The influence of aft control surface configuration of a submarine on the submerged operational performance

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Agenda

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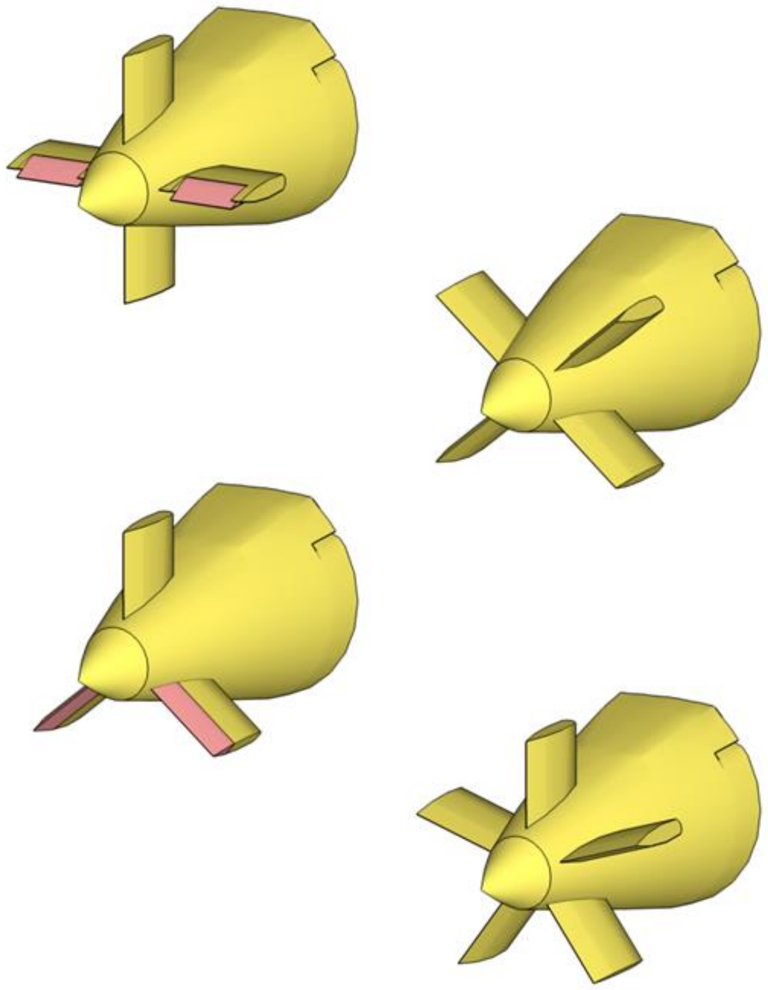
Submarine control surfaces (i)

- A submerged submarine is required to manoeuvre in both the vertical and horizontal planes.
  - Horizontal plane = higher agility, high rates of turn → low tactical diameters.
  - Vertical plane = lower agility required because:
    - High agility generates large pitch angles and depth excursions.
    - If a malfunction in the hydroplane control system occurs (a “jam”), this could place the submarine in danger in broaching or exceeding the maximum depth.
- Traditionally, control surfaces consist of a set of forward and aft hydroplanes and rudders in a cruciform configuration.
  - Large rudders, Smaller hydroplanes with stabilisers.
- However alternative configurations for the aft control surfaces are possible:
  - X-plane: - has been adopted by many SSKs.
  - Inverted Y: - no in-service examples.
  - Pentaform: - no in-service examples.



Images courtesy of UK MoD

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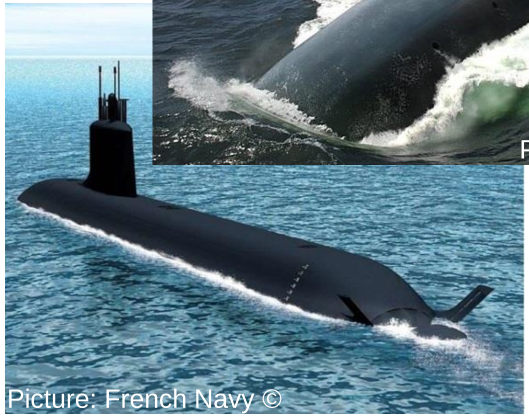
Submarine control surfaces (ii)

- However, recently X-planes have also been proposed for a number of larger nuclear powered submarine projects:
  - Ohio replacement SSBN (Columbia Class) USA.
  - Vanguard Successor SSBN (Dreadnought Class) UK.
  - Barracuda SSN (Suffren Class) France.
- Nuclear powered submarines traditionally have a higher degree of safety analysis conducted on the designs.
- Vertical plane manoeuvring and control is mitigated by a Safe Operating Envelope (SOE).
  - An x-y plot of speed vs depth.
  - Provides guidance to operators on safe combinations of speed and depth, if an incident were to occur.
  - Incidents considered are hydroplane jams and floods.
  - Calculated using a mathematical model – batch processing 1000's of trajectories to derive the SOE.


Picture: US Navy ©


Picture: UK Navy ©


Picture: French Navy ©

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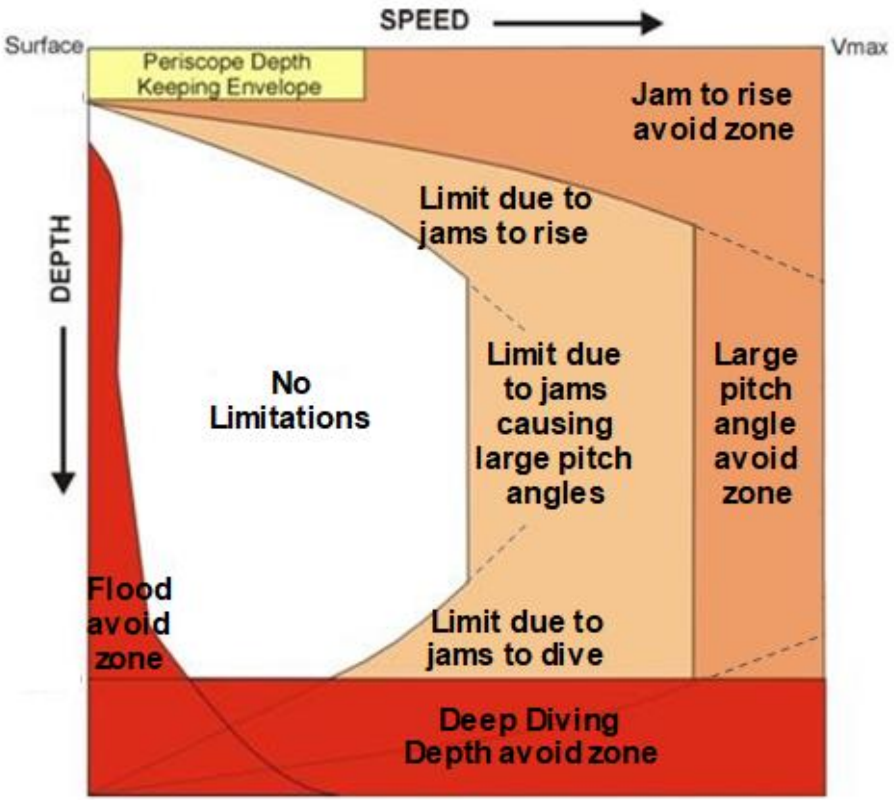
Safe Operating Envelope (i)

- Jam line boundaries on a typical SOE are a composite of results from a number of different hydroplane jam scenarios:
  - Jams to rise and dive.
  - Different hydroplane jam combinations.
- An SOE is most often considered for in-service submarines.
  - Mitigating against the risk of platform loss, if an incident occurs at sea.
- SOEs can also be used as part of the design process for a new submarine. The SOE can:
  - Influence the design process.
  - Ensure the final design is able to meet the required concept of operations.
    - Highlights if there is a need to change the:
      - Hydrodynamics of the platform.
      - Systems that actuate the hydroplanes.



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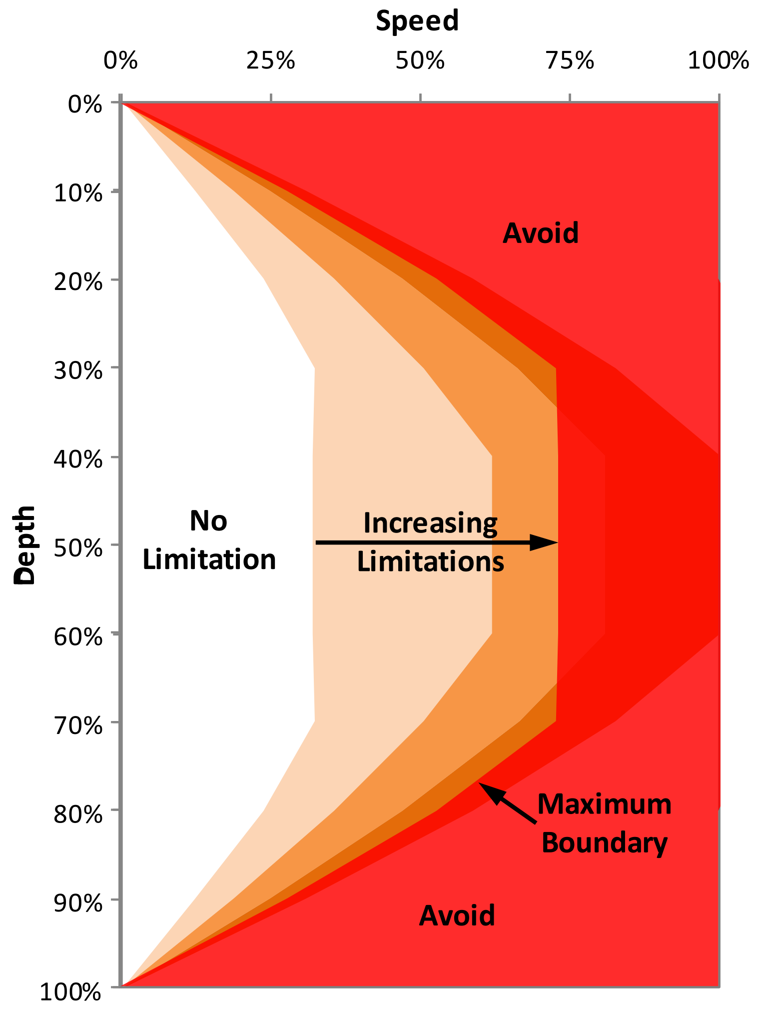
Safe Operating Envelope (ii)

- Typically two types of jam scenario:
  - Jam limitations: - multiple sets of similar scenarios with increasing severity.
    - In the main body of the SOE.
    - A single isolated failure – depends on actuators and linkages → a single aft hydroplane or two aft hydroplanes if they are linked on a common stock.
    - A permanent failure – backup systems cannot override the jam
  - Jam maximum boundary: - a single scenario of maximum severity.
    - A case that bounds the limits of the SOE.
    - Potentially multiple failures depending on the mechanical, hydraulic and electrical linkages or the control logic of the steering and diving control system
    - A temporary jam – backup systems can override the jam and regain control.
  - The final SOE is a composite of these two scenarios.



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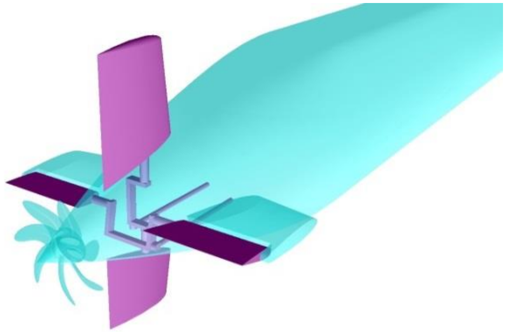
Control surface configuration impact on jam limitation case

- The configuration of the aft control surfaces can have a significant impact on the type of jam incidents that need to be assessed for defining the SOE limitations.
- Some examples of common arrangements for the cruciform and X-plane designs are shown below:

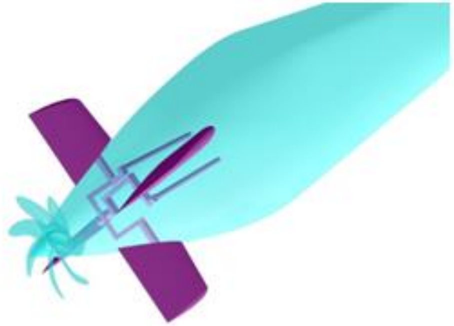
Linked cruciform (2xCS)

- Port and starboard hydroplanes linked by a common stock.
- Upper and lower rudder linked by a common stock.
- One set of control surfaces for each manoeuvring axis.
- No redundancy.
- **Permanent double sternplane jam.**



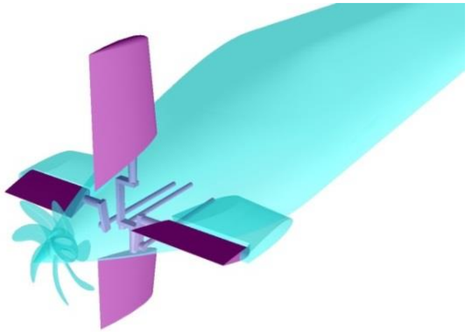
Linked X-plane (2xXP)

- Diagonally opposite planes linked by a common stock.
- Both sets of control surfaces act in both manoeuvring axes.
- Some redundancy as the opposite pair can still affect depth/pitch & heading.
- **Permanent X-plane diagonal pair jam.**



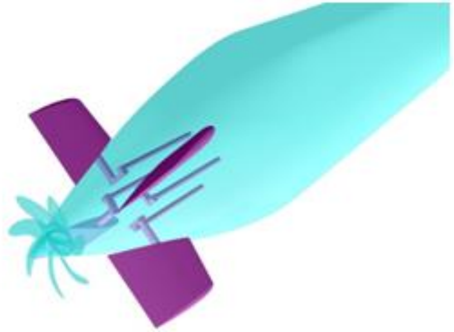
Independently actuated cruciform (1xCS)

- Port and starboard hydroplanes have individual actuator & stock.
- Control surfaces for each manoeuvring axis (rudder as above).
- Some redundancy as the actuator only controls a single sternplane.
- **Permanent single sternplane jam.**



Independently actuated X-plane (1xXP)

- Each plane has its own actuator & stock.
- All four control surfaces act in both manoeuvring axes.
- Significant redundancy as the remaining planes can all affect depth/pitch & heading.
- **Permanent single X-plane jam.**



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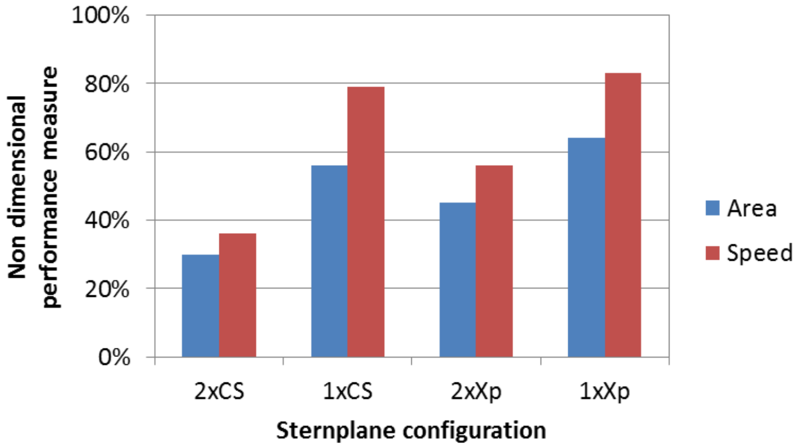
SOE jam limitation – normal operating condition

- If the submarine operates with all sternplanes fully functional, but then experiences a permanent single sternplane failure:
- 2xCS arrangement has the smallest operational area (30%) and lowest allowable maximum speed (36%).
- 2xXp configuration is better with a slightly bigger operational area 45% and speed 56%.
- 1xCS and 1xXp arrangements have the best performance (area 56% vs 64% and speed 79% vs 83% respectively).
  - Only one possible recovery strategy for 1xCS:
    - Put the working hydroplane in the opposite direction to the jam.
  - Several possible recovery strategy options for a 1xXP configuration:
    - Use the three remaining X-planes in the opposite direction to the jam (shown in figure).
      - High manoeuvrability can results in large pitch angles during recovery.
    - Order a turn, neutralising the jam's tendency to cause a depth excursion, with the bowplanes being used for depth control.
      - Benign vertical plane manoeuvre results in little pitch – but not as efficient in recovery.
      - SOE performance of 56% area and 74% speed.



Key

Non dimensional area = SOE area / max speed x max depth.

Non dimensional speed = SOE max speed / platform max speed.

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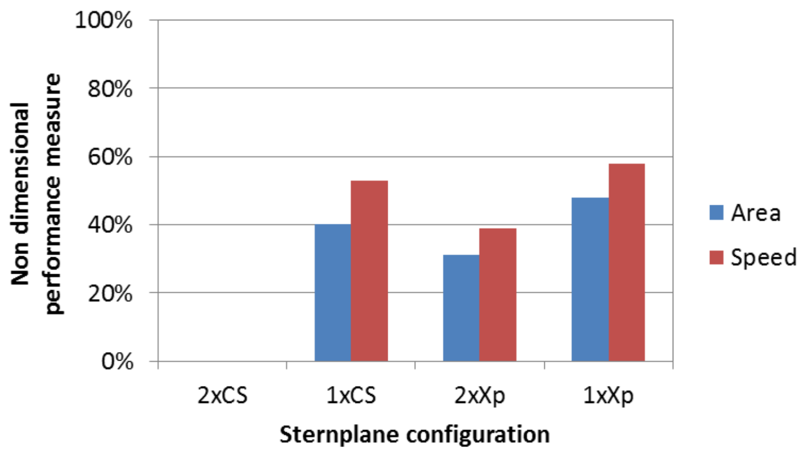
SOE jam limitation – degraded operating condition

- If the submarine continues to operate with an existing non-functioning sternplane and experiences a further permanent single sternplane failure:
- 2xCS has no redundancy against a stern hydroplane jam. Any failure must be immediately rectified at sea if the submarine is to continue submerged operations.
- 1xCS configuration has an SOE performance of 40% for area and 53% for speed, a reduction of 16% and 26% respectively compared with the normal condition.
  - The existing non-functioning control surface must be regained for the recovery action to occur.
- 2xXP arrangement has an SOE performance of 31% area and 39% speed, a reduction of 17% and 14% respectively compared with the normal condition.
  - The existing non-functioning control surface must be regained for the recovery action to occur.
- 1xXP configuration has an SOE performance of 48% area and 58% speed, a reduction of 16% and 25% respectively compared with the normal condition.
  - Does not require the regain of the degraded control surface.



Key

Non dimensional area = SOE area / max speed x max depth.

Non dimensional speed = SOE max speed / platform max speed.

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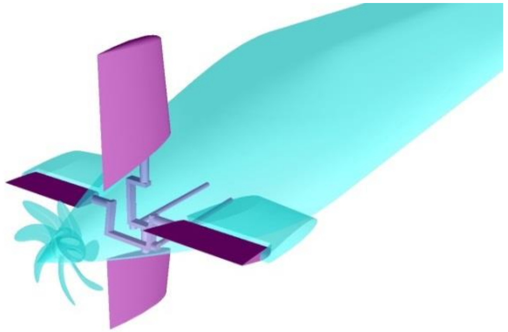
Control surface actuation architecture impact on jam max boundary

- The SOE jam maximum boundary case is highly dependent on what possible failure modes could exist, which itself is a function of the architecture of the steering and diving control system.
- Some examples of common arrangements for the cruciform and X-plane designs are shown below:

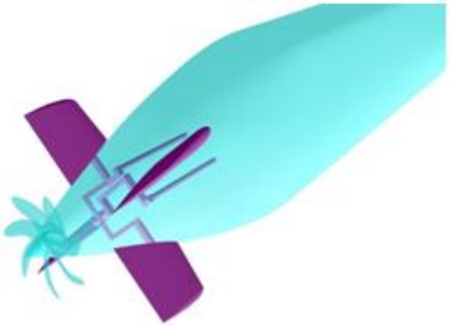
Linked cruciform

- Minimal automation of control systems – flight yoke primary interface.
- Basic autopilot for heading and depth (only used occasionally).
- **Temporary double sternplane jam.**



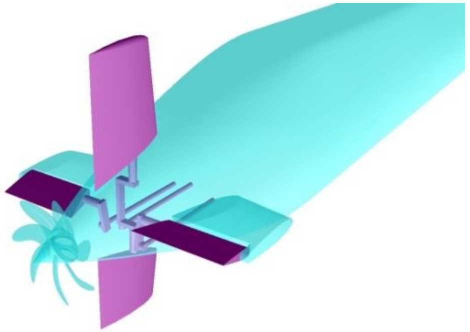
Linked X-plane

- Minimal automation of control systems – flight yoke primary interface.
- Basic autopilot for heading and depth (only used occasionally).
- **Temporary X-plane diagonal pair jam.**



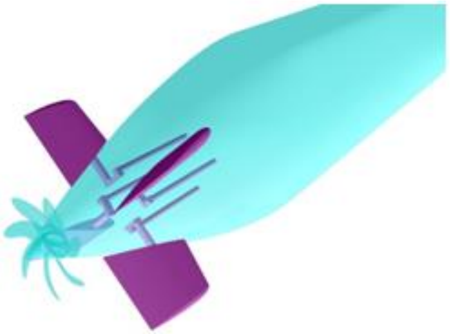
Independently actuated cruciform

- Increased levels of automation, designed to be used extensively under autopilot control.
- A steering and diving control system interfaces between the planesman input and the actuators.
- **Temporary double stern & bow plane jam.**



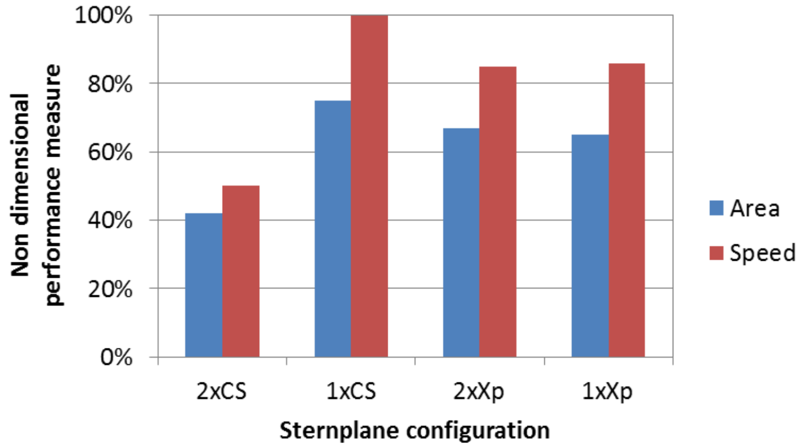
Independently actuated X-plane

- Increased levels of automation, designed to be used extensively under autopilot control.
- A diving and steering control system interfaces between the planesman input and the actuators.
- **Temporary four X-planes and two bowplanes jam.**



SOE maximum boundary jam – normal operating condition

- If the submarine operates with all sternplanes fully functional, but then experiences a temporary failure of multiple hydroplanes:
- 2xCS arrangement has the smallest maximum boundary operational area (42%) and speed (50%).
- 1xCS configuration has the largest maximum boundary operational area (75%) and speed (100%).
- The 1xXP and 2xXP results are both of a similar magnitude, for area (65% vs 67% respectively) and for speed (86% vs 85% respectively).
  - 1xCS result is better where "all planes jam" i.e. double bow and stern.
  - 1xXP result is worse for "all planes jam" as its 2x bow + 4x stern.



Key

Non dimensional area = SOE area / max speed x max depth.

Non dimensional speed = SOE max speed / platform max speed.

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Concluding discussion (i)

- This presentation has shown comparisons of SOE areas and speeds for different aft control surface configurations for a submerged submarine. This has showed that:
  - Traditional cruciform designs have a limited SOE area, because of the architecture and the control systems for the arrangement.
    - Simple systems, often operated in manual control
  - Improving the architecture and control systems results in a significant increase in the SOE area, whilst maintaining the overall cruciform arrangement.
    - More complex systems, often operated in autopilot control
  - Changing the cruciform arrangement to that for an X-plane, but not improving the architecture and control systems, results in a modest improvement to the SOE area.
    - Simple systems, often operated in manual control, but requiring a improved understanding by operators
  - Changing the cruciform arrangement to that for an X-plane and improving the architecture and control systems results in an SOE has minimal impact on the intact SOE, but has a significant impact on the ability to recover from a degraded plane condition.
    - Very complex systems that are heavily reliant on autopilot control and electronic safe guards

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Concluding discussion (ii)

- An ***evolution*** in the design of both the control surface configuration and the actuation can result in a ***revolution*** in platform operability for nuclear powered submarines.

	Cruciform	X-plane
Linked	Traditional submarine design. Small SOE, no redundancy	Medium improvement to the SOE (normal) Can cope with degraded condition, but small SOE. (If degraded plane can be regained for recovery)
Independently actuated	Large improvement to the SOE (normal). Can cope with degraded condition, with medium SOE. (If degraded sternplane can be regained for recovery.)	Small improvement Medium improvement - to the SOE (normal & degraded). (Degraded plane does not need to be regained)

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