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The Grounding of *Exxon Valdez*: An Examination of the Human and Organizational Factors

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Abstract

Just after midnight on March 24, 1989 the tankship Exxon Valdez ran aground on Bligh Reef in Prince William Sound, Alaska. The consequences of the accident was the loss of 258,000 barrels of crude oil resulting in substantial environmental and economic loss. The vessel possessed the best technology available in the tanker industry and was the pride of the Exxon fleet. However, the complexity and the potential catastrophic consequences of using these new technologies is leading us to examine a more critical element: the human factor.

It has been determined that approximately 65% of catastrophic marine related accidents have been the result of compounded human and organizational errors (HOE) during operations. Consequently, tanker operators and regulatory agencies have begun to realize the importance in examining the critical human factor element in tankship operations. Probabilistic risk analysis (PRA) procedures using influence diagramming are currently being developed to examine the effects HOE in marine related accidents.

This paper examines: (1) the human and organizational elements which led to the grounding of Exxon Valdez, (2) structuring of the accident cause-effect relationships into an analytical framework, (3) methods for probabilistic risk analysis (PRA) of HOE in the accident, (4) changes in operational and regulatory policy in post-Exxon Valdez era, and (5) methods for determining HOE management alternatives for future tanker operations.

Introduction

Just after midnight on March 24, 1989 the tankship *Exxon Valdez* ran aground on Bligh Reef in Prince William Sound, Alaska. Within the next 24 hours, the tankship spilled 258,000 barrels of oil into Prince William Sound. The vessel possessed the best technology available in the tanker industry and was the pride of the Exxon fleet. Nevertheless, the grounding led to the worst environmental and economic tanker oil spill in U.S. history. It has been stated that the Exxon Valdez had run aground on Bligh Reef the day oil was discovered on the Alaskan North Slope such that a catastrophic oil spill in Prince William Sound (PWS) was an accident waiting to happen. It just so happened to Exxon before anyone else.

This paper examines: (1) the human and organizational elements which led to the grounding of *Exxon Valdez*, (2) structuring of the accident cause-effect relationships into an analytical framework, (3) methods for probabilistic risk analysis (PRA) of HOE in the accident, (4) changes in operational and regulatory policy in post-*Exxon Valdez* era, and (5) methods for determining HOE management alternatives for future tanker operations.

Background

The events surrounding the accident has brought to surface a critical element in tankship operations: the human factor. Historically, engineers, operators, and regulators of marine systems have looked toward "technological fixes" to reduce the chances of accidents. Only after the grounding of *Exxon Valdez* have we looked to address the human element since sufficient technology was available to prevent the accident from occurring. Approximately 65% of all catastrophic marine related accidents are the result of compounded *human and organizational errors* (HOE) during operations [1, 2].

In a world of increasing technological growth, society has looked at the benefits of new technologies and the seemingly endless opportunities in their use. However, accidents such as *Bhopal*, *Three Mile Island*, *Chernyobl*, and *Piper Alpha* disasters have led us to realize our limited understanding of complex technological systems and reassess the potentially catastrophic consequences of high technology disasters [3]. Two major factors are involved in analyzing these "high consequence - low probability" accidents: (1) the complexity and limitations of the technological systems were not well understood by the operators (latent flaws leading to catastrophic consequences, excessive reliance on technology), and (2) human and organizational elements were major contributing factors (individual errors, lack of information and incentives).

As engineers, operators, and regulators of potentially catastrophic systems, it has become critical to directly consider the effects of HOE on tanker operations in reliability based analysis. Currently there is no structured quantitative approach to assist engineers, operators and regulators in addressing HOE factors in tanker operations. Qualitative (social and management issues) and quantitative should be used concurrently to address HOE factors. Qualitative analysis should be used as a framework for quantitative analysis [4]. One method of examining HOE related factors in accident scenarios is through the analysis of case history examples. Well documented case histories can give valuable insight into the interaction of causal factors over an extended time (contributing, direct and compounding HOE's) [5].

Established HOE quantitative analysis methodologies for tanker and offshore platform operations are currently being researched through a joint-industry project, *Management of Human Error In Operations of Marine Systems* in the Department of Naval Architecture & Offshore Engineering at the University of California, Berkeley. In the first year of the project, the effort was directed at identification, acquisition, and analysis of well-documented case histories and databases of high consequence tanker and offshore platform accidents whose root causes are founded in operations HOE. Current focus on the second year of the project has been to develop an organization and classify (taxonomy) the sources of HOE, and to develop data bases that can be used to quantify the rates of HOE. An analytical framework is being developed that will allow evaluations of the interactions of HOE errors in causing accidents. In the third year of the project, the effort is to be directed at the verification of the quantitative analyses, and development of examples that will demonstrate the effectiveness (costs and safety benefits) of various alternatives to reduce incidents of high consequence HOE.

The *Exxon Valdez* is being used as a tanker case study example (the *Piper Alpha* disaster is a case study example for platforms). The current status of the research is in the developments of the analytical framework models. Quantitative analysis of the accident will be conducted within the following months.

The grounding of *Exxon Valdez*

The events described surrounding the grounding of *Exxon Valdez* have been taken primarily from the National Transportation Safety Board Report (1990) and National Transportation Safety Board Factual Reports (1990). The events described primarily focus upon the actions of the *Exxon Valdez* crew, the Vessel Traffic System (VTS) crew, and the pilot.

Captain Hazelwood had been off the ship during the day she was loading crude oil in Valdez. By his own confirmation he was drinking that day. The NTSB's proposed findings of the facts conclusions and recommendations states, his blood alcohol level would have been approximately .285 at the time he boarded the ship, to do so without showing some evidence of physical impairment or needing some assistance. Additionally a cab driver and an Alyeska guard interviewed by the Board investigators reported none of the *Exxon Valdez* crew members returning to the vessel were "under the influence of alcohol". During the time the pilot was aboard the ship, the pilot smelled alcohol on Captain Hazelwood's breath. He had been off of the bridge for approximately one hour and thirty-five minutes before returning at the time of the departure of the pilot.

Late on March 23rd, shortly prior to his relief, the helmsman responded to an order from the master to sail the ship 180° and put her on automatic pilot. Helmsman Harry Claar was puzzled by this order. He didn't check it with the master. The master left the bridge but not before asking the third mate, Cousins, if he felt comfortable sailing the ship under these conditions. Despite his limited experience in sailing the ship, he replied that he did. Federal and Alaska state law require that ships be under the control of a federally licensed pilot when transiting in U.S. pilotage waters (inside the three mile territorial seas).

At 2347 the ship left the Traffic Separation Scheme (TSS) going into the inbound lane to avoid the ice. At 2355 the helmsman was relieved by Robert Kagan [6]. The NTSB has simulated the path which *Exxon Valdez* traveled once deviating from the TSS and is shown in Figure 1. The ship was on "load program up" which meant she was increasing her speed while exiting the harbor. Thus, *Exxon Valdez* was traveling at 12 knots and on automatic pilot just prior to hitting Bligh Reef. Putting the ship on automatic pilot in confined waters and not telling the third mate the master had done so was extremely inconsistent with normal practice. At his relief at 2350, the helmsman reported to the third mate that the ship was on automatic pilot, something the third mate did not know about (there is some speculation that the ship was operating on automatic pilot until the grounding). The third mate did not discuss the reason for the automatic pilot with the master.

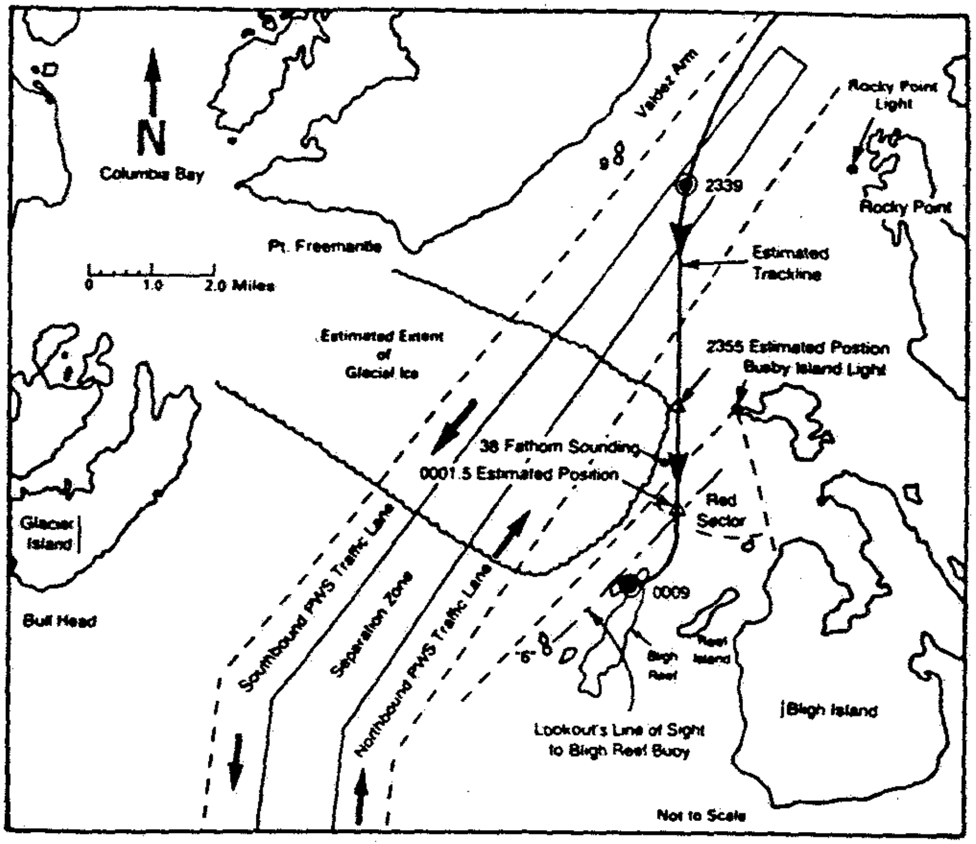

Figure 1: Trackline of *Exxon Valdez* [9]

The third mate was Gregory Cousins. He holds a second mate's license, and first sailed as the third mate on an Exxon tanker in January, 1987. He had sailed on five tank vessels owned by the company and had been employed by Exxon for nine years. He had completed approximately 18 voyages in and out of Valdez, sailing in both unlicensed and licensed categories. At the time of the grounding he had approximately 199 days of at sea experience as a third mate.

The night before he slept from 0100 to 0720, then after lunch had a cat nap (1300 to 1350) and relieved the chief mate for supper and worked through to the grounding. The third mate had only about a year's experience as a deck officer. The situation is further complicated because the chief mate had worked the entire time of the loading, was asleep, and was unavailable as an additional resource. In addition to his bridge duties, the cargo is the primary responsibility of a chief mate in the Merchant Marine. This includes loading and discharge of cargo could only be conducted by the second and third mate on duty, the chief mate is normally on hand for loading and discharging are initiated and concluded. The ship left port at about 2054.

The third mate decided not to call his relief, the second mate, until after they cleared the ice (the error might have been detected through the watch relief procedures). The third mate determined there was .9 mile between Busby Island and the ice floe and felt he could pass around the ice. The master left the bridge at 2352. The third mate relied considerably on the radar, but did not correlate the radar information with the navigation charts through position fixing. The submerged reef was not displayed on the radar.

Watch condition C (Exxon Bridge Organizational Manual) stated that two officers be on the bridge during this transit. The chief mate was sleeping. Some time before 2355 the third mate put the ship on manual control. At 2355 he plotted the ship as 1.1 miles from Busby Island. Before midnight the AB reported a red light flashing every five seconds to the third mate. He acknowledged her and stated that he knew the light to be Bligh Reef, light #6. The third mate ordered a right 10 degree rudder but the vessel did not move to this position. There is a six minute delay before the third mate and helmsman respond to the fact that the ship did not begin to turn. The Kings Point simulation of the exercise shows the helmsman could have turned the rudder 10 degrees and shortly thereafter inadvertently moved it to four or five degrees. The third mate might well have failed to detect such an error for six minutes.

About this time the AB reported the light flashing every 4 seconds on the wrong side of the ship. Now the third mate orders a right 20 degree rudder. Moving at 12 knots while the ship was still engaged in maneuvering evolutions to avoid ice violated prudent ship handling practices while increasing risk of damage to the ship if ice floes had been struck. He then orders hard right rudder. The third mate testified that two officers normally served on the navigation watch when Exxon vessels were maneuvering in confined or congested waters.

When the vessel struck the reef, the third mate ordered a hard left rudder to get the ship to stop swinging to the right and prevent the stern from swinging around. The ship had clearly skidded into Bligh Reef. The helmsman was confused about some aspects of the situation. He also reported that the third mate was panicky. The chief engineer stopped the engines at 0020. It's not clear from the NTSB report what time the ship hit the reef, but the engineer acts as if he stopped the engines after the ship hit. It's possible the ship didn't stop until 0090. At 0027 the master lets VTS know the ship had run aground and at 0035 the master ordered the main engine restarted.

For approximately 45 minutes the master made an attempt to remove the vessel from the reef, probably moving from dead slow ahead to full ahead, and finally slowing down and stopping. The chief engineer had advised the master not to move the ship. VTS had advised to move cautiously.

Exxon states that Hazelwood was not trying to dislodge the ship from the reef because he never put the ship astern. According to NTSB documentation the record fully supports the fact that Hazelwood gotten the ship off the reef it would have capsized. Other evidence suggests it might not have [7]. However, Captain Deppe, Exxon Shipping spokesperson, testified that only the support offered by Bligh Reef kept them afloat. VTS had advised to move cautiously. XO and Senior Investigating Officer (SIO) from the CG Marine Safety Office (MSO) boarded the ship at 0335.

VTS involvement the night of grounding

The lack of vigilance with which the VTS handled operations the night of the accident is another factor in the grounding. Only one civilian watchstander and one enlisted radioman were on duty. But the accountability and responsibility rested with people who weren't there. Neither the Commanding Officer (CO) nor the Executive Officer (XO) were at the VTS. The VTC manual requires the watchstander to advise the Officer on Duty (OOD) when a vessel deviates due to ice in the lanes. The 1600 to 2400 watchstander failed to do this. The 1600-2400 watchstander said he believed the radar didn't detect *Exxon Valdez* because it wasn't working properly. However, he did not report a malfunction to his relief or the electronics technician on duty. The watchstander's relief came on at 2333, and checked things out. Neither watchstander was aware that *Exxon Valdez* had altered course from 200° to 180°. *Exxon Valdez* was lost on the radar but could have been acquired. The 0000-0800 watchstander said he didn't try to do this because he'd been told by the other watchstander that the *Exxon Valdez* was no longer visible on radar. At the time of the accident the watchstander was away getting a cup of coffee. That the radar was operating appropriately is evidenced by the fact that the watchstander had no difficulty detecting the grounded ship.

The ship previously leaving the port reported heavy ice to the VTS but the VTS saw no reason to report this to *Exxon Valdez* or to more carefully monitor her. At about 1930 a passenger ship approached Valdez. Her captain said the ice was some of the worst he had ever seen and reduced speed. He did not report this to the VTS. At 1930 the outbound *Arco Juneau* reported ice in the TSS. The VTC operator said he was concerned about the heavy ice reported by the *Arco Juneau* but that didn't motivate him to have the ship report her position more frequently, nor did he report that to the *Exxon Valdez*. Both ships transited during the day and neither had as far outside the TSS to go as the *Exxon Valdez* because when she transited the ice was much further to the northeast.

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Exxon Valdez remained on course 180° for nearly 18 minutes. The VTC operator had ample time to call the vessel and ascertain her intentions. Any inquiry from the VTC regarding the vessel's intentions probably would have alerted the third mate to turn earlier or apply more rudder. The VTS communication system failed to meet the Coast Guard's requirement of 99.9% operational status. During the evening of March 23rd the Naked Island and Cape Hinchinbrook remote communication sites were inoperable. The system was old, requests for money had been denied, and the harsh Alaskan climate degrades the system easily.

Only when *Exxon Valdez* called the VTS did the watchstander know she had gone aground. He then adjusted the radar and picked her up. There's a lot of testimony about how watchstanders thought the radar wasn't working well. The number 1 (master) radar which synthetically displayed the TSS boundary lines was burned out. The Coast Guard was warned in 1984 that the system would begin deteriorating in the next two years without attention. After the accident the Operations Officer testified that he noted its deterioration in the last two years. The contractor didn't keep the system well maintained and as a result it was inoperable up to 28% of the time.

The human and organizational elements

The human and organizational contributions can be separated into: (1) underlying factors creating a reduced tolerance of the state of the system (primarily the organizations) and (2) actions by the front line operators (primarily the individuals) whose errors initiate the catastrophic events [5]. The underlying contributors were Exxon Shipping Company and the U.S. Coast Guard. The initiating contributors were the crew aboard the vessel and the VTS crew stationed in Valdez. The failure of these individuals in preventing the accident can be attributed to both individual errors by the tanker crew and VTS personnel. In addition, the Exxon Shipping and the Coast Guard played contributing roles in establishing an operation which had few checks and balances to maintain safe tanker operations. The system had atrophied through the years and little effort had been put forward to maintain reliable operations [8].

Exxon Valdez crew

The NTSB concludes that considerable uncertainty remains concerning the master's intentions for maneuvering the vessel back toward the Traffic Separation Scheme (TSS). The master would have to begin turning back into the lanes when he was abeam Busby Light. However, both he and the third mate noted on the chart a position about 7/10 of a mile further to begin the turn. By making the turn abeam Busby Light the ship would have drifted about a half mile further but then would have come parallel to the lane. By advancing further the navigational maneuvering required to bring the ship back into the lanes was considerably more extreme. The board concluded that it was feasible to begin the turn either abeam Busby light or 7/10 of a mile further south, as long as the watch was capable of simultaneously monitoring the vessel's position relative to Bligh Reef, watching out for ice, and conning the vessel.

"The frequent fixing of the vessel's position could have taken a substantial amount of the third mate's time and would have limited his ability to concentrate on other important functions, such as watching for ice and conning the vessel. Conning also requires careful supervision of the helmsman. Under normal conditions, when a master or a pilot is conning the vessel, the watch officer assists by carefully observing the actions of the helmsman in response to orders from the master or pilot. This enables the officer conning the vessel to concentrate on observing and directions the vessel's movements. In this instance, the helmsman had limited steering experience and required additional supervision. The master was aware of the helmsman's limitations and should have considered them before leaving the bridge [9]."

Testimony given the investigating board indicated that there could be a period of 20 minutes when no lookout is posted. This period is caused then the lookout and helmsman change assignments. In this instance there is no evidence that the lack of a lookout from 2340 to 2350, when the AB assumed her lookout, contributed to the accident.

Exxon Shipping Company

Several operational policies and procedures of operations of Exxon Shipping Company were observed to have potentially contributed either directly or indirectly to the accident:

(1) Reduced manning levels led to fatigue and job overload.

(2) There were no established policies regarding procedures to reduce the risks of operating with smaller crews.

(3) Lack of compliance with federal statues regarding work schedules for deck officers.

(4) Tanker crews had not complied with written company policies regarding drug and alcohol internal policing to ensure compliance.

Reduced manning in the U.S. merchant marine fleet has become a high profile issue in both the domestic and foreign the maritime industries. The industry and regulators have conducted, funded, and participated in studies to determine the cost and effects of reduced manning. Many of these studied have been conducted to justify crew reductions to cut operating costs. The policies Exxon Shipping Company had in updating fleet and reducing crew are consistent with those of the industry.

Yet, there is no evidence Exxon Shipping Company had policies or procedures to examine the risks and reliability of using reduced crews. No supervisory training recognized such factors as fatigue, social isolation, longer hours at sea, etc. There was no company program to monitor officer's work in excess of eight hours a day. There was evidence that officers now did deck work that unlicensed workers do before the accident.

In June, 1988, Frank Iarossi (former president of Exxon Shipping) presented a paper titled "Surrendering the Memories" in which he stated that it was Exxon's policy to reduce its standard crew compliment to sixteen by 1990. He noted that other ships (mostly foreign flag) successfully operated at such levels. The paper focuses on economic issues yet makes little mention of considerations of ship safety and crew fatigue. The NTSB came to possess three memos to Exxon Shipping Company masters ordering them to purposefully reduce overtime to satisfy Coast Guard overtime concerns and to better argue for reduced manning levels.

Reduced manning may certainly have led to Exxon Shipping Company's failure to comply with two federal statutes regarding work hours for deck watches. The first states that an officer cannot take charge of the deck watch on a vessel when leaving a port unless he has been off duty for at least six of the twelve hours immediately before leaving. The second states a licensed individual or seaman is not required to work more than eight hours a day except for safety related functions (the average workday was approximately 10 hours including voluntary overtime). Apparently Exxon Shipping Company had no provision for giving six hours of rest to any deck officer before getting underway.

It appears that company's written policies about alcohol and drug use weren't taken very seriously. The policy instructs supervisors to report to the medical department employees whose performance was unsatisfactory due to alcohol use. Crew members are not to perform job duties within four hours of having a drink. Hazelwood entered an alcohol rehabilitation program in 1985 which the company learned about when his supervisor tried to contact him. No supervision was involved in making sure he continued with some sort of support group. The disability began April 1, 1985 and ended on May 16, 1985 and was followed by a 90 day leave of absence. Captain Hazelwood then returned to sea duty. The NTSB concludes that he should have been confined to shore duty until there was ample proof this problem was under control. After the leave of absence the fleet manager and ship coordinator were given follow up responsibility including visits to his ship.

Captain Hazelwood's performance evaluation of 1988 had been more than satisfactory. Yet he had two convictions for DUI (1985, 1988) and had a suspended drivers license at the time *Exxon Valdez ran* aground. Annual performance appraisals for the masters were not available for every year. The company has made no statement about how it follows up on appraisals. A number of statements about Hazelwood's performance lead to the conclusion that he had difficulties managing people as early as 1974 [9].

U.S. Coast Guard

Three Coast Guard HOE factors are observed to be contributors to the accident.

(1) Supporting (whether voluntarily or involuntarily) the reduction of crew sizes leading to fatigue and job overload.

(2) Deterioration and downgrading of the VTS in Valdez over the years.

(3) Reorganization, loss of billets, and use of inexperienced personnel for VTS duties in Valdez.

Vessel Manning

Reductions in vessel manning requirements has become a increasingly controversial topic of debate. The controversy is fueled by operators using reduced crews for foreign flagged vessels not under U.S. Coast Guard jurisdiction. The Coast Guard currently depends on an integration of laws, regulations, informal policy guidelines and maritime tradition to establish guidelines for crew manning levels [9]. The Coast Guard earlier concluded that minimum manning for the vessel would be fifteen crew members (*Exxon Valdez* had 20 crew members when she grounded on Bligh Reef). Events aboard *Exxon Valdez* indicate that fatigue and job overload had led to the chief mate not being present on the bridge while transiting PWS as would his normal duties dictate. The presence of the chief mate may have led to better decision making while in transit. In addition, the presence of an additional mate on the bridge could have added to the redundancy of the bridge watch.

Vessel Traffic System (VTS)

In 1971 the Coast Guard developed preliminary concepts for VTS and in 1973 submitted a final VTS study report estimating there would be a reduction of approximately 70% of the accidents caused by collisions, rammings and groundings. In 1977, the U.S. Coast Guard VTS systems were being planned and operated in San Francisco, Puget Sound, New York, New Orleans and Berwick Bay, Houston/Galveston, and Prince William Sound (PWS).

In 1988, Coast Guard fiscal budget constraints resulted in the closure of both the New York and New Orleans VTSes. In a report to Congress, the General Accounting Office issued a report stating that the Coast Guard had chosen both New York and New Orleans VTSes: "to resolve it's immediate problem of reducing operating expenses and gave little consideration to the effectiveness of each of the VTS's in enhancing safety." [11]. This general lack of importance manifest itself in the deterioration of the VTS in PWS over the ensuing years.

Before VTS was established for PWS in 1977, marine safety functions were conducted by the Marine Safety Detachment (MSD) under the authority of the MSO Anchorage. When the MSO was established in Valdez, additional duties were taken on which had normally been performed by the MSO Anchorage. Unlike other VTSes across the country, Valdez VTS personnel could be utilized in non-VTS duties at the discretion of the Commanding Officer (CO). This gave the green light to the CO MSO Valdez to distribute MSO duties as he wished. In a letter to the CO of the USCG headquarters in 1985 he stated, "...what MSO Valdez does much larger than just having a few people watch radar screens in the least-trafficked, yet fully federally mandated, VTS in the country" [9].

The VTS consisted of a Vessel Traffic Center (VTC), radar surveillance system, and a communication system. The VTC is manned 24-hours around the clock by two watchstanders (one radar watchstander and one radio watchstander). The radar watchstanders responsibilities were to maintain vessel positions while the radio watchstander established and monitored radio contact for PWS. The radar surveillance system had initially been able to maintain contact with vessels from Port Valdez to areas south of Bligh Reef. Vessels were required to give VTS general information about vessel name, position, estimated time of arrival (ETA) to navigation in VTS area, speed, cargo type, towing, vessel impairments, and additional requested information three hours before entering PWS. Once in VTS waters vessels were required to report speed changes, intentions of crossing the TSS 10 minutes prior to crossing, when clearing the Traffic Separation Scheme (TSS), and when vessels pass a reporting point.

One obtains a picture of a deteriorating service over the years preceding the accident. A greater burden had increasingly been placed on the commanding officer to engage duties not directly related to VTS. Monitoring procedures were changed and became less rigorous over the years. When the VTS was installed in 1977 the watchstander plotted the range and bearing of all vessels transiting the part of the port under radar control. In 1984 new Raytheon equipment was installed and plotting was discontinued. This change wasn't noted in writing until 1987. The 1987 memo was issued because the dramatic increase in shipping traffic was placing too many burdens on the operators. The memo was designed to reduce work associated with vessels in Valdez Arm. Vessels transiting Valdez Arm were to be monitored, but no written guidance about how far to monitor outbound traffic or when to acquire inbound traffic. This was left to the discretion of each watchstander.

VTS was a part of the Operations Department and performed duties other than watchstanding. Watchstanding had been reduced at the same time that the potential for problems due to ice floes in the sound was increasing. Procedures for certain eventualities were not well spelled out or implemented. In addition, it appears the current CG CO had not put the pressure on his superiors to upgrade equipment in the way his predecessor had done.

The VTS was reorganized in 1982, making four of the five watch supervisors department heads who had little to do with supervising watches. In 1986 the CO of MSO Valdez proposed that MSO Valdez be downgraded to a MSD. The proposal also eliminated five VTS officer watchstander billets. In 1987 the watches were discontinued and replaced by a Command Duty Officer (CDO). The CDO was not required to be at the VTS during routine vessel transits. However, it was required that he be contacted in the event that vessels deviated from the TSS. The CDO could be contacted 24 hours a day if conditions arose where vessels need to deviate from the traffic scheme.

In 1988 the VTS lost five billets. As a result remaining personnel took on additional functions having little to do with VTS and by default the senior watchstander became responsible for supervising the day to day operations of the VTS. This person worked days and stood watches when anyone called in sick. In 1988 the OOD and CDO functions were merged and called the OOD and the duties were expanded. Several of the OODs were enlisted personnel, junior to the civilian watchstanders they supervised. On the day of the accident only one OOD was a qualified watchstander. The station OOD on duty prior to the accident had never qualified as a watchstander. Because of the replacement of the CDO with the OOD supervision and communication between the VTC and senior MSO/VTS personnel probably declined. No officer's primary duty was to be in charge of the VTS.

Despite the fact that ships were regularly deviating from the TSS the CO of MSO Valdez reported that if a vessel knows its position and is maneuvering no further radio contact is required. He continued, there is no good reason for a ship to deviate from the TSS, a vessel requesting deviation is requesting something out of the norm. VTC watchstanders don't have the authority to allow vessels to leave the lanes and if a vessel requests deviation the request is forwarded to the Operations Officer (OO) who forwards it to the CO or Executive Officer (XO) for a reply. The fact that neither the CO nor the OO appeared to be aware of the fact that vessels regularly departed the TSS, indicates the data forms were not reviewed to determine routes vessels followed. Since no data were kept there was no standard against which to measure radar or personnel performance.

In 1980, after the *Prince William Sound* lost power and almost ran aground in PWS, the Coast Guard recommended installing reinforced tow lines on the tankers and requiring a tugboat to escort tankers to Hinchinbrook Island. The lines were installed. In 1981, James Woodle, the CO of Valdez, recommended that the Coast Guard radar system be improved in response to the break up of the Columbia Glacier [6]. Nothing was done. In 1986 his successor, Steve McCall, favored downgrading the system. According to the NTSB Report (1990) in 1984 the Coast Guard requested the installation of an additional radar site on either Glacier or Bligh Island. In 1984 the CG and oil companies met to talk about the increasing ice and decided to operate as before. In neither instance was anything done. For a time the oil companies ordered their vessels to operate at reduced speed or only during daylight.

In 1986 the CG issued a series of recommendations and directives that made pilotage so complicated no one knew what was required [6 ,12]. A study done after the accident showed that the existing radar was incapable of reliable radar coverage of Valdez Arm.

Through the years, tanker crews became unaware of the extent of the VTS system [12]. In 1988 the CO of the MSO sent the commander of maintenance for the Pacific a letter requesting information on the 1984 request for update. He was notified that as off February 13, 1989 there was no plan for update.

By the early 1980's both the Coast Guard and the maritime industry were concerned about the ice in the sound. Between 1981 and 1984 18.9% of the vessels transiting the VTS area deviated from the TSS because of ice. In August of 1984 a meeting was called between operators, Coast Guard, State Pilots, and Alyeska to discuss ice conditions. A Coast Guard representative makes mention of the true concern of ice conditions in PWS though representatives at the meeting tried to downplay the problem [13]. Nonetheless, an Exxon representative said he was confident in the abilities of the masters and their vessels to handle the situation and would like to see things operate as they were. An Arco representative agreed saying that he believed in preliminary planning reports but no need for further controls. Pilots concurred that the masters would not transit if they felt the ice was too dangerous.

In summer, 1985, a new CO took over at MSO Valdez. He did not require the VTS to keep a record of the number of vessel transits affected by ice. Ice reports provided by the VTC were retransmissions of earlier reports from transiting vessels. Thus, they may well be out of date for the next vessel.

Pilotage

The initial plan of the U.S. based oil companies were to use the pilots for transiting PWS until their masters fulfilled the Federal pilotage requirements. This plan included using docking masters for docking the vessels at the terminals. The Southwest Alaska Pilot's Association succeeded in lobbying and obtaining legislation requiring tankships in excess of 50,000 dead weight tons to employ a pilot while transiting state waters. This law included that the control of the vessel by state or federal pilots during docking thus excluding the use of docking masters. The state pilots each held federal pilotage certification.

In 1977 the state pilot association established a pilot station at Cape Hinchinbrook using a converted fishing vessel, the *Blue Moon*. In 1980 the *Blue Moon* foundered. Due to the dangers involved in embarking and disembarking pilots in the outer Prince William Sound, the pilot station was then moved to Rocky Point at Valdez Arm. At this point, the Alaska Board of Marine Pilots decided not to reestablish the pilot station at Cape Hinchinbrook and eliminated the state requirement for state pilotage between Cape Hinchinbrook and the pilot station at Rocky Point.

The Federal Pilotage requirements still were in effect though there were no transport pilots between Cape Hinchinbrook and Rocky Point.

This created few problems since most TAPS trade masters held pilotage between Cape Hinchinbrook and Rocky Point. However, this did cause some difficulty for the foreign flagged vessels who found themselves dependent upon the pilots for navigating the entire Prince William Sound. Soon after the sinking of the *Blue Moon*, the Coast Guard it was revealed that they had no authority to require foreign flagged vessels from obtaining Federal pilotage. Though the Ports and Waterways Safety Act requiring such pilotage there is no indication that the Coast Guard had established enforcement regulations.

To accommodate the foreign flag tank vessels and U.S. flagged vessels without Prince William Sound pilotage endorsements, the COTP for the Port of Valdez established a set of requirements for transit of these vessels (Port Order 1-80, February 25, 1980). The determination of whether pilotage was necessary was left to the discretion of the duty officer or COTP. The regulations included the limited transit of non-pilotage vessels from Cape Hinchinbrook to the pilot station during daylight hours and two licensed officers on the bridge while transiting the sound (one on watch and the other navigating).

In June 1985, proposed changes in pilotage regulations were introduced (funny that this was soon after McCall arrived on the scene). The Coast Guard reduced the areas of required pilotage. In September 1986, the Coast Guard decided to cancel COTP Order 1-80 and issued requests for pilotage on a case by case basis for tank vessels without pilotage endorsements. The major change was in the requirement of a 2 mile visibility in the sound with potential reassessment of this proposal during averse weather conditions.

After the *Exxon Valdez* ran aground, the pilot station was reestablished at Bligh Reef.

Developing an analytical framework model

Constructing accident analysis framework models involves: (1) structuring the primary events and decisions leading to the grounding, (2) using a human and organizational error classification to determine the contributing causes, and (3) quantitative analysis using either reliable data information and/or expert opinion when reliable data is unavailable.

This analysis follows a progression of modeling stages:

Stage 1: Use influence diagramming structure to establish the dependency of events leading to the grounding.

Stage 2: Establish the accident causes using a human and organizational error classification and model them into the influence diagram framework.

Stage 3: Generate conditional probability distributions using Bayesian statistical techniques from available data sources.

Stage 4: Final construction and evaluation of the influence diagram models to determine overall probabilities of failure and expected returns.

Stage 1: Establishing dependency of events

The model represent the set of events that occurred aboard the *Exxon Valdez*, the vessel transit in and out of the TSS, and at VTC in Valdez. Figure 2 summarizes the dependency of events, direct causes and decisions involved in the grounding discussed above. These influences are represented by nodes, (events, causes, and decisions) and arcs which establish the dependencies. Probabilities are represented by oval nodes, deterministic events are represented by double-lined oval nodes, decisions are represented by rectangular nodes, and expected returns are represented by double-lined rectangular nodes. The development of influence diagram models should be the effort of a group of experts. Discussion of differences in opinion of the relationships of between events and their causes illicit the development of more realistic models [14].

Stage 2: Establishing accident cause

In establishing the accident cause, the first-generation taxonomy being developed for the *Management of Human Error in Operations of Marine Systems* project identifies the contributing causes to marine related accidents:

(1) *human/system interface* (operating environment, normal and emergency control systems)
(2) *knowledge/experience/training* (normal and emergency operating systems)
(3) *maintenance* (normal and emergency operating systems)
(4) *physical/mental lapse*
(5) *violations* (organizational or regulatory procedure or policy)
(6) *morale/incentives*
(7) *job design*
(8) *commitment to safety* (front line operator or organizational)
(9) *regulating/policing* (organizational or regulatory)

(10) *operating policy* (organizational or regulatory)
(11) *communication & information* (operator control system, front line operators, and organizational)
(12) *manning requirements*
(13) *resources* (organizational, regulatory)

The *Annotated Human Factors Taxonomy* (AHFT), soon to be used by U.S. Coast Guard marine casualty investigators, form the basis for the U.C. Berkeley HOE project taxonomy. The AHFT distinguishes underlying, direct, and compounding causes to marine casualty events as exemplified in Figure 3. Additional sources are used to examine *violations, commitment to safety*, and *resources*. The influence of causes upon the decisions and events specific to *Exxon Valdez* are shown in Figure 4.

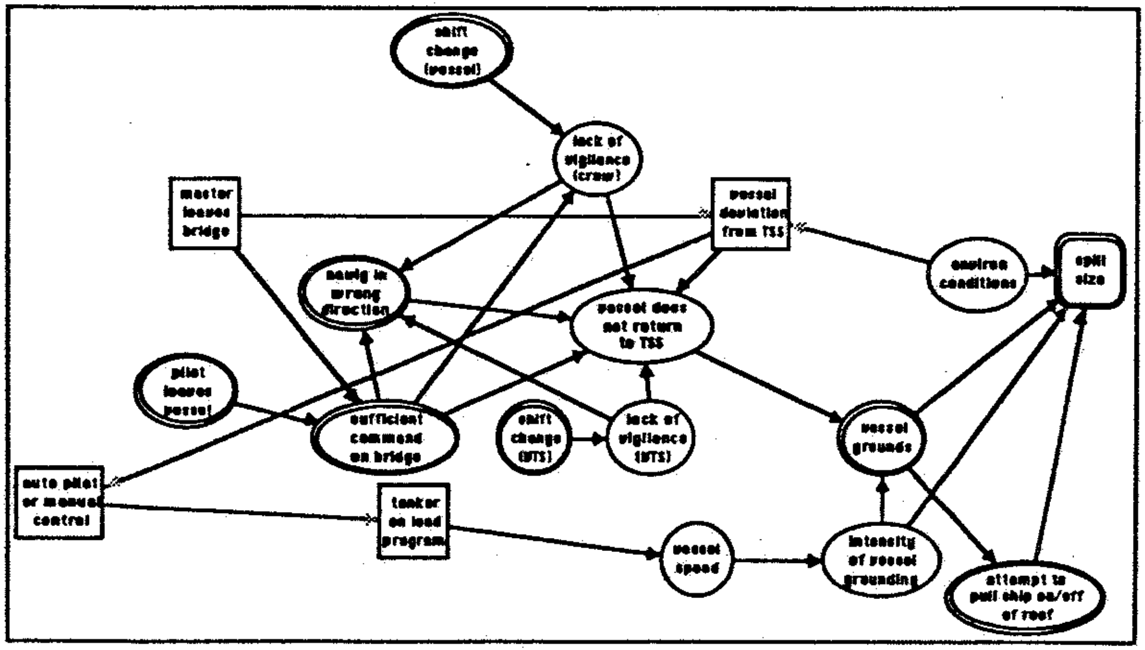

Figure 2: Influence of events and decisions leading to the grounding of *Exxon Valdez*

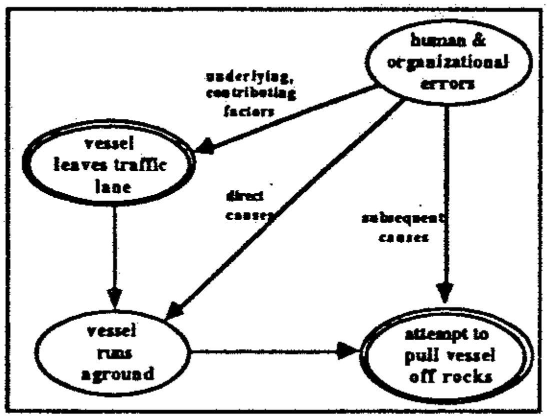

Figure 3: Influence of HOE on sequence of grounding events

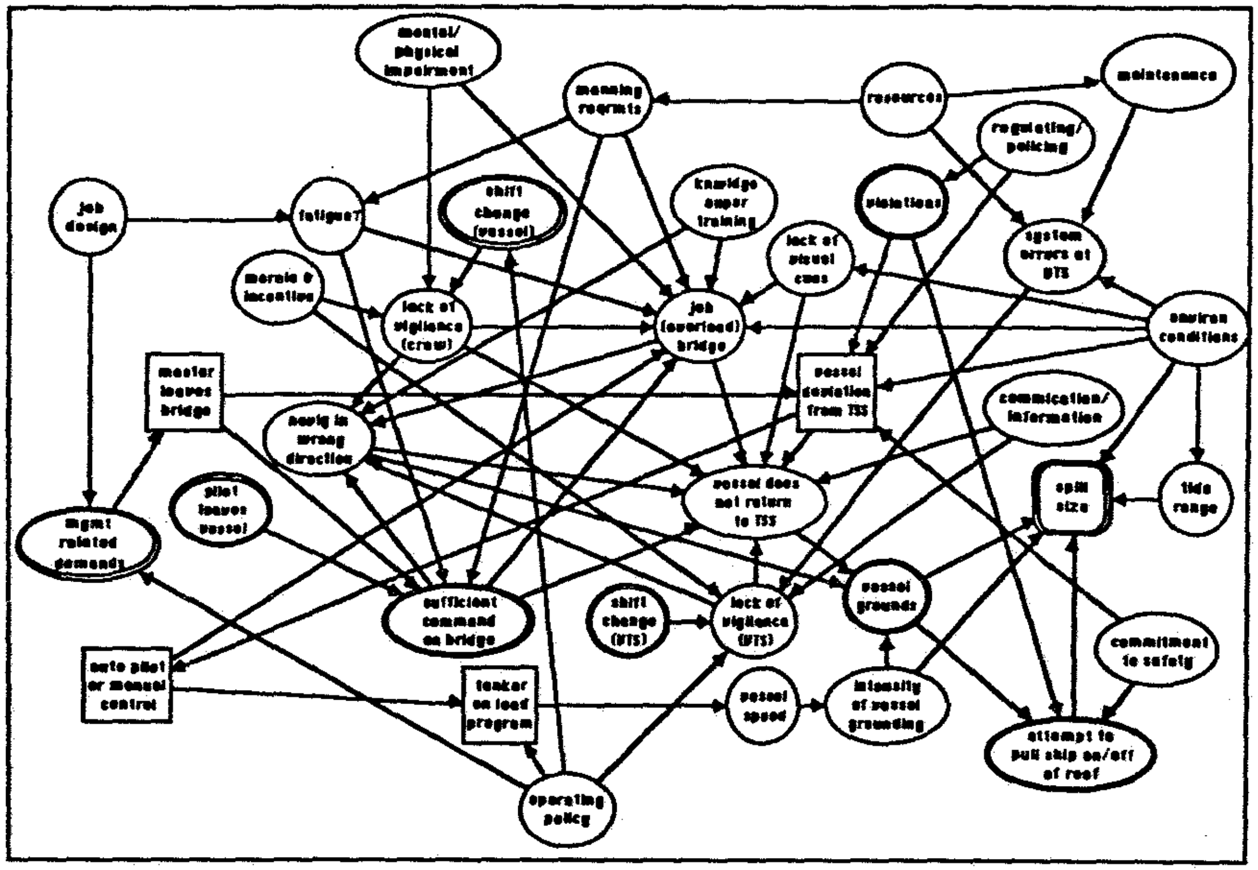

Figure 4: Influence of HOE causes on the grounding of *Exxon Valdez*

Stages 3-4: Probabilistic Risk Analysis

Current quantitative analysis of HOE data is limited to the use of subjective expert opinion. However, computer codes using the AHFT and additional data sources are in the process of development. These codes include the examination of conditional probabilities between events, events, and their causes. Bayes Theorem is used to determine the dependency of events and causes:

$$P(E_i|C) = \frac{P(C \mid E_i)\,P(E_i)}{P(C)} \tag{1a}$$

$$= \frac{P(C \mid E_i)\,P(E_i)}{\sum_{j=1}^{n} P(C \mid E_j)\,P(E_j)}\,, \tag{1b}$$

where E_i is the event or decision i and C is the HOE related cause. Similar relations can be determined between decisions, events and causes. Once the set of conditional probabilities have been established they can be used in the influence diagram models shown in Figure 2 to determine failure probabilities (of grounding) and expected returns (spill size). Dissemination of results of the model calculations are expected in the coming months.

The post-*Exxon Valdez* era

Since the grounding of *Exxon Valdez*, the most influential changes in tanker operations has been the Oil Pollution Act of 1990 (OPA 90). OPA 90 addresses a wide variety of tanker operation issues. These are represent current HOE management alternatives. As an overview, Title IV of OPA 90 [15]:

(1) mandates that the Coast Guard tie into the National Driving Register to detect individuals with drunk driving convictions;

(2) increases Coast Guard authority to deny or revoke mariner licenses and documents;

(3) authorizes removal of incompetent personnel;

(4) increases Coast Guard authority to deny entry of foreign vessels into the U.S. waters on the grounds of deficient manning;

(5) limit crew workhours aboard tankers to 15 hrs/day but no more than 36 hours in any 72 hour period;

(6) mandates the Coast Guard conduct studies on vessel traffic and tanker navigation;

(7) requires all new tanker builds to be double-hulled in addition to the phasing out of existing tankers beginning in 1995 and concluding in 2010; and,

(8) require the Coast Guard to designate areas where two licensed personnel are required to navigate and tug escorts are necessary.

The influence diagram frameworks in Figure 4 can be used to determine the effectiveness HOE related management alternatives of OPA 90 on the overall failure probabilities of the system. Figure 5 summarizes the influences of OPA 90 on the various contributing causes of marine related accidents discussed above. The importance in evaluating are to determine their effectiveness in reducing the overall failure probability of this class of grounding accidents. For example, when legislating OPA 90, was the reduction of cargo capacity of double-hull tankers resulting in more tanker traffic to maintain capacities taken into account [15]? The additional traffic could increase the risk of other classes of accidents such as collisions. It is imperative that these issues are addressed in the PRA analyses framework.

Operational reliability of future tanker operations

There are three primary purposes of conducting post-mortem HOE analysis studies such as the one being conducted on *Exxon Valdez*. First, well documented case histories can give valuable insight into the interaction of causal factors over an extended time. This assists in determining the sources of human errors in various states and stages of accident scenarios. Second, they provide a basis in which to examine the effects of HOE management alternatives of various classes of accidents. Figure 4 provides a basis for a "template" to examine the impacts of OPA 90 and similar existing regulation, policy or operating procedures. Third, general templates are to be formed to examine the impact of a class of accidents similar to *Exxon Valdez*. For example, Figure 6 is a generalized template of the class of grounding accidents. Establishing dependencies between events, decisions, and HOE causes would be at the discretion of the user. Additional nodes and arcs unique to the operating system, environment, procedures or policies are added by the users. The models are then evaluated to determine the overall failure probabilities.

Conclusions

The close examination of the events surrounding the *Exxon Valdez* results in realization of the impact of the human element in a high-technology society. Research and experience indicate that the majority of high consequence, low probability marine accidents have one common theme: *a chain of important errors made by people in critical situations involving complex technological and organizational systems* [16].

Formulation of the events, decisions, and causes of accidents such as *Exxon Valdez* lead to further understanding of how to manage controllable errors in operations of marine systems. Engineers, managers, regulators, and operators must be made aware of their role in reducing human and organizational errors. Qualitative and quantitative HOE analyses should compliment each other: qualitative analysis should form a basis for quantitative analysis. Only through making explicit considerations for human errors in reliability based analyses, can we reduce the likelihood of similar accidents like *Exxon Valdez*.

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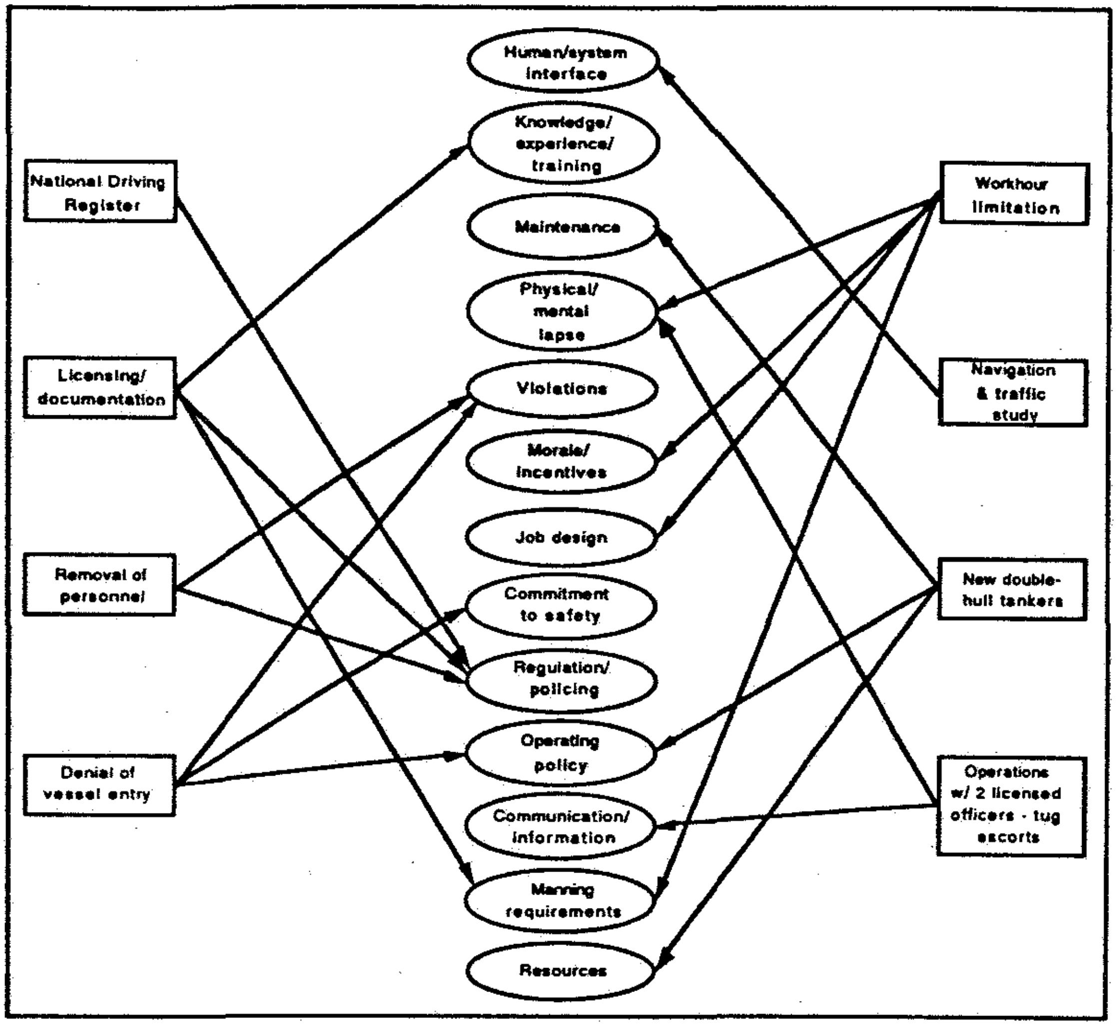

Figure 5: Influences of Oil Pollution Act of 1990 on HOE related accident causes

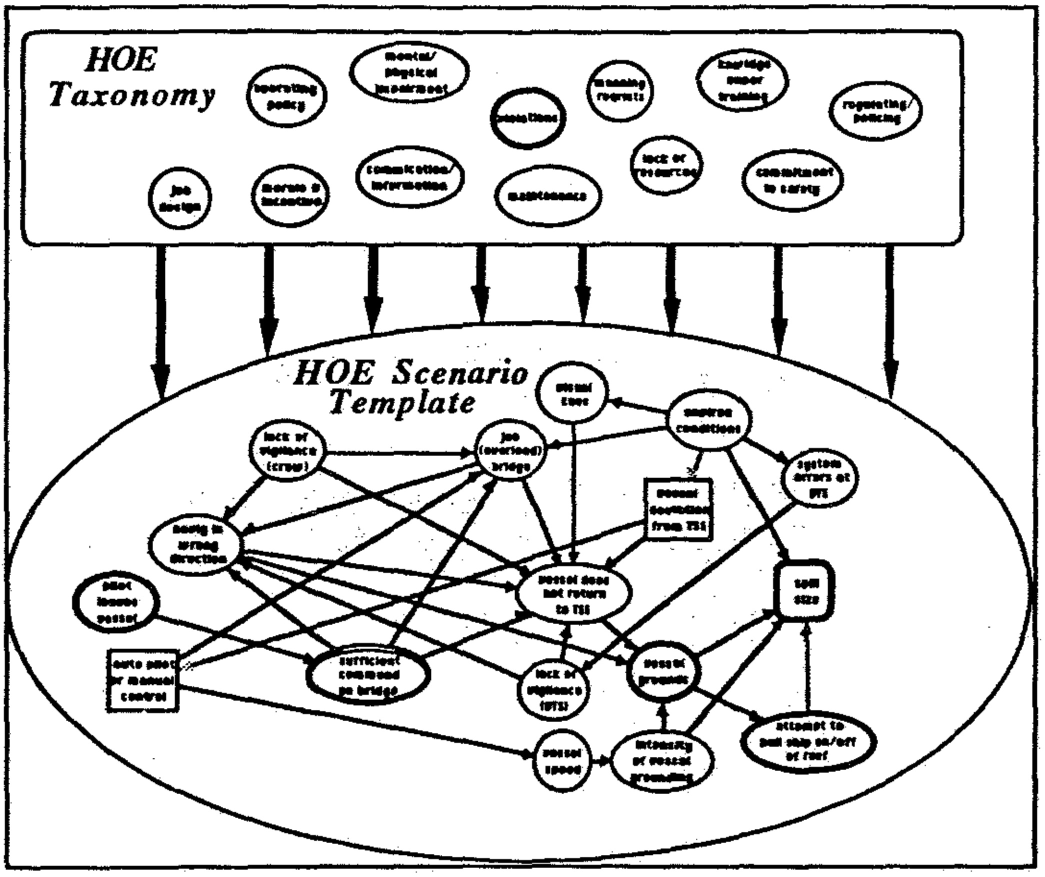

Figure 6: Influence diagram template for vessel groundings

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