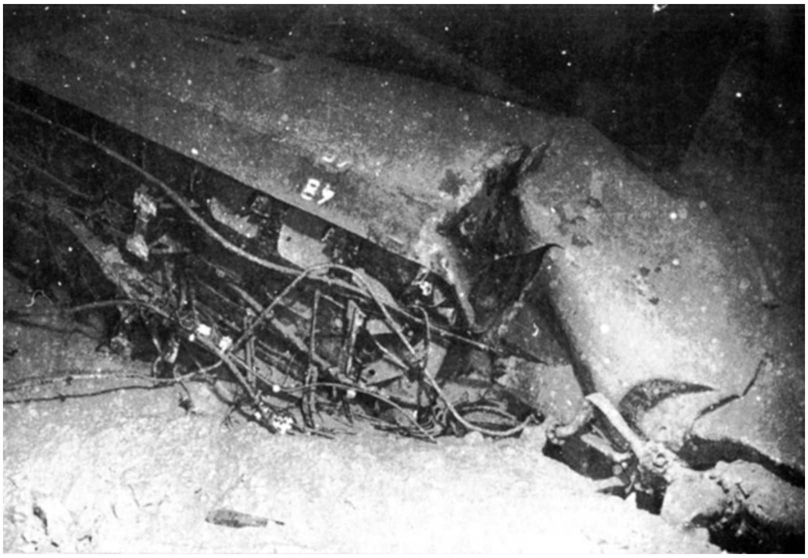


PHOTO COURTESY THE HOUOT ESTATE

Photo 3: ***Eurydice*** **lies shattered and twisted on the bottom in 1971, 1 year after an onboard explosion apparently destroyed her.**

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.

Figure 2

Normalized SUBSUNK & Submarine Fatalities

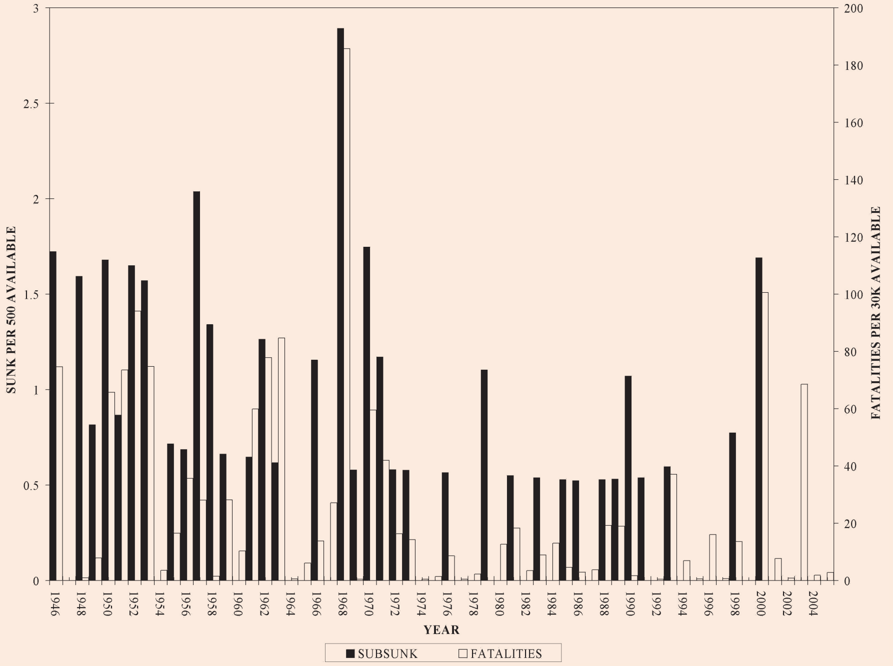


Figure 3

Control Chart: Normalized SUBSUNK, 1946 to 2005

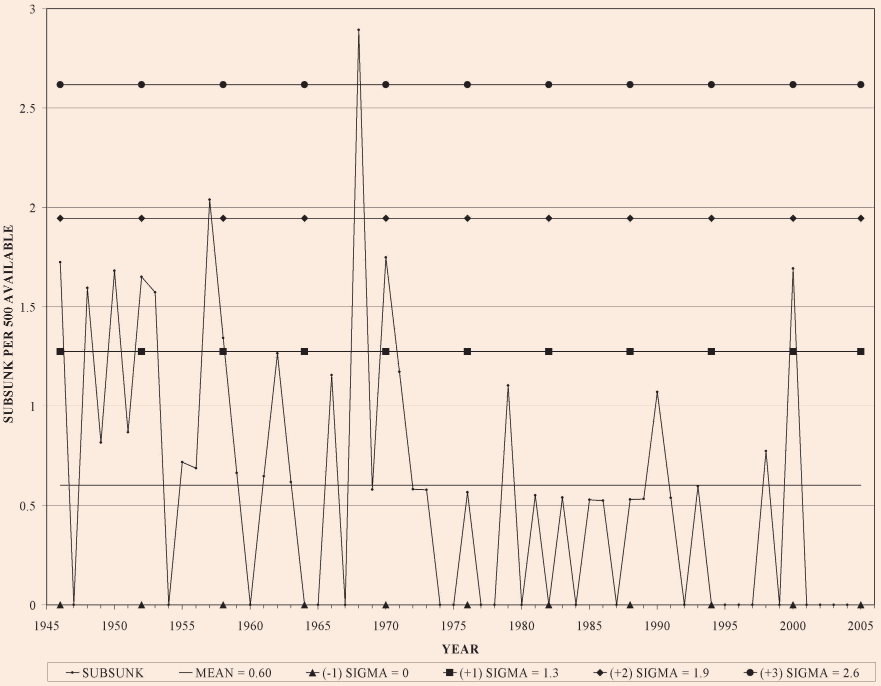
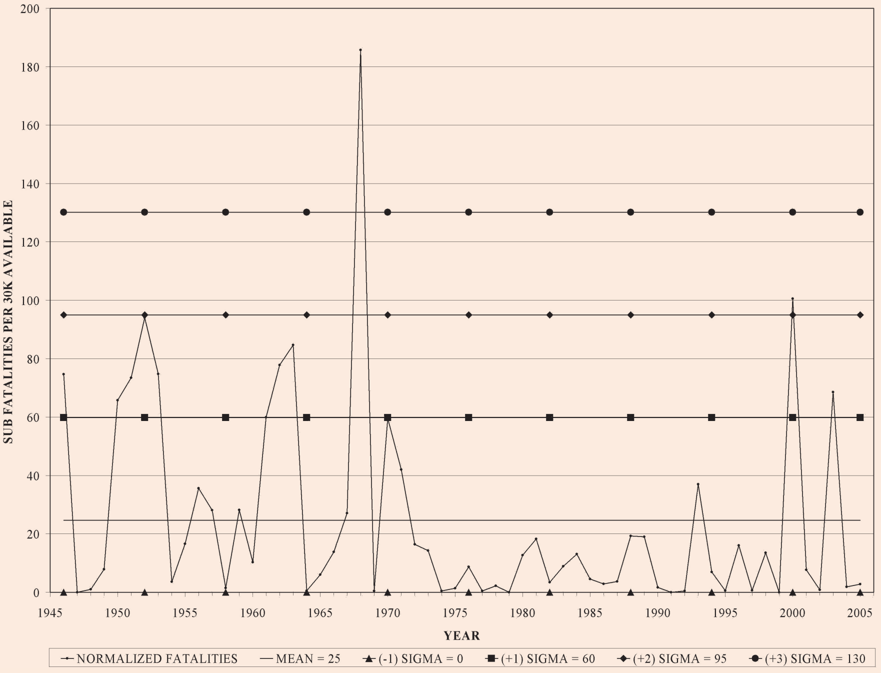


Figure 4

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 DAPHNÉ-Class submarines in the French Navy, four suffered catastrophic accidents.

Safer Submarines

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.

Indeed, the data suggest that a submarine was almost three times more likely to sink at sea during the period 1946 to 1974 than during the subsequent period. That coupled with a similar improvement in fatality statistics can only yield the conclusion that submarines have been designed better and operated more safely in the past 30 years.

Incident Classification

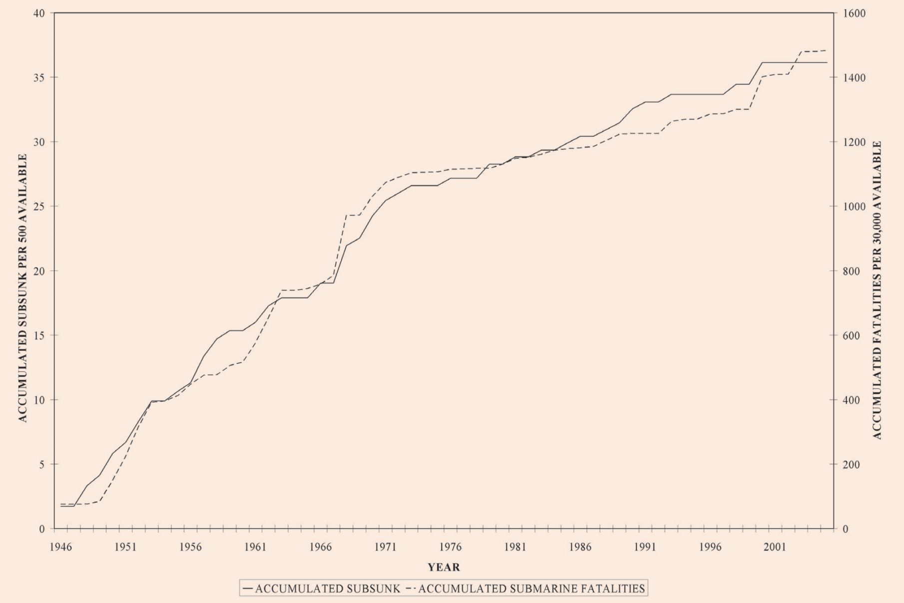
The nature of the incidents that yielded significant losses (sunk, significant damage or sunk vessel) was classified and investigated. Figure 6 (p. 38) depicts the breakdown of the incident types for all submarine fatalities that occurred between 1946 and 2005.

It should come as little surprise that the incident type which resulted in the greatest source of loss for submarines was a flood (21%) followed closely by collision (18%). Floods are the result of a loss of reserve of buoyancy due to a catastrophic watertight integrity failure, which may in turn be caused by the other types of incidents that dominate the record, including collisions.

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

Figure 5

Accumulated SUBSUNK & Submarine Fatalities



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.

Benchmarking: Comparing Apples to Apples

Benchmarks provide a means by which to compare performance. Several large maritime insurance carriers hold data in this respect for shipping and offshore industries. In the public domain, several national-level maritime safety agencies are beginning to

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.

Table 2

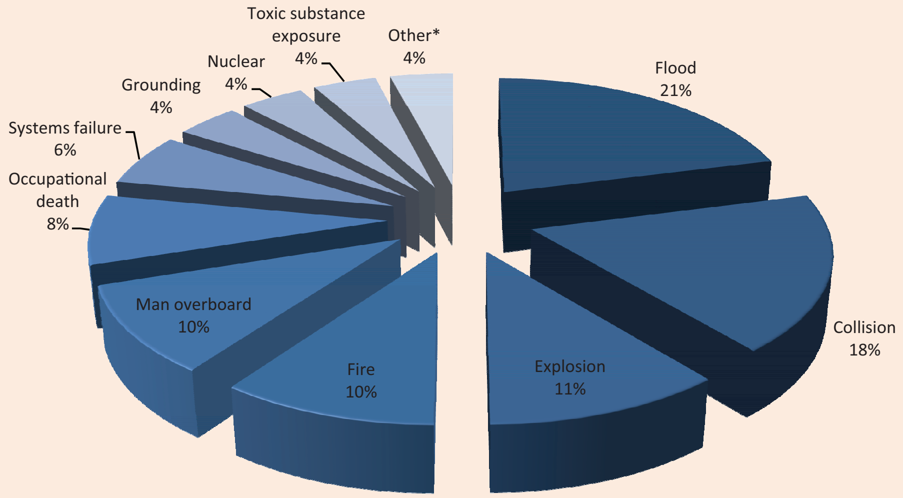
SUBSUNK & Submarine Fatality Means

Parameter	Period	Mean		Correlation[a]	Ratio of means[b]
SUBSUNK	1946-1974	0.92	SUBSUNK/500 available subs	0.99	3.0
	1975-2005	0.31		0.98	
Submarine Fatalities	1946-1974	38	Fatalities/30,000 submariners	0.98	3.1
	1975-2005	12		0.91	

Note. *[a]Correlation (or R^2) is a term describing the degree of variation in the data; as R^2 approaches unity, a regression approaches a perfect fit. [b]Ratio = $Mean_{(1946\text{-}1974)}/Mean_{(1975\text{-}2005)}$.*

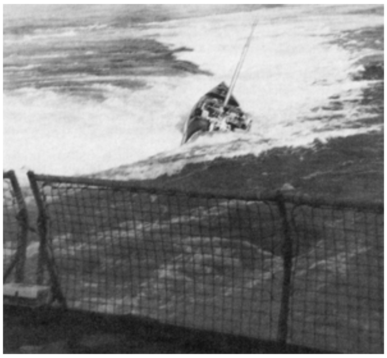
Figure 6

Relative Contribution of Submarine Accident Types, 1946 to 2005



*Includes *unknown, murder, suicide* and *disease* accidents

Photo 4 (below): The top of Soviet submarine *K-22's* fin is exposed after bouncing off *USS Voge's* starboard bow. Both vessels were seriously damaged. Later, both captains, then retired, met to swap stories much to the relief of the *Voge's* captain who thought he had sunk *K-22*.



capture and promulgate these types of data as well.

The U.K.'s Marine Accident Investigation Board (MAIB) analysis (2002) on fishing vessel accident data for 1992 to 2000 provides one of the few statistical reports by which submarine losses may be benchmarked against another similarly hazardous maritime industry. Indeed, the U.K. Health and Safety Executive (HSE) doctrine on risk-based decision-making would suggest that the U.K. fishing industry, with 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.

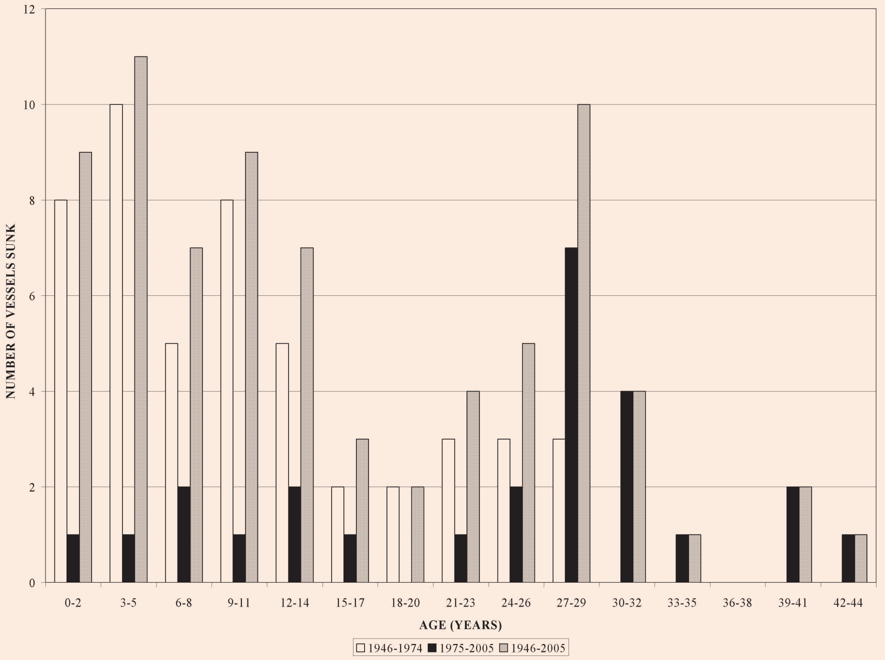
The use of advanced statistical process tools such as control charts has been demonstrated and proven useful for identifying periods where special causes dominated. Concentrating efforts on root-cause analysis for these periods can aid in the mitigation of significant risks and improvement in performance.

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

Figure 7

Age of Vessel When Sunk



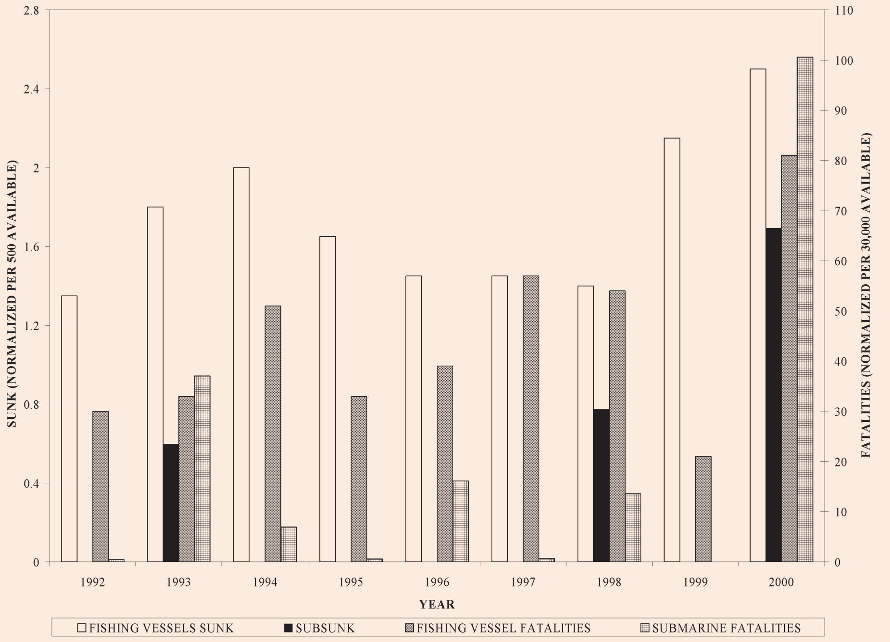
into the design process, builders are minimizing risks and costs later in the running period. Along these same lines, new innovations such as unmanned underwater vehicles eliminate the risks to humans by removing them from the equation.

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. ■

Figure 8

U.K. Fishing Vessels & Submarines: Sunk & Fatalities, 1992 to 2000



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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

Parameter	Period	Mean		Ratio of means (F/V:submarine)
SUNK	1992 to 2000	1.8	F/V SUNK/500 available	5.3
		0.34	SUBSUNK/500 available	
Fatalities		44	F/V fatalities/30,000 available	2.2
		20	Submariner fatalities/30,000 available	