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FIELD DEMONSTRATION WORKSHOP ON PERFORMANCE-BASED INSPECTION OF VESSELS ENTERING THE ST. LAWRENCE SEAWAY
(Establishing Specific Inspection Plans)

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SUMMARY

This report illustrates the use of fault tree analysis and failure modes and effects analysis (FMEA) for systematically identifying applicable and effective inspection tasks that should be included in Enhanced Seaway Inspections (ESIs) for Priority 1 vessels. (A separate report documents the results of another risk-based decision-making workshop that addressed how to more effectively determine which vessels should be classified as Priority 1 and subsequently boarded by U.S. Coast Guard [Coast Guard] inspectors.) Representatives from the Coast Guard's Marine Safety Office Buffalo, Marine Safety Detachment Massena, and Research and Development Center, as well as those from the St. Lawrence Seaway Development Corporation, the St. Lawrence Seaway Management Corporation, and EQE International, Inc. (EQE), teamed to address this topic.

Specifically, the team wanted to investigate a systematic process for answering the following questions:

- What reportable marine events are most likely to occur during transit through the seaway?
- What types of system failures are most likely to contribute to those events?
- What functional failures stemming from system malfunctions, which might be caused by actual component failures and/or human mistakes in operating/maintaining the equipment, pose the greatest risks?
- What possible inspection activities would be credible candidates (i.e., applicable) for helping to manage the areas of greatest risk?
- How cost-effective are the candidate inspection activities?
- What current inspection activities might be reduced without causing a substantial increase in risk?

The key objective was to determine whether a risk-based decision-making process could add value to inspection planning and serve as a model for further development in the future.

EQE recommended that the team use fault tree analysis to systematically identify the types of marine casualties most likely to occur in the seaway, as well as the most important contributors to those casualties.

As a follow-on to the high-level fault tree analysis, EQE recommended that the team use FMEA to examine potentially important system problems in more detail.

The use of fault tree analysis and FMEA helped the team to identify some potentially important observations about the current ESI process:

- Reducing the time spent on document processing would lead to a more effective use of inspection time and, subsequently, to less risk from inspectable problems that contribute to reportable marine events.
- The current inspection activities related to the function "Providing Start Air for Engines" seem well justified based on the importance of a failure of this function.
- The team developed the following three new inspection ideas to help prevent reportable marine events because of no/insufficient volume of start air provided to engines:
    - **Potentially high impact:** Verify that regular blowdowns are scheduled and are occurring (ESI record review) [<5 minutes of inspection time with a possibly high impact]. The team believes

that this is a good idea to implement.

- **Potentially small impact (with modest resource allocation):** Verify that preventive maintenance has been scheduled and performed on the air start valves (ESI record review, if documentation is available) [approximately 15 minutes of inspection time with a small impact]. The team believes that this should be considered because start air problems are such large contributors, but the team admits that the impact may be small.

- **Potentially small impact (with extensive resource allocation)**: Perform multiple start tests to confirm proper valve operation [approximately a 30-minute test with more than a 1-hour recovery time for small (if any) impact]. The team does not believe that this inspection would be worth the associated resource allocation.

- The current inspection activities related to the function "Providing Seaway Fittings" seem well justified based on the team's expectation that seaway fittings problems would become a dominant contributor to reportable marine events (i.e., highly negative risk impacts) if these tasks are not performed.

The analysis tools did provide a systematic and understandable process for inspection task planning. Because ESIs are already highly evolved inspection plans, the team did not expect major changes from the current inspection strategy. However, the team did expect some new inspection ideas to surface. The team also expected the analysis to help defend the currently defined inspection tasks. A less mature inspection program (or an ineffective program that is allowing a number of losses to occur) would likely experience more changes by applying this process.

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1. INTRODUCTION

Marine Safety Office (MSO) Buffalo and Marine Safety Detachment (MSD) Massena apply the U.S. Coast Guard's (Coast Guard's) Port State Control Targeting Matrix (PSCTM) to prioritize vessels for boarding inspections upon entry into the St. Lawrence Seaway. The PSCTM has four priority levels, ranging from Priority 1 (the highest) to Priority 4 (the lowest). By agreement among the Coast Guard, the St. Lawrence Seaway Development Corporation (SLSDC), and Canadian authorities (Transport Canada and the St. Lawrence Seaway Management Corporation [SLSMC]), Coast Guard personnel (accompanied by Canadian officials) board only Priority 1 vessels. During these boardings, which normally occur in Montreal, Coast Guard personnel perform an Enhanced Seaway Inspection (ESI). The ESIs are actually streamlined versions of standard inspections, which normally take about 3 hours. The ESIs attempt to focus on the key elements of major vessel systems, basic safety checks (no drills), seaway fittings, and some special issues for seaway transit. MSO Buffalo/MSD Massena personnel currently board three to four dozen vessels each year using this strategy.

Coast Guard units across the country use the PSCTM. The PSCTM assigns priorities by scoring a series of criteria (flags, companies, class societies, etc.) to produce a cumulative prioritization score. Cumulative scores of 17 or greater produce a Priority 1 ranking. Because the PSCTM is broadly applicable, it does not specifically focus on the criteria that MSO Buffalo and MSD Massena consider most relevant for this location. Specifically, MSO Buffalo and MSD Massena believe that the following weaknesses exist in the PSCTM for their work:

- A few problem ships/companies (i.e., bad actors) in any scoring group can have an inordinately large influence on rankings for all vessels in the group, skewing the priorities
- Individual vessel performance is not well addressed
- The specific types of concerns most important for passage through the seaway are not emphasized

In addition, there is no specific direction (e.g., risk-based criteria) about what to inspect (and in what detail) during a Priority 1 boarding.

This report illustrates the use of fault tree analysis and failure modes and effects analysis (FMEA) for systematically identifying applicable and effective inspection tasks that should be included in ESIs for Priority 1 vessels. (A separate report documents the results of another risk-based decision-making workshop that addressed how to more effectively determine which vessels should be classified as Priority 1 and subsequently boarded by Coast Guard inspectors.) Representatives from the Coast Guard's MSO Buffalo, MSD Massena, and Research and Development Center (R&DC), as well as those from the SLSDC, the SLSMC, and EQE International, Inc. (EQE), teamed to address this topic.

2. *OBJECTIVES*

The stakeholders had no specific improvement priorities/initiatives for ESI plans coming into this segment of the overall workshop. For this reason, the team focused on investigating the added value of using risk analysis tools to help the stakeholders achieve their goal of having a performance-oriented approach to conducting ESIs. Specifically, the team wanted to investigate a systematic process for answering the following questions:

- What reportable marine events are most likely to occur during transit through the seaway?
- What types of system failures are most likely to contribute to those events?
- What functional failures stemming from system malfunctions, which might be caused by actual component failures and/or human mistakes in operating/maintaining the equipment, pose the greatest risks?
- What possible inspection activities would be credible candidates (i.e., applicable) for helping to manage the areas of greatest risk?
- How cost-effective are the candidate inspection activities?
- What current inspection activities might be reduced without causing a substantial increase in risk?

The key objective was to determine whether a risk-based decision-making process could add value to inspection planning and serve as a model for further development in the future.

3. APPROACH

Based on the objectives outlined in Section 2, EQE recommended that the team use fault tree analysis to systematically identify the types of marine casualties most likely to occur in the seaway, as well as the most important contributors to those casualties. EQE recommended fault tree analysis because fault tree analysis has the following characteristics:

- Is a systematic, highly structured assessment that can generate a comprehensive review (within the defined scope of the analysis)
- Provides the capability to deal with complex scenario modeling issues (although this capability ultimately was not needed in this analysis)
- Accounts for both equipment failures and human mistakes that lead to consequences of interest
- Generates qualitative descriptions of potential problems, as well as quantitative estimates of relative importances of various contributing events
- Easily incorporates other quantitative summary information (such as percentage of inspection time associated with certain issues)
- Graphically portrays the risk information in an effective manner

As a follow-on to the high-level fault tree analysis, EQE recommended that the team use FMEA to examine potentially important system problems in more detail. EQE recommended FMEA for the more narrowly focused analysis because FMEA has the following characteristics:

- Focuses on specific failure modes that can lead to the broader priorities identified through the fault tree analysis
- Uses a tabular format that directly correlates failure modes with candidate inspection activities (as has been done for many years in FMEAs performed under MIL-STD-1629 and as part of traditional reliability-centered maintenance studies)
- Focuses attention on equipment deficiencies (actual failures or degraded conditions) that are generally inspectable (as opposed to human factors issues related to training, procedures, supervision, etc., which are typically not inspectable during an ESI)

The project team performed the following four steps for demonstrating the use of fault tree analysis and FMEA for inspection task planning:

1. Define the activity or situation of interest
2. Define the consequences of interest for the analysis
3. Perform a high-level (limited detail) fault tree analysis
4. Select a few potential system problems for FMEAs focused on inspection planning

Table 3.1 lists the members of the analysis team.

Table 3.1 Members of the Analysis Team

Team Member	Organization
Paul Wisniewski	MSD Massena
Terry Jordan	SLSDC
Peter Burgess	SLSMC
Brian Dolph	R&DC
David Walker	EQE

STEP 1. DEFINE THE ACTIVITY OR SITUATION OF INTEREST

The project team focused on deep draft vessels subject to ESIs upon entering the St. Lawrence Seaway. The team considered all types of ESIs, not just ESIs of Priority 1 vessels that Coast Guard personnel would board.

STEP 2. DEFINE THE CONSEQUENCES OF INTEREST FOR THE ANALYSIS

The project team defined reportable marine events as the consequences of interest that the ESIs are intended to help prevent. The team considered reportable marine events to include the following:

- Maneuvering incidents during transit (collision, allision, grounding, etc.)
- Fires during transit
- Seaway fitting problems during transit
- Pollution during transit
- Material condition problems during transit (i.e., various ship system/equipment failures not leading to other consequences)

STEP 3. PERFORM A HIGH-LEVEL (LIMITED DETAIL) FAULT TREE ANALYSIS

In a group brainstorming environment, the team applied the basic steps of fault tree analysis to identify where the best opportunities for inspection improvements might be found. The team performed the following tasks to construct the fault tree (shown in the results presented in Section 4 of this report):

- **Define the TOP event for the analysis.** The team began the analysis with the event "Reportable Marine Event in the St. Lawrence Seaway."

- **Define the treetop structure.** The team developed the TOP event by showing the various types of marine events of interest in this study (i.e., the list provided in Step 2).

- **Explore each branch in successive levels of detail.** The team determined whether to develop each branch further by considering the expected relative contribution of that branch to the expected overall number of reportable marine events. If a branch was not expected to be a significant contributor to the overall number of reportable marine events, then the team did not develop that branch any further. The team used rough estimates (based on available data and the experience of team members) about the relative importance of each branch of the tree. The analysis team only developed the fault tree to the major functional failure level, providing only a high-level look at the key risk contributors.

Because this simple fault tree did not involve any complex logic and the team did not plan to perform sophisticated numerical analysis on detailed loss sequences, the team did not need to solve the fault tree for cut sets or address dependent failures.

To help identify inspection improvement opportunities, the analysis team also estimated the amount of time that ESI teams spend on inspections intended to prevent each type of reportable marine event. The team recorded these estimates directly with the risk contribution estimates for comparing the resource allocation with the associated risks. In addition, the analysis team estimated how effective inspections could be for various branches of the fault tree by estimating what fraction of the risk contributors are "inspectable" (i.e., Can a reasonable ESI task credibly identify deficiencies and reduce risks?).

STEP 4. SELECT A FEW POTENTIAL SYSTEM PROBLEMS FOR FMEAs FOCUSED ON INSPECTION PLANNING

The analysis team selected two major types of functional failures that the team expects to contribute significantly to reportable marine events. For each of these functional failures, the team demonstrated how FMEA can be used to (1) analyze the failure contributors in more detail and (2) develop/defend applicable and effective inspection strategies targeted at preventing the failures. For the selected functional failures, the analysis team addressed the following:

- Effects of the functional failure
- Overall contribution of the functional failure to reportable marine events
- Dominant causes of the functional failure (both equipment failures and human errors)

In addition to this information, the team considered possible inspection activities for each cause of each functional failure. For each cause, the team listed the following:

- Applicable inspection activities
- Associated inspection effort (measured in inspection time)
- Criteria about when to (or not to) apply the inspection activity
- A measure of the expected change in risk for the functional failure if the inspection activity is institutionalized

Section 4 of this report provides the results from the demonstration FMEAs.

4. RESULTS

This section presents the following key results of the risk-based decision-making field demonstration workshop:

- High-level fault tree analysis
- Demonstration FMEAs

4.1 HIGH-LEVEL FAULT TREE ANALYSIS

Figure 4.1 is the high-level fault tree analysis that the analysis team generated during the meetings. (The team actually developed the information in an electronic spreadsheet, but the information was later re-formatted into the fault tree format seen in Figure 4.1.) The top (shaded) portion of each box describes the event contributing to the next higher level, while the bottom portion of each box provides insight into (1) how likely the event is to contribute to reportable marine events and (2) how "inspectable" the causes of the event might be. In the treetop structure (i.e., the first level of development in the fault tree), note that the fraction of overall inspection time related to the major groupings of reportable marine events is included.

The fault tree reveals several key areas of interest for inspection planning (as identified by the numbered notes on the fault tree):

1. **Significant contributor, relatively low inspection resource allocation.** The team expects maneuvering incidents during transit to cause approximately 90% of all the reportable marine events; however, only about 30% of the inspection resources are currently targeted at issues leading to these events. This is an area in which increased inspection could provide substantial benefits, if the additional inspection activities are effective.

2. **Significant contributor, not highly inspectable.** The team expects allisions during transits to cause approximately 40% of all the reportable marine events; however, the team believes that the dominant contributors to allisions are mostly related to uninspectable human factors issues (e.g., ship-handling mistakes). This is an area in which increased inspection would probably not provide substantial benefits, even though allisions are important contributors to reportable marine events. Other types of risk management actions (other than inspections) should be considered for the allision potentials.

3. **Significant contributor, highly inspectable.** The team expects disabled vessels during transits to cause approximately 40% of all the reportable marine events, and the team believes that the dominant contributors to disabled vessels can be addressed during ESIs. This is an area in which increased inspection could provide substantial benefits, if the additional inspection activities are effective.

4. **Significant contributor, highly inspectable.** The team believes that propulsion system problems will cause most of the disabled vessels (approximately 80%) and, consequently, a significant fraction (approximately 32%) of all the reportable marine events. The team also believes that ESI can address the dominant causes of expected propulsion system problems; thus, this is an area in which increased inspection could provide substantial benefits, if the additional inspection activities are effective. In particular, the failure to provide start air for engines (particularly important for the maneuvering necessary to navigate the St. Lawrence Seaway) seems to be the dominant issue. The team

Figure 4.1 High-level Fault Tree Analysis

selected this item for more detailed examination during the subsequent FMEA, focusing on the need for additional inspection tasks (or revisions to existing inspections).

5. **Not a significant contributor, relatively high inspection resource allocation.** The team believes that seaway fitting problems will cause only about 2% of the reportable marine events. However, approximately 30% of the total inspection time focuses on seaway fitting considerations. The high resource allocation to a relatively small contributor to marine events indicates a possible area of improvement in the inspection resource allocation. One of two possibilities exists: (1) too much inspection time is being spent on seaway fitting inspections or (2) this level of inspection is needed to keep seaway fitting problems from becoming a more dominant contributor. Although the team believed that the current inspection resource allocation for seaway fittings was appropriate, the team selected this item for more detailed examination during the subsequent FMEA, focusing on potentially unnecessary inspection tasks.

6. **Low impact use of inspection resources.** The team noted that document processing consumes approximately 25% of the total inspection time during ESIs. After reviewing some inspection records, the team realized that much of the information was redundant with other forms/records. The team believed that document processing during ESIs could be substantially streamlined, allowing inspectors to focus additional time on potentially significant risk contributors.

4.2 DEMONSTRATION FMEAs

Table 4.1 provides a demonstration of a functional failure-based FMEA for examining inspection issues in more detail. This demonstration addresses the two issues that the analysis team selected for more detailed analysis during the fault tree analysis (see items 4 and 5 in Section 4.1). These issues focus on preserving two important functions necessary for preventing reportable marine events:

1. Providing start air for engines
2. Providing seaway fittings

Separate sections of Table 4.1 address each function individually, and the columns provide all of the information developed in accordance with the approach outlined in Section 3, Step 4. Under the column "Applicable Inspection Activity," new or substantially revised inspection activities that the team suggested through the FMEA discussions are highlighted with shading.

Table 4.1 Functional Failure-based FMEA

Functional Failure	Loss Scenario (Effect)	% of All Reportable Marine Events	Dominant Causes	Applicable Inspection Activity	Inspection Effort	Criteria	Change Risk
Function: Providing Start Air for Engines							
No or insufficient volume of start air provided to engines	No engine start, which can lead to loss of propulsion and a disabled vessel Could possibly lead to a grounding, collision/allision, etc.	~25%	Condensation in bottles (62%)	Blow down bottles during inspection	<10 minutes	Do not have to do on variable pitch propellers	Current practice (high negative impact if not performe
				Verify that regular blowdowns are scheduled and occurring (by record review)	<5 minutes	See above	Possibly high positive impact
				Communicate importance of blowdowns to crew	<5 minutes	See above	Current practice (high negative impact if not performe
			Disabled compressors (multiple compressors) (5%)	Operation verification (measure discharge pressure)	<10 minutes	See above	Current practice (high negative impact if not performe
				Visual inspection for leaks, gauges functioning, obvious defects, etc.	<5 minutes	See above	Current practice (high negative impact if not performe
				Communication with pilots about known problems during transit	<5 minutes	See above	Current practice (high negative impact if not performe

Table 4.1 Functional Failure-based FMEA (cont'd)

Functional Failure	Loss Scenario (Effect)	% of All Reportable Marine Events	Dominant Causes	Applicable Inspection Activity	Inspection Effort	Criteria	Change in Risk
Function: Providing Start Air for Engines (cont'd)							
No or insufficient volume of start air provided to engines (cont'd)	(cont'd)	(cont'd)	Major leaks (<1%)	Visual inspection for leaks, gauges functioning, obvious defects, etc.	<5 minutes	See above	Current practice
			Starting engines off of one bottle (holding one bottle in reserve)(<2%)	Communicate importance of having both bottles on-line for seaway transit	<5 minutes	See above	Current practice
			Valve failures (25%)	Perform multiple start test to confirm proper valve operation	~30 minutes + ~1 hour recovery	See above	Small (if any) positive impact
				Verify that preventive maintenance has been scheduled and performed on air start valves	~15 minutes	See above (but information may not be available for many ships)	Small positive impact
			Failing to pressurize the bottles before maneuverings (5%)	Check bottle pressure on both bottles	<5 minutes	See above	Current practice (high negative impact if not performed)

Table 4.1 Functional Failure-based FMEA (cont'd)

Functional Failure	Loss Scenario (Effect)	% of All Reportable Marine Events	Dominant Causes	Applicable Inspection Activity	Inspection Effort	Criteria	Change in Risk
Function: Providing Seaway Fittings							
Fairleads free turning	Potential for line parting, possibly resulting in personnel injury and/or property damage		Fairleads not maintained (seldom, if ever, used outside of the seaway)	Verify fairleads free turning	~10 minutes	All vessels	Current practice (high negative impact if not performed)
Pedestal rollers not free turning	Potential for line parting, possibly resulting in personnel injury and/or property damage		Rollers not maintained (seldom, if ever, used outside of the seaway)	Verify pedestal rollers not free turning	~5 minutes	All vessels	Current practice (high negative impact if not performed)
Incorrect size and condition of mooring wires	Potential for line parting, possibly resulting in personnel injury and/or property damage	<1% for all of these functional failures	Wrong lines in use Degraded line conditions	Verify size and condition of mooring wires	~10 minutes	All vessels	Current practice (high negative impact if not performed)
Improperly rigged landing booms	Potential for failure during use, resulting in personnel injury and/or property damage		Landing booms not maintained (seldom used outside of the seaway)	Verify rigging for landing boom	~10 minutes	All vessels	Current practice (high negative impact if not performed)
Not fitted or operational stern anchors	Potential for a grounding, allision, or collision if the anchor is needed during the transit (e.g., to maintain position if the ship is		Not fitted with a stern anchor Anchor not maintained (seldom, if ever, used outside of the seaway)	Verify stern anchor is present and operational	~5 minutes	All vessels	Current practice (high negative impact if not performed)

	disabled because of a propulsion system problem)						
Incorrect size and condition of heaving lines	Potential for line parting, possibly resulting in personnel injury and/or property damage		Wrong lines in use Degraded line conditions	Verify size/condition of heaving lines	~5 minutes	All vessels	Current practice (medium negative impact if not performed)

Table 4.1 Functional Failure-based FMEA (cont'd)

Functional Failure	Loss Scenario (Effect)	% of All Reportable Marine Events	Dominant Causes	Applicable Inspection Activity	Inspection Effort	Criteria	Change in Risk
Function: Providing Seaway Fittings (cont'd)							
Inadequate fender number, location, condition	Potential for contact between ships and shore-side structures (especially in the locks), resulting in damage to the ships and/or the shore-side structures	<1% for all of these functional failures	Adequate number of fenders not available Fenders not deployed Fenders' condition poor	Verify fender number, location, and condition	~10 minutes	All vessels	Current practice (high negative impact if not performed)

5. OBSERVATIONS AND CONCLUSIONS

The use of fault tree analysis and FMEA helped the team to identify some potentially important observations about the current ESI process:

- Reducing the time spent on document processing would lead to a more effective use of inspection time and, subsequently, to less risk from inspectable problems that contribute to reportable marine events.

- The current inspection activities related to the function "Providing Start Air for Engines" seem well justified based on the importance of a failure of this function.

- The team developed the following three new inspection ideas to help prevent reportable marine events because of no/insufficient volume of start air provided to engines:

    - **Potentially high impact:** Verify that regular blowdowns are scheduled and are occurring (ESI record review) [<5 minutes of inspection time with a possibly high impact]. The team believes that this is a good idea to implement.

    - **Potentially small impact (with modest resource allocation):** Verify that preventive maintenance has been scheduled and performed on the air start valves (ESI record review, if documentation is available) [approximately 15 minutes of inspection time with a small impact]. The team believes that this should be considered because start air problems are such large contributors, but the team admits that the impact may be small.

    - **Potentially small impact (with extensive resource allocation)**: Perform multiple start tests to confirm proper valve operation [approximately a 30-minute test with more than a 1-hour recovery time for small (if any) impact]. The team does not believe that this inspection would be worth the associated resource allocation.

- The current inspection activities related to the function "Providing Seaway Fittings" seem well justified based on the team's expectation that seaway fittings problems would become a dominant contributor to reportable marine events (i.e., highly negative risk impacts) if these tasks are not performed.

The analysis tools did provide a systematic and understandable process for inspection task planning. Because ESIs are already highly evolved inspection plans, the team did not expect major changes from the current inspection strategy. However, the team did expect some new inspection ideas to surface. The team also expected the analysis to help defend the currently defined inspection tasks. A less mature inspection program (or an ineffective program that is allowing a number of losses to occur) would likely experience more changes by applying this process.