THE PROBABILITY OF A SHIP SINKING OR CAPSIZING DUE TO SHIP-TO-SHIP COLLISION

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abstract: A fault tree is constructed as a logic model to represent the sequences of events necessary for a ship to collide with another ship and then for it to sink or capsize. Previous work on the probability of ship collisions and previous work on the probability of ship survival, given the fact that a collision has occurred, are put together in a model to determine the probability that a ship will capsize or sink in its intended service.

1. THE MAJOR BRANCHES OF THE FAULT TREE

The top event of the fault tree is: *ship sinks or capsizes when struck by another ship while in transit.* For this to occur the ship must first be struck by another ship while in transit **AND** it must sink or capsize after being struck. (Please refer to the diagram of the fault tree in the Appendix.) Thus one major branch of the tree deals with the probability of the ship being struck by another ship while in transit. The other major branch deals with the probability of the ship sinking or capsizing after being struck.

2. THE PROBABILITY OF A SHIP BEING STRUCK BY ANOTHER

The branch dealing with the probability of ship-to-ship collision is constructed as shown in sheets 1 to 8 of the fault tree shown in the Appendix. The ship may be struck while steaming in a port or while in a high traffic density area or a low traffic density area outside of the port. It may be struck in good or bad weather. In any case either ship must not have noticed the other's presence. This may be due to the radar lookout in either ship not noticing the other ship. This may also be due to either ship not giving a fog signal. Both of these occurrences may in turn be caused by human error or equipment failure. Not noticing each other's presence, the ships may get to be on a collision course. While on a collision course, the communication between the two ships may fail. The course or intention of one ship is not understood by the other in time. It may occur that either ship does not send out a signal due to human error or equipment failure. Once aware of the danger, the moves of each ship to avoid collision may fail because it loses speed control, steering control or guidance. All three may be due to human error or equipment failure.

The tree considers the following factors affecting the probability of ship-to-ship collision: human error; equipment effectiveness and reliability; weather; traffic density; ship speed, size and maneuverability; the Rules of the Road, special rules and traffic separation and traffic separation and monitoring schemes. Morrel (1961) states that the process of collision avoidance consists of five steps which, in chronological order, are: 1) discovery of the presence of the second ship; 2) data acquisition on the positions and motions of both ships; 3) prediction of the degree of danger; 4) decision whether to maneuver, and if so, when and how; and 5) action: if risk is too great, maneuver; if not, hold course and speed. All steps have to be carried out correctly in order to avoid a collision. The human factor is involved in all steps, notwithstanding efforts at greater degrees of automation in collision avoidance systems.

Prior to the widespread use of radio and radar on merchant vessels, the primary collision avoidance tools were: the Rules of the Road, the pelorus, the binoculars and the lookout. The pelorus and binoculars have been replaced by compass repeaters; the Rules of the Road are still around and have since been revised to account for the effect of radar upon ship maneuvering. The National Maritime Research Center (1978) states that it is a widely accepted fact that the introduction of radar has not brought about a definite and dramatic reduction in collision frequency. Among the possible answers to the puzzle are the misuse or misinterpretation of radar information or the failure to keep a good lookout. These again bring out the human factor. Barlow and Lambert (1979) treat loss of radar as a human error event because records show that "when radar is ineffective in preventing ship collisions, it has been ignored by the ship's crew."

2.1 Rules of the Road.

The U.S. Coast Guard (1972) in its Rules of the Road prescribe actions to be taken by ships in basically six situations: 1) vessels passing each other; 2) vessels approaching each other head and head, end on; 3) vessels nearing a bend or curve in a channel; 4) vessels moving from dock; 5) vessels approaching each other at right angles or obliquely; and 6) fog. The Rules prescribe audible (whistle/siren) and visible (lights) signals to be sent by the vessels to each other to communicate and thus head off a collision. There are signals to indicate presence in the area and signals to indicate intention to turn port or starboard or do some other maneuvers. In case of misunderstanding of or objection to a signal, an audible danger signal is to be sent. In the case of vessels approaching each other at right angles or obliquely, if there is misunderstanding, each vessel is supposed to stop and back if necessary until signals for passing with safety are understood. In fog, falling snow or heavy rainstorms, whether by day or night, a vessel, while moving at moderate speed, is required to sound at intervals of not more than one minute, on the whistle or siren, a prolonged blast to indicate its presence.

Rules of the Road notwithstanding, collisions do occur. If failure of equipment cannot be blamed, it must be human error. In any case, in the event of a collision, there must have been miscommunication or either or both vessels must have lost control of speed or steering or must have lost guidance.

2.2 Traffic density.

Oudet (1961) states that among the areas of high traffic density are; straits, approach to large ports, capes on the great ocean routes and neighborhood of headlands and hazards which the great ocean routes skirt. He estimates that in the Straits of Dover of the English Channel, for example, it is estimated that everyday nearly a thousand ships pass through a five-mile wide stretch of sea between the English coast and the Varne. McDuff (1974) states that the institution of a traffic separation scheme in this area has reduced the probability of collision significantly. The scheme is analogous to road traffic on land. Ships stick to the starboard side of the buoys marking the middle of the channel. This reduces the probability of head-on collisions but the probability of collisions due to overtaking situations still exits. For a specific ship on a specific trade, one must look up the relevant traffic separation scheme along its route for incorporation into the fault tree.

3. THE PROBABILITY OF SINKING OR CAPSIZING AFTER COLLISION

The branch of the fault tree dealing with the sinking or capsizing of the ship while in transit is constructed as shown in the Appendix, sheet 1 and sheets 9 to 12. The considerations in constructing the details of this branch are given below.

3.1 Sinking and capsizing.

A ship is considered to have sunk if it does not retain intact buoyancy greater than its own weight and if any openings through which progressive flooding may occur have been immersed below the flooded waterline. Progressive flooding openings include vents, overflows and weathertight doors and hatches. Watertight doors, manholes and small watertight hatch covers are assumed closed and are not to be considered as points of progressive flooding.

The mechanisms of capsize are much more difficult. For the purposes of this paper, flooded stability criteria which are part of international regulations shall be used. Violations of these criteria, which relate to residual stability after flooding, shall be taken to be synonymous to a capsize condition. These criteria according to Tagg (1982) are: 1) static heel angle is to be no greater than 25 degrees; 2) dynamic range of righting levers (GZ) to 20 degrees beyond the static heel angle, to both port and starboard, must exist with a maximum value of at least 0.1 meter; and 3) positive upright damaged metacentric height must be maintained in the case of symmetric flooding.

3.2 Factors affecting the probability of sinking or capsizing.

The probability that a ship will sink or capsize depends upon the following factors: 1) the location and extent of damage; 2) the metacentric height at intact condition; 3) the draft at intact condition; 4) the permeability (percentage of space that can be occupied by water) of flooded spaces; and 5) applied forces and moments due to wind, sea, location or movement of tankage, persons or other weights and entrapped water on decks.

These factors have to be incorporated into the fault tree in a rational fashion. First we look at some simplifications. 1) A rigorous probabilistic treatment should include the distribution of permeabilities for each draft, as well as the variation of permeability within the ship. It is here assumed that permeability is constant throughout each compartment and that cargo space permeability can be related to the draft deterministically. Robertson, J.B. *et al* (1974) give just such a relation. Established practice is to use 0.85 for machinery spaces and 0.95 for liquid and empty compartments. 2) The applied forces and moments due to wind and sea are assumed to be accounted for in the criteria used for capsize, which were developed partly through model tests in waves. Robertson, J.B. *et al* (1974) observed that a fair proportion of damage cases occur in the more protected near-harbor approach areas and during foggy conditions, when low sea states are more prevalent. 3) The applied forces and moments from other causes are neglected.

3.3 The location and extent of damage.

A good data base of actual location and extent of damage exists. If the data on extent of damage, specifically damage penetration, were to be used to generate probabilities of basic events for the fault tree, then this will implicitly take care of two factors affecting the probability that the ship cannot survive the collision, namely: 1) the mass and velocity of the striking ship; and 2) the ship's structural resistance to collision. If fine tuning can be carried out reasonably accurately, account must be taken of the ship type in reckoning the extent of damage. The collision protection of ships is provided mainly by horizontal decks in way of the collision. Therefore according to Robertson, J.B. *et al* (1974) ships with multiple decks or 'tween decks provide more collision resistance while tankers or bulkers are more prone to larger damage due to the lack of 'tween decks to absorb the collision energy. At the extreme, nuclear vessels or vessels transporting very hazardous materials are sometimes fitted with additional horizontal stringers or even honeycomb or nested tube absorb collision energy as stated by Tagg (1982).

3.4 The longitudinal location of the midpoint of damage.

Figure 1, which is adopted from Tagg (1982), shows the distribution of the longitudinal location of the midpoint of the damage.

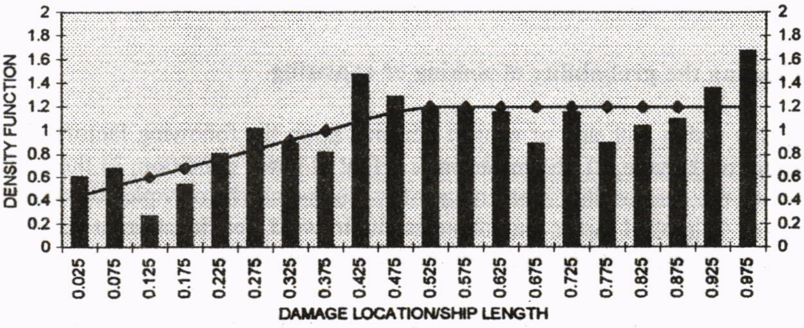

Figure 1. Longitudinal distribution of damage

3.5 Damage Length.

The distribution of damage lengths is shown in Figure 2, taken from Tagg (1982). For the development of regulations, the damage length has been assumed to vary from zero up to 24% of the ship's length with a maximum of 48 meters for ships longer than 200 metes. For most ships, Tagg (1982) states that the maximum damage would involve 3 or more watertight compartments .

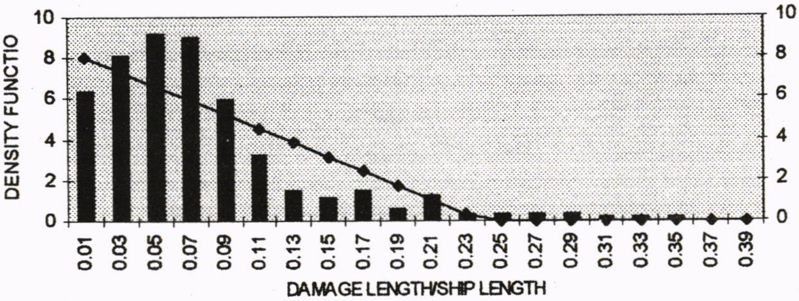

Figure 2. Damage length

3.6 Damage penetration.

The distribution of the inboard extent of damage penetration is shown in Figure 3, lifted from Tagg (1982). The penetration varies from 0 to 80% of ship's beam at load waterline measured at the longitudinal center of damage.

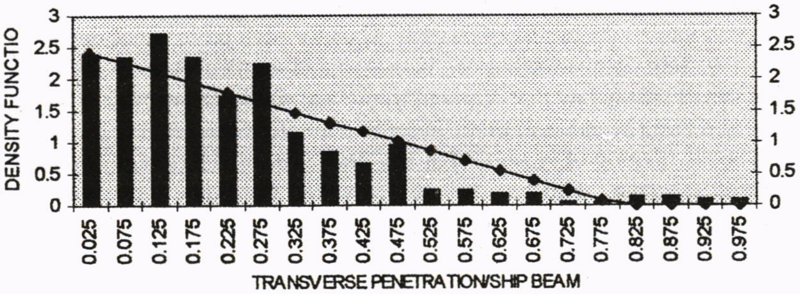

Figure 3. Damage penetration

3.7 Vertical extent of damage.

Tagg (1982) assumes the vertical center of damage to be located at the load waterline. The vertical extent varies linearly from zero with mean damage extending from the baseline to the height of a standard forecastle deck on a similar size ship. See Figure 4.

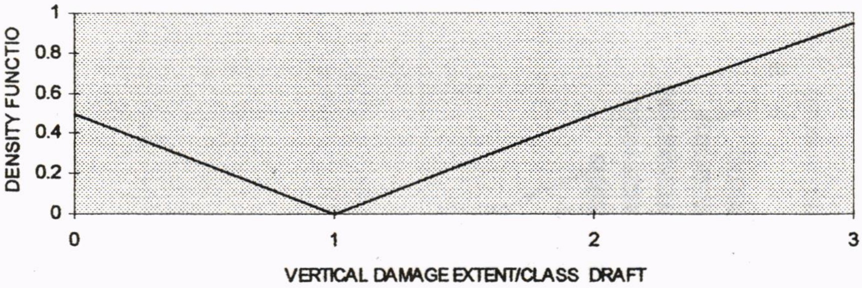

Figure 4. Vertical damage extent

3.8 Probability of damage to any compartment.

Given the above distributions of the location and extent of damage, the probability of damage to any compartment or group of compartments for any given ship can be directly calculated. Tagg (1982) gives an algorithm for doing this. In the fault tree, the breaching of groups of compartments can be used as basic events to which probability values can be assigned in the way mentioned above.

3.9 The metacentric height at intact condition.

For the breaching of any group of compartments, the intact metacentric height GM required so that not any of the criteria for sinking or capsizing is violated can be determined using standard damaged stability calculations. The governing condition and the governing value of the required intact GM can be evaluated. Thus for each basic event defined as the breaching of a set of ship compartments can be associated another basic event – that the intact GM of the vessel falls below that required to prevent sinking or capsize. Through an AND gate, these two basic events lead to the event that a criterion of sinking or capsize has been violated. The distribution of intact GM at any draft is needed to assign a value to the basic event mentioned above. This may be approximated from data for similar ships or from an early stage projection of cargo carriage pattern by the ship.

3.10 The draft at intact condition.

The value of the required intact GM for the breaching of any set of compartments depends on the vessel's draft at the intact condition. With a change in intact draft, the governing criterion for the breaching of any set of compartments can also conceivably change. The variation of ship's intact draft is, of course, continuous. But for purposes of fault tree construction, we assume a probability mass function for the intact draft. We can include only the most probable values of intact draft based on probable cargoes to be carried. Robertson, J.B. *et al* (1974) state that different types of ships have different peaks in the draft distribution. For long-voyage ships carrying appreciable cargo and short-voyage passenger-vehicle ferries of relatively small tank capacity, draft variations may be due principally to variations in loading. In such cases, and for reasons related to the economics of ship operation, the peak of the draft density function may be nearer the deepest operating draft. In the case of ships for which the lightest operating draft is stability limited, the most probable draft tends to be nearer the lightest operating draft.

4. USES OF THE FAULT TREE

The fault tree can be used to determine what compartments are most critical to a ship. In the context of a ship design process, if an analysis is done early enough then steps may be taken to provide the appropriate structural reinforcements for these compartments. In this connection, it may be noted that the damage criteria for capsizing used in the fault tree enable the analysis to be done early enough in a ship design process.

As in Barlow and Lambert (1979), the fault tree can conceivably be employed to study the effect of changes in the Rules of the Road or the institution of some traffic separation scheme or of some special rules. The fault tree, of course, has to be accordingly modified for this purpose. In a similar manner, a study of the effect of changes in damage survivability criteria on ship safety can be performed.

Another possible use of the fault tree is the determination of the desired GM for a certain ship draft. If a certain probability of sinking or capsizing be deemed acceptable, then it is possible to determine a desired intact GM for any intact draft. This is not to suggest that the fault tree be worked backwards. Rather, by systematically varying the value of desired GM (to be substituted into the value of intact GM) and running a quantitative analysis of the fault tree for each such value, then a relation between desired GM and probability of sinking or capsizing may be generated.

Barlow and Lambert (1979) got a most important result regarding human error events. In the particular case it studied, it found that accident scenarios involving a chain of human error events generally dominate. It found that the top event probability is very sensitive to the assumption about the s-independence of human error events. However, the ratio of top event probabilities for the two cases being compared is relatively insensitive to the assumption of independence.

Barlow and Lambert (1979) use reference 2 to set the probability of breakdown of vessels within U.S. ports at 8.7×10^{-6}/hour. They estimate the probability of human error under normal operating conditions at 10^{-2} per occurrence. They state that this is consistent with the estimate of Reference 10. From these numbers it is easy to understand why accident scenarios involving human error dominate. In this light, the importance of the human factor in the design of collision avoidance systems (CAS) may be better appreciated. If the relevant sections of the fault tree presented here is further elaborated on, the effect of proposed CAS systems may be put in the larger context of the ship sinking or capsizing due to a collision with another ship.

5. CONCLUSIONS

The degree of detail in the fault tree is based on considerations of currently available data and the tractability of ship calculations that have to be performed to carry out a quantitative analysis of the fault tree. The fault tree developed is very general and may have to be further elaborated on for application to a particular ship on a particular route. In a sense, it simply provides a framework which logically relates all the factors affecting the probability that a ship, in its intended service, will sink or capsize due to a collision with another ship.

A fault tree as a logic model to describe the sinking or capsizing of a ship due to being struck by another ship can be used to study many aspects of the problem, from structural arrangements to traffic separation schemes. A distinct advantage in the use of a fault tree is the inclusion of the human factor into the analysis.

To implement a fault tree analysis, data requirements have to be met. For example, draft distribution and intact GM distribution for different types of ships have to be studied further.

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APPENDIX

This appendix details the fault tree model. The following points should be noted about this fault tree:

1. On sheet 1, the symbol "__ . . . __" appears three times along the lines connecting the events. This means that one or more events similar to the adjacent events may be inserted. For example, say the number of ports the ship makes a call on is Np. Then there should be Np gate events reflecting the possibility that the ship may be struck by another ship while it is in any of these ports. For convenience, only the gate events relating to port #1 and port #Np are shown.

2. On sheet 1, to remove "__. . . __", we have to know the number of high traffic density areas along the ship's route and the number of drafts at which the possibility of sinking or capsizing is to be evaluated in addition to the number of ports of call.

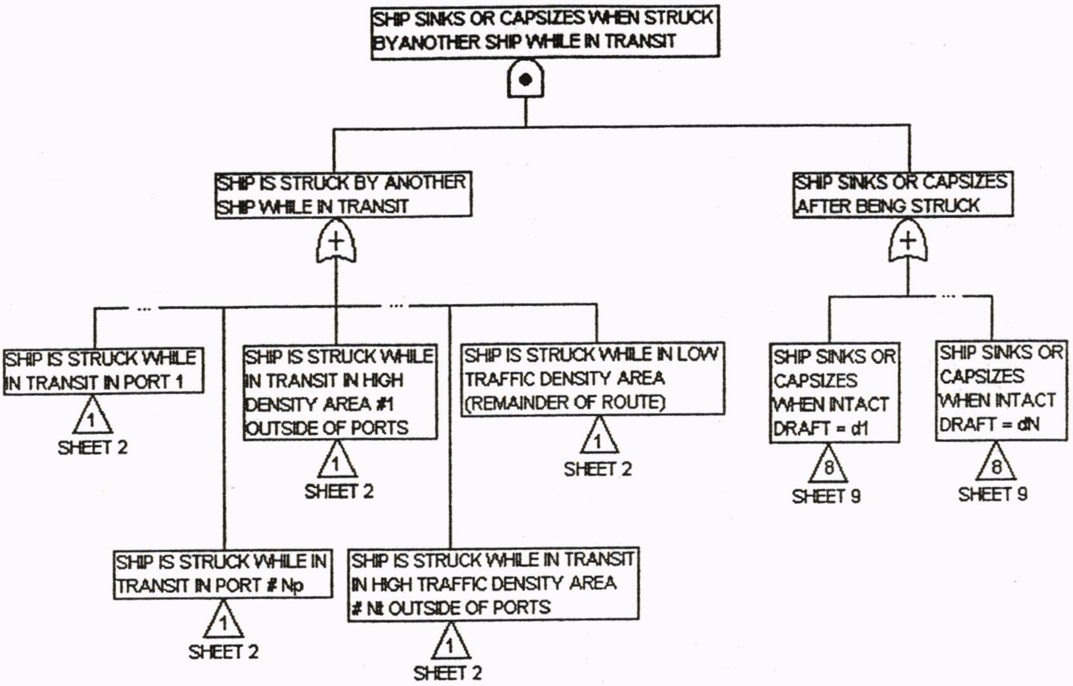
3. On sheet 9, 10 and 11, to remove the "__ . . . __", we have to determine the sets of compartments the breaching of which leads to the violation of damage survivability criteria at any particular value of draft.

4. The gate events defined as the ship being struck by another ship in different areas along its route are dependent on the same set of basic events which are related in the same way. Thus the branching of the tree below the typical event "ship is struck while in transit in area along route" is the same for all areas. To simplify the drawing of the fault tree, only one such typical branch is shown. See sheet 2. The blanks may be filled in with the appropriate area. In an application to a particular ship, this should not prevent drawing a different and separate branch for a certain area in the route should circumstances warrant.

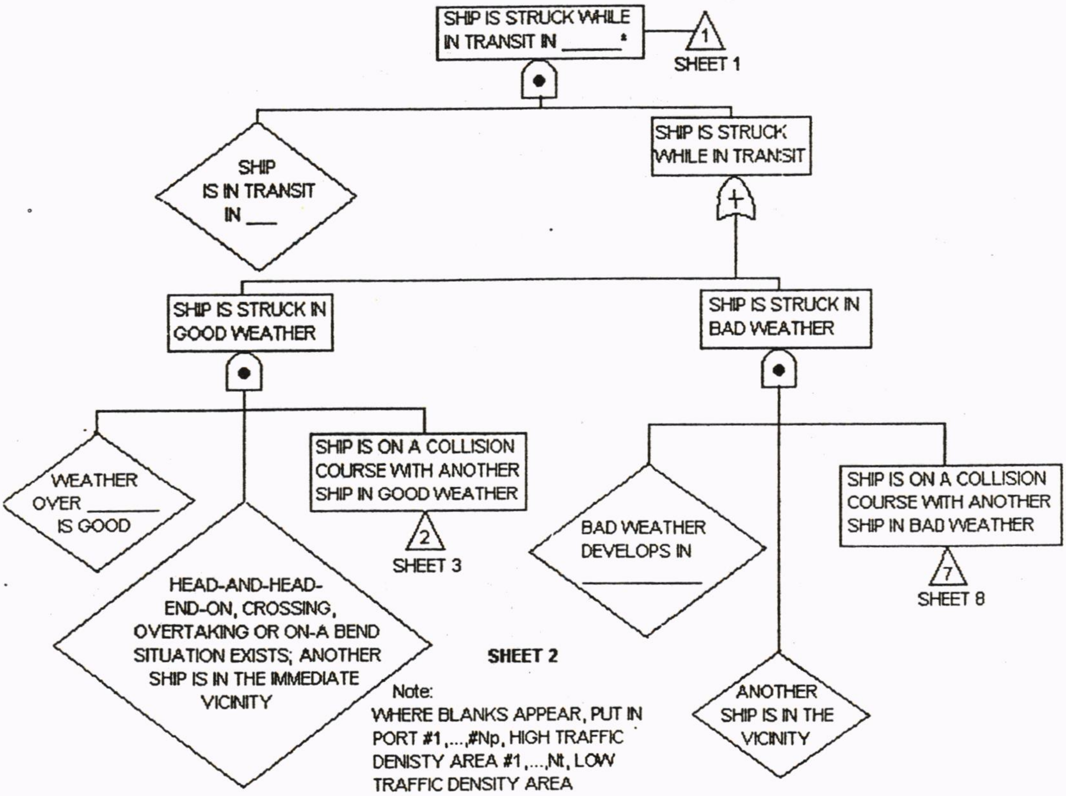
5. The ship may sink or capsize for different values of intact draft. The same situation exists as in note 3 above. The branching of the tree below the gate event "ship sinks or capsizes at intact draft = _______" is the same for different values of draft. Thus we again have to fill in the blanks.

6. It is to be noted that even though there are branches which are alike, as explained in notes 3 and 4 above, the probabilities of the basic events for each such branch may be different. Thus the branches are really different as far as fault tree analysis is concerned.

7. The fault tree may be further specialized in a way that cannot be shown in the figure. If they exist, the following have to be incorporated: specific traffic schemes in high-traffic density areas and special rules for special ships as they transit specific areas

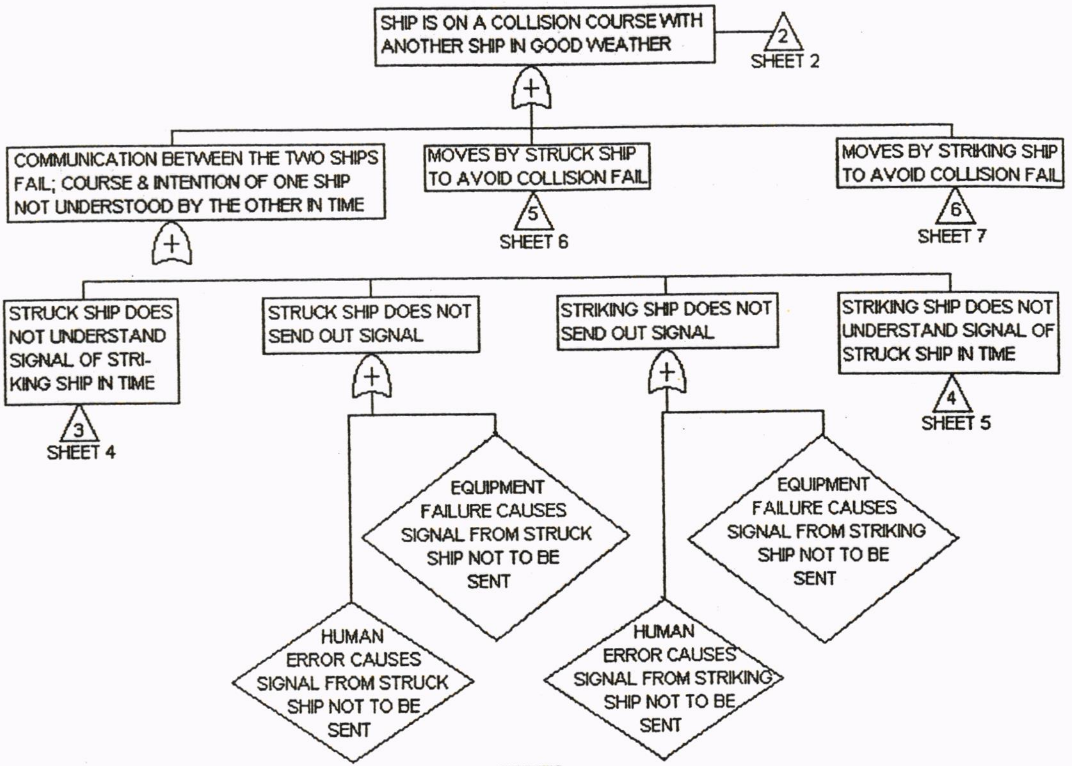


SHEET 1



SHEET 2

Note:
WHERE BLANKS APPEAR, PUT IN PORT #1,...,#Np, HIGH TRAFFIC DENISTY AREA #1,...,Nt, LOW TRAFFIC DENSITY AREA



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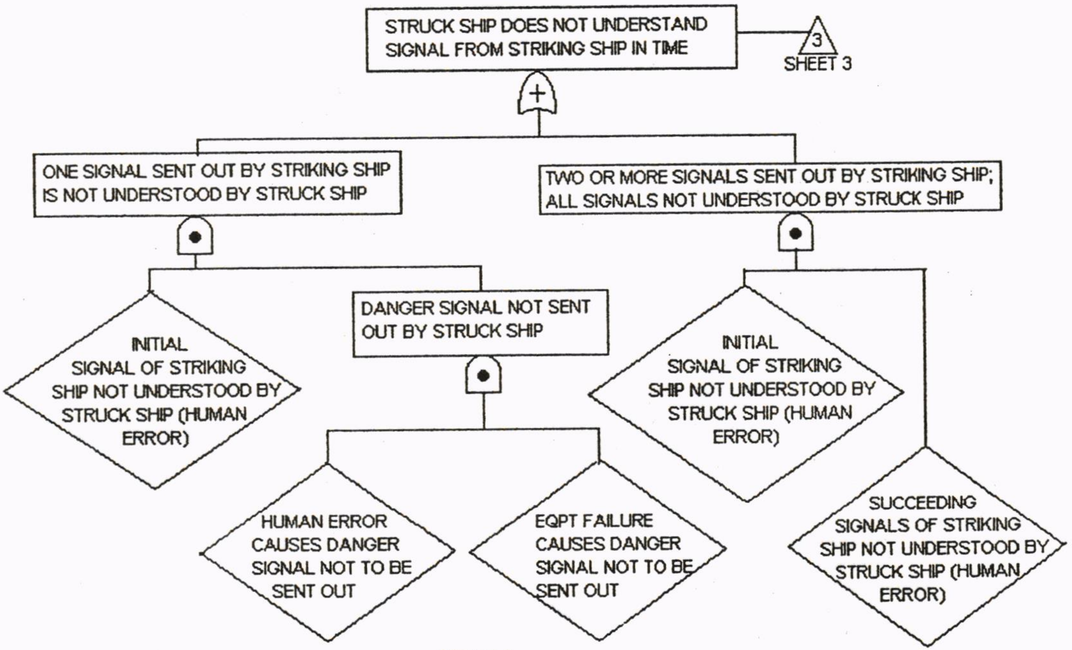

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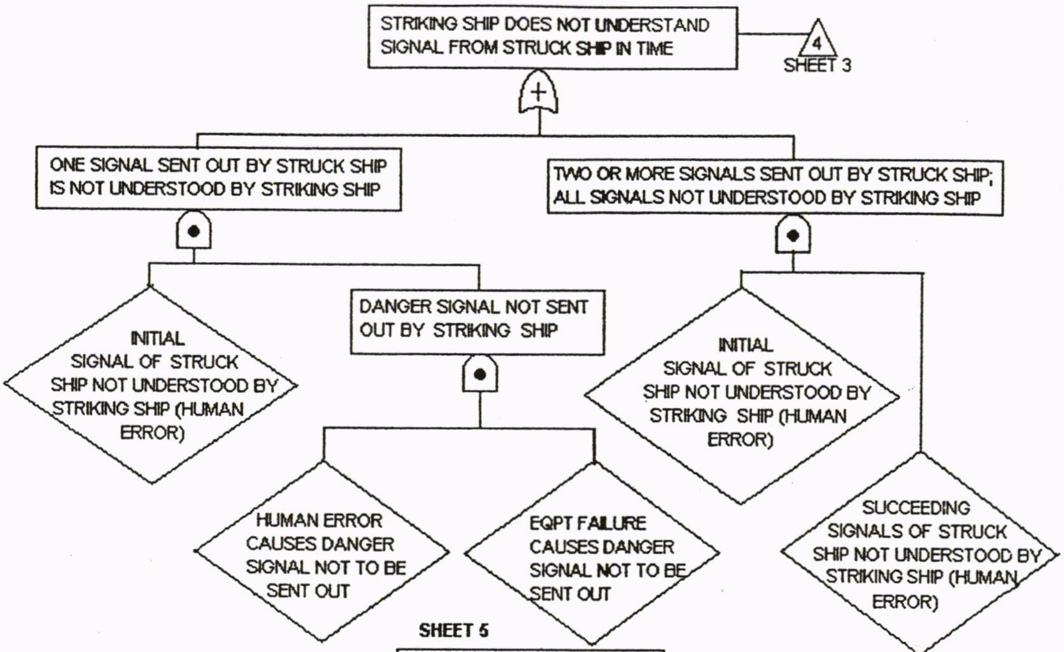

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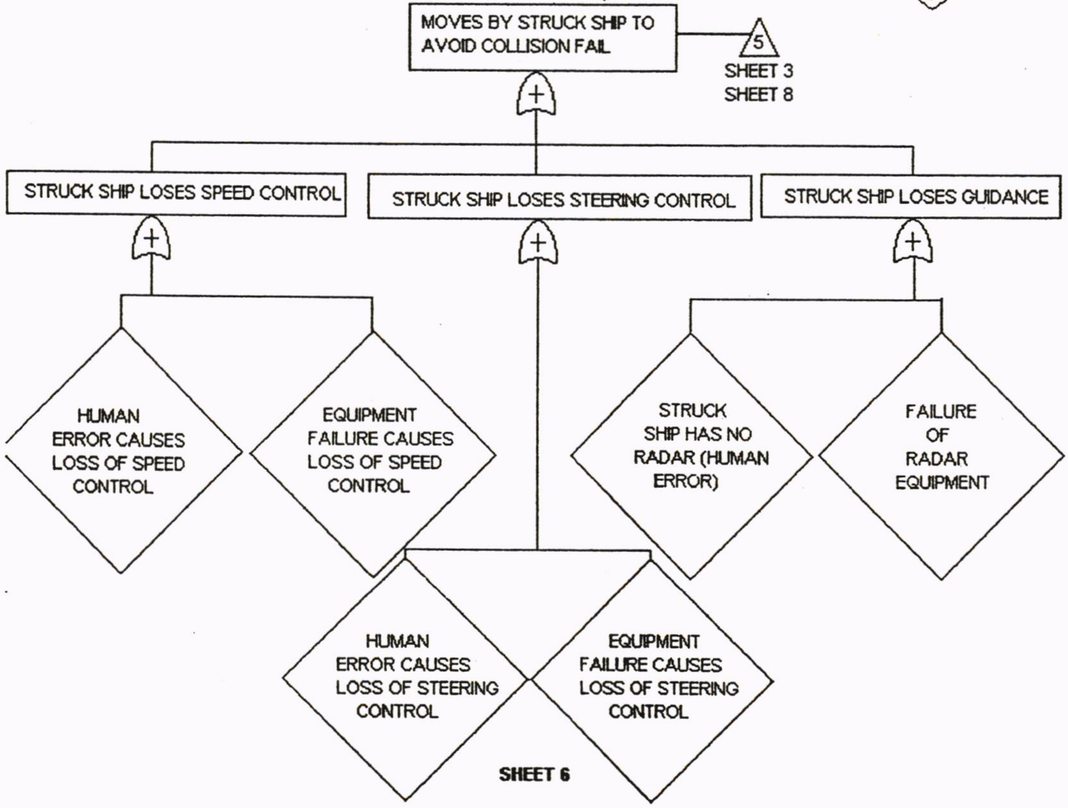
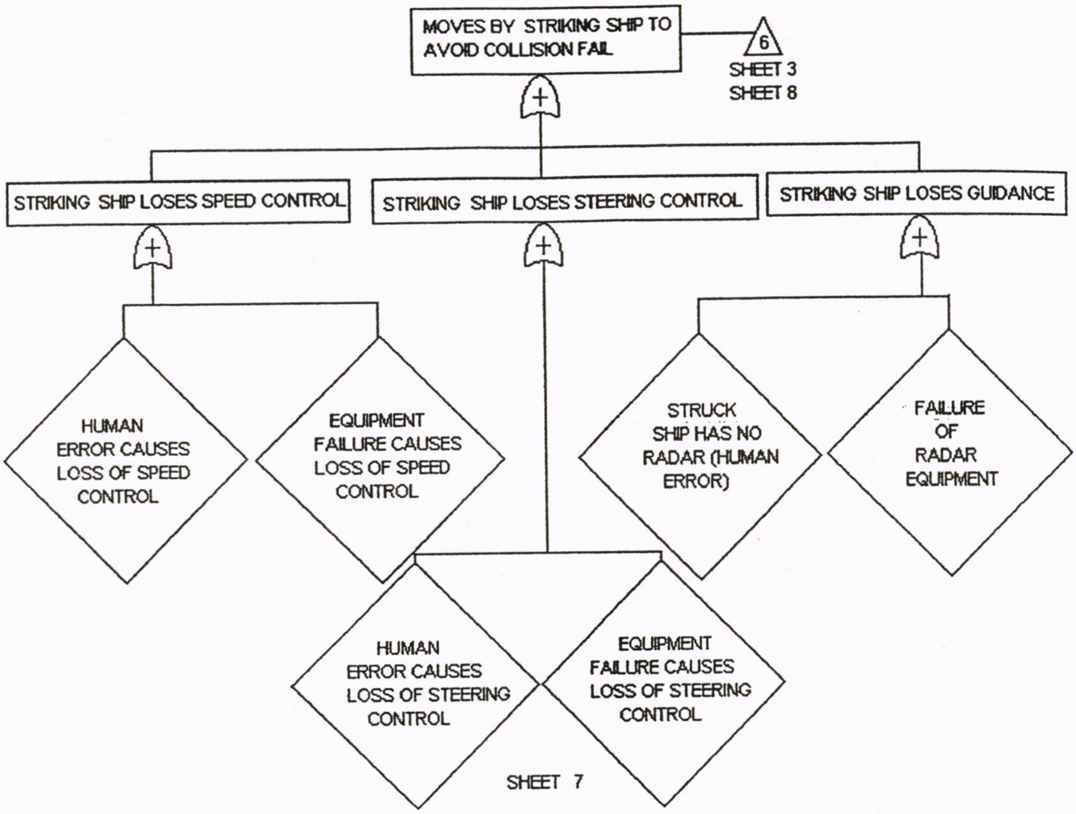
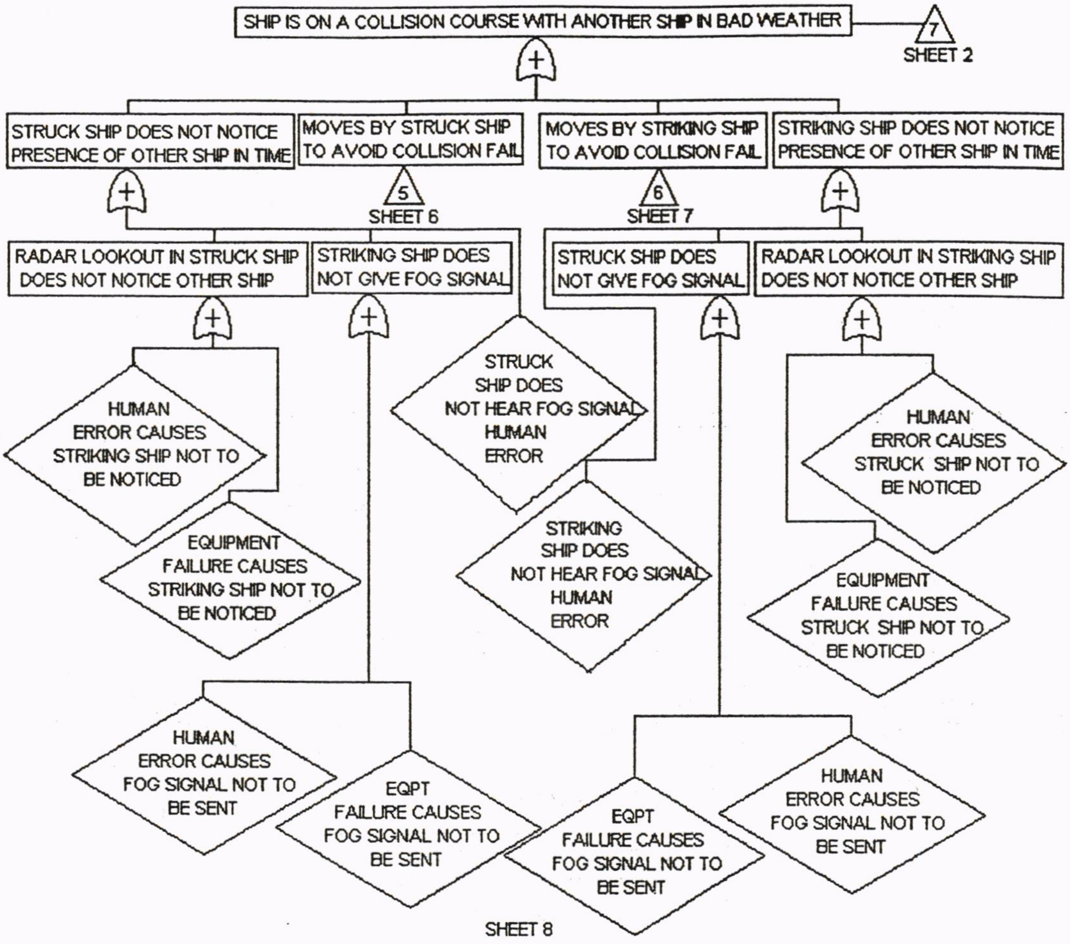


SHEET 6


MOVES BY STRIKING SHIP TO AVOID COLLISION FAIL
6
SHEET 3
SHEET 8
+
STRIKING SHIP LOSES SPEED CONTROL
STRIKING SHIP LOSES STEERING CONTROL
STRIKING SHIP LOSES GUIDANCE
HUMAN ERROR CAUSES LOSS OF SPEED CONTROL
EQUIPMENT FAILURE CAUSES LOSS OF SPEED CONTROL
STRUCK SHIP HAS NO RADAR (HUMAN ERROR)
FAILURE OF RADAR EQUIPMENT
HUMAN ERROR CAUSES LOSS OF STEERING CONTROL
EQUIPMENT FAILURE CAUSES LOSS OF STEERING CONTROL
SHEET 7


SHIP IS ON A COLLISION COURSE WITH ANOTHER SHIP IN BAD WEATHER
7
SHEET 2
+
STRUCK SHIP DOES NOT NOTICE PRESENCE OF OTHER SHIP IN TIME
MOVES BY STRUCK SHIP TO AVOID COLLISION FAIL
MOVES BY STRIKING SHIP TO AVOID COLLISION FAIL
STRIKING SHIP DOES NOT NOTICE PRESENCE OF OTHER SHIP IN TIME
+
5
SHEET 6
6
SHEET 7
+
RADAR LOOKOUT IN STRUCK SHIP DOES NOT NOTICE OTHER SHIP
STRIKING SHIP DOES NOT GIVE FOG SIGNAL
STRUCK SHIP DOES NOT GIVE FOG SIGNAL
RADAR LOOKOUT IN STRIKING SHIP DOES NOT NOTICE OTHER SHIP
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HUMAN ERROR CAUSES STRIKING SHIP NOT TO BE NOTICED
STRUCK SHIP DOES NOT HEAR FOG SIGNAL HUMAN ERROR
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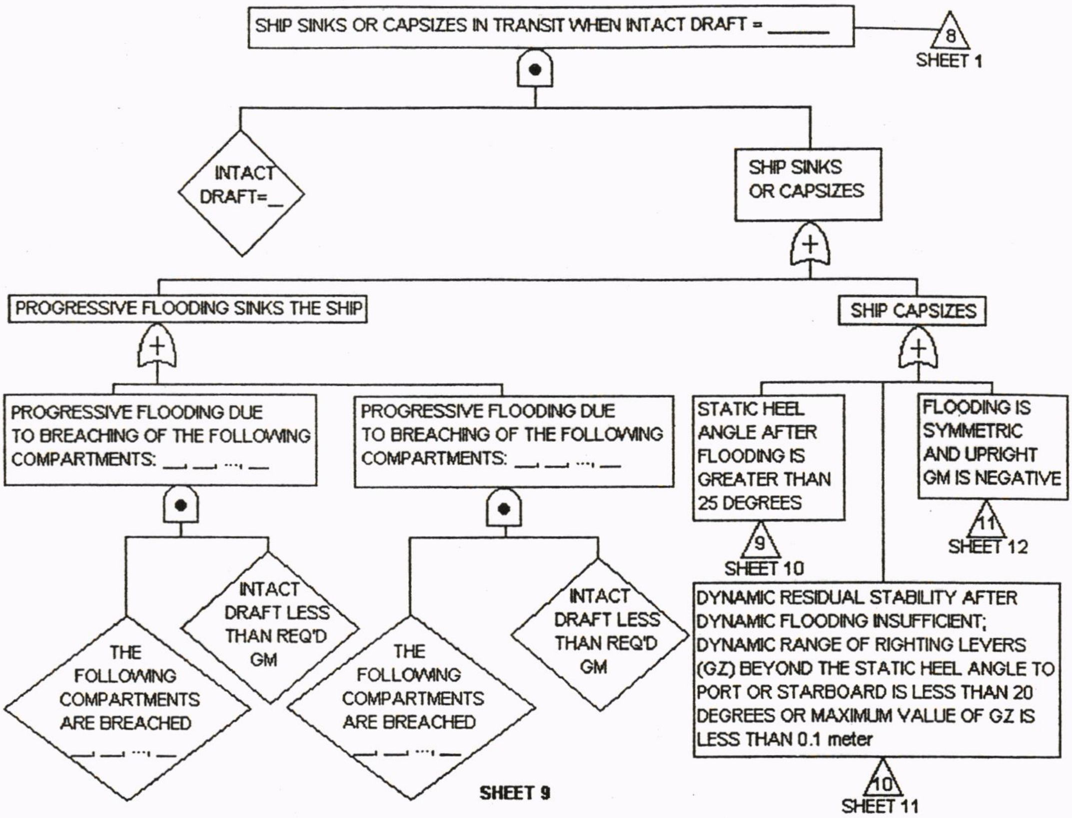
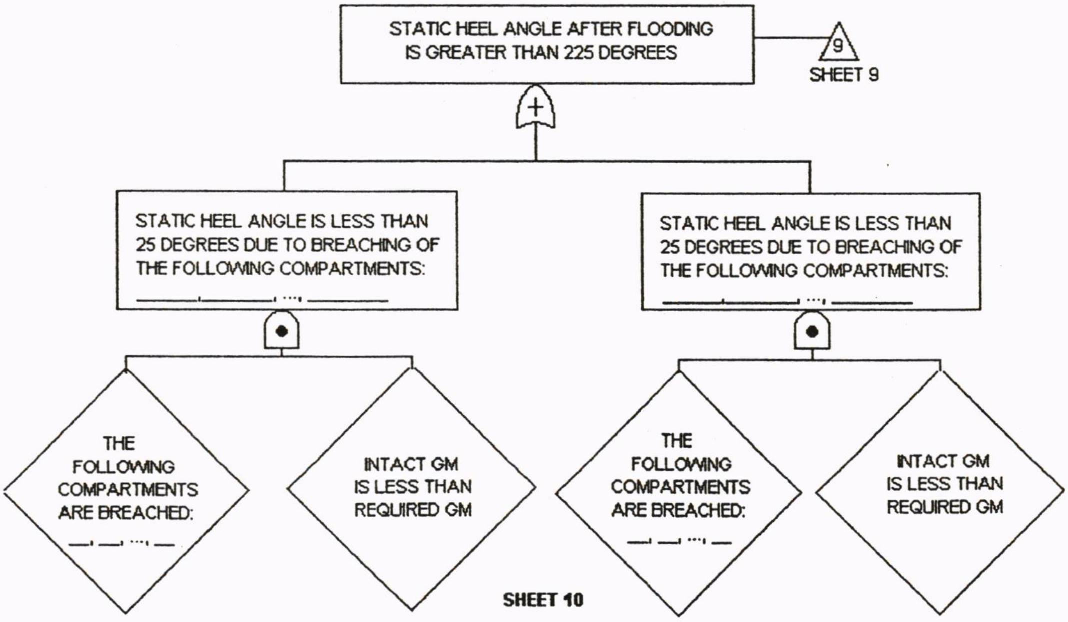
SHEET 8



SHEET 9



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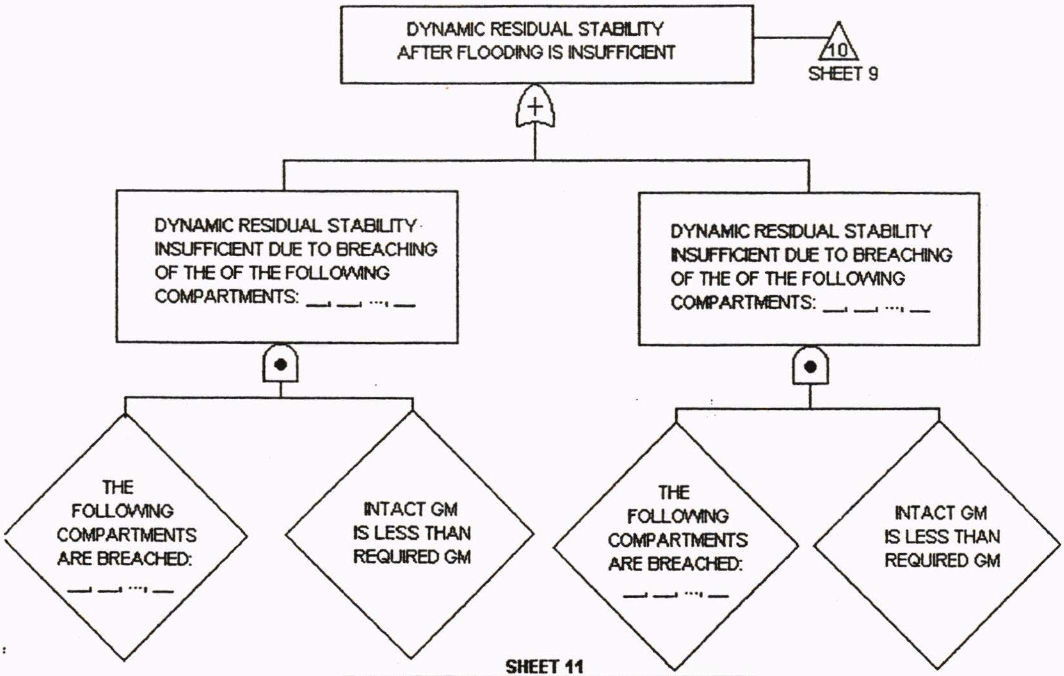
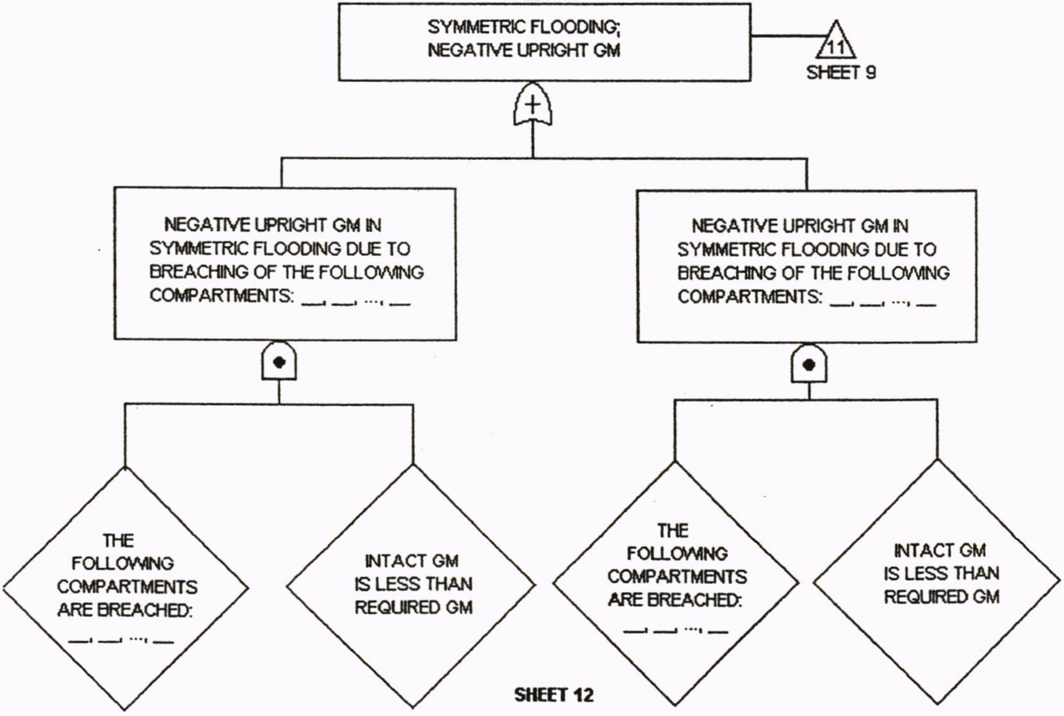


SHEET 11



SHEET 12