NTEC Radiation Shielding Module :

A Shielding Application

BAESYSTEMS Submarine Solutions : Radiation Physics & Shielding

In association with The Shielding Forum

Overview

1. Nuclear Powered Submarines
2. Constraints placed on shield design for submarines
3. Pressurised Water Reactors – Radiation Sources
4. Submarine radiation shields
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7. Occupancy Model
8. Optimisation
9. ALARP
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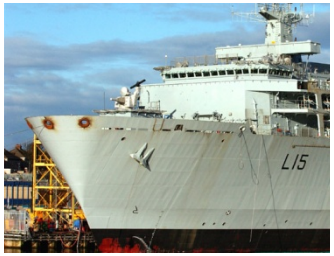

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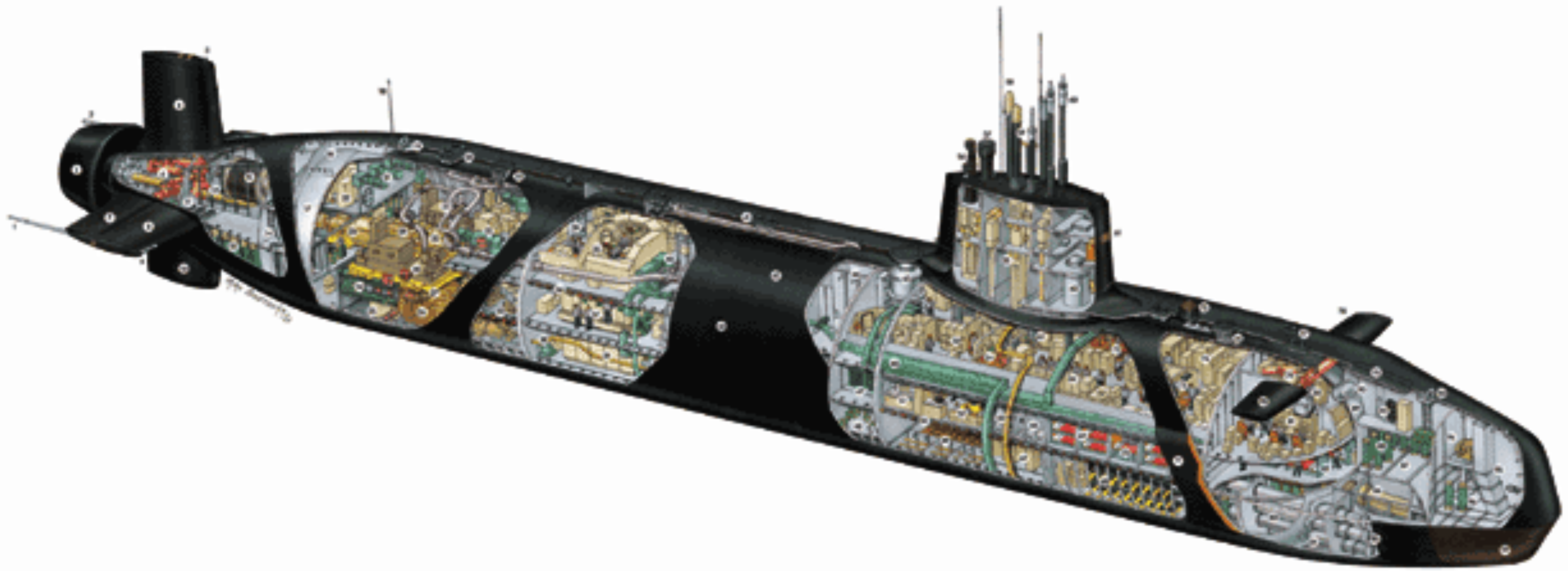
Nuclear Powered Submarines



- A complete contained operating environment, capable of spending months at sea without returning to base.
- Crew cannot switch off and go home they are working in close proximity to a nuclear reactor 24 hrs a day.
- While radiation awareness is important part of training, it is not good to work, eat & sleep next to radiation hazard signs.

Nuclear Powered Submarines

- Submarines present a unique challenge for radiological safety engineers
- Personnel may have to work, eat and sleep within 20-30ft of the centre of a Pressurised Water Reactor core.
- We cannot add 100's of tonnes of shielding as the submarine is unlikely to surface again.
- Weight distribution is important as it affects ship stability
- Need to provide a solution that balances risk, i.e. ship safety and radiological safety
- Optimisation within the environment constraints is crucial

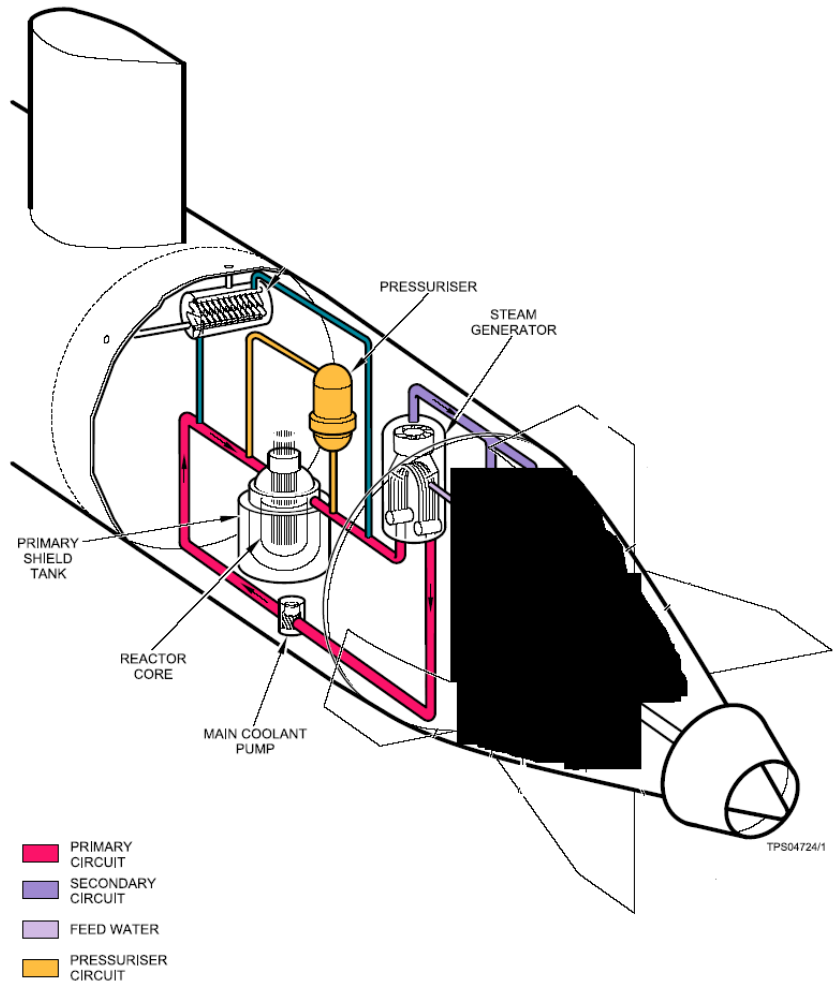
Design Constraints

- Weight
  - Submarine designers have to control weight closely. There is a Weight Engineering Department in Submarines
  - All systems have weight budgets.
  - Weight Budgets mean that we cannot install unlimited shielding.
  - Stability Considerations

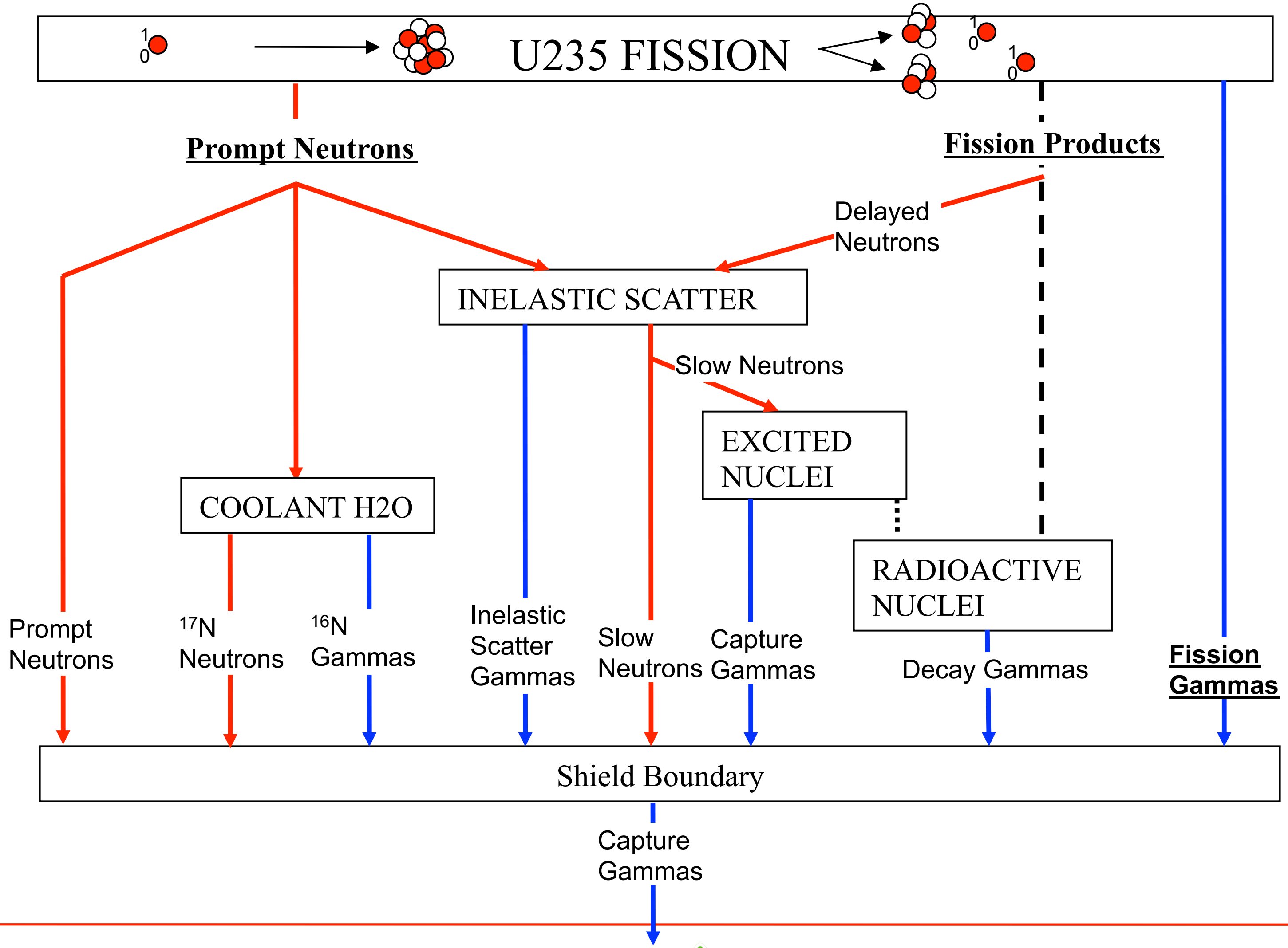
- Location & Volume
  - Needs sturdy mounting point : Shock considerations
  - Stiffener Depth
  - Step increase in cost when breached

Schematic of Reactor and Propulsion Systems

- Nuclear submarines are powered by Pressurised Water Reactors (PWRs)
- They are very similar in function to standard civil power generation PWRs
- PWRs use water for the coolant and the moderator
- Heated water leaves the reactor vessel and travels via pipework to a heat exchanger, Steam Generator. It then returns to the reactor vessel.



Pressurised Water Reactor : Radiation Sources



Radiation Production in a PWR

- The fission process is the primary source of all radiation from a PWR. It gives rise to the following radiations:
- Neutrons produced from fission escape the reactor
- Neutrons cause activation of the coolant water as it passes through the core. The ^{16}O is converted to ^{16}N in the following reaction:

$$^{16}_{8}O + ^{1}_{0}n \longrightarrow ^{16}_{7}N + ^{1}_{1}p$$

$$^{16}_{7}N \Rightarrow radioactive \xrightarrow{\text{7.4 second half life}} ^{16}_{8}O + ^{0}_{-1}e + \gamma\ (6MeV)$$

High atomic number materials are required to stop gammas. Lead is the preferred choice.

- Thermal neutrons are captured in the iron and hydrogen constituents of the reactor and the compartment bulkheads and produce Capture Gammas. Boronated Polythene is used to reduce this effect.

$$^{56}_{26}Fe + ^{1}_{0}n \longrightarrow ^{57}_{26}Fe + \gamma\ (3\text{-}10MeV)$$

Shielded using lead

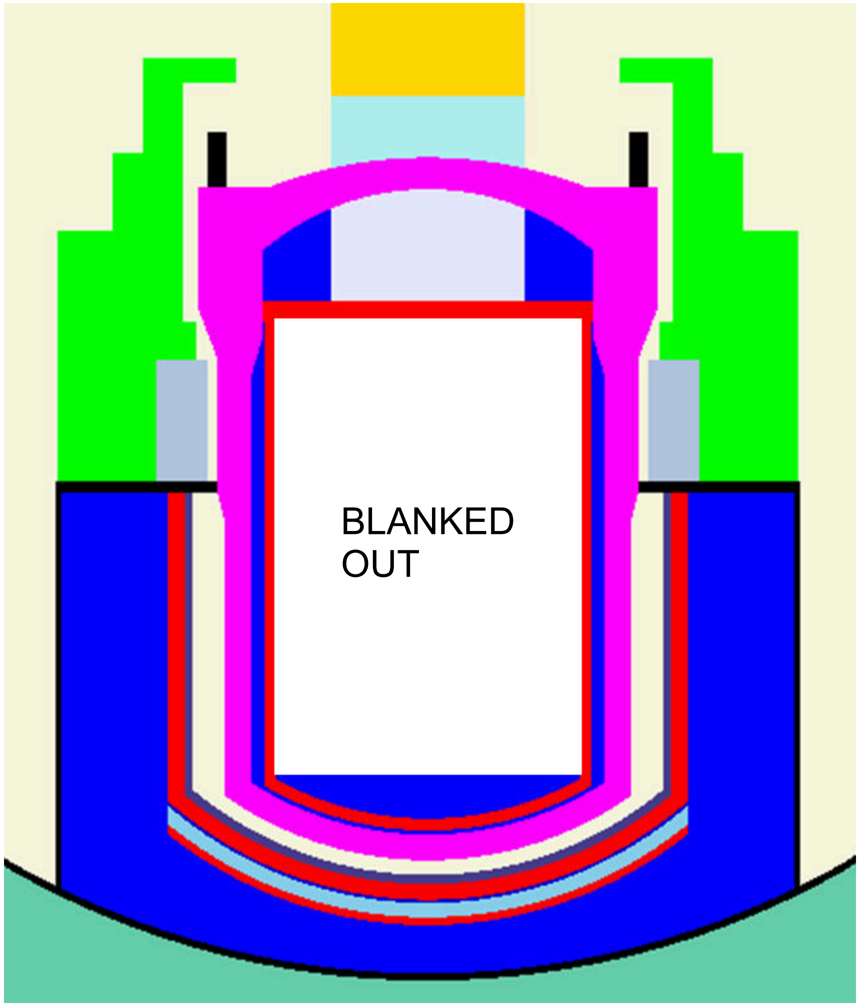
- Gammas produced in the fission process escape the reactor
- Neutrons cause activation of ^{17}O in the same way as with ^{16}O

$$^{17}_{7}N \Rightarrow radioactive \xrightarrow{\text{4.14 second half life}} ^{16}_{8}O + ^{1}_{0}n(0.9MeV) + ^{0}_{-1}e$$

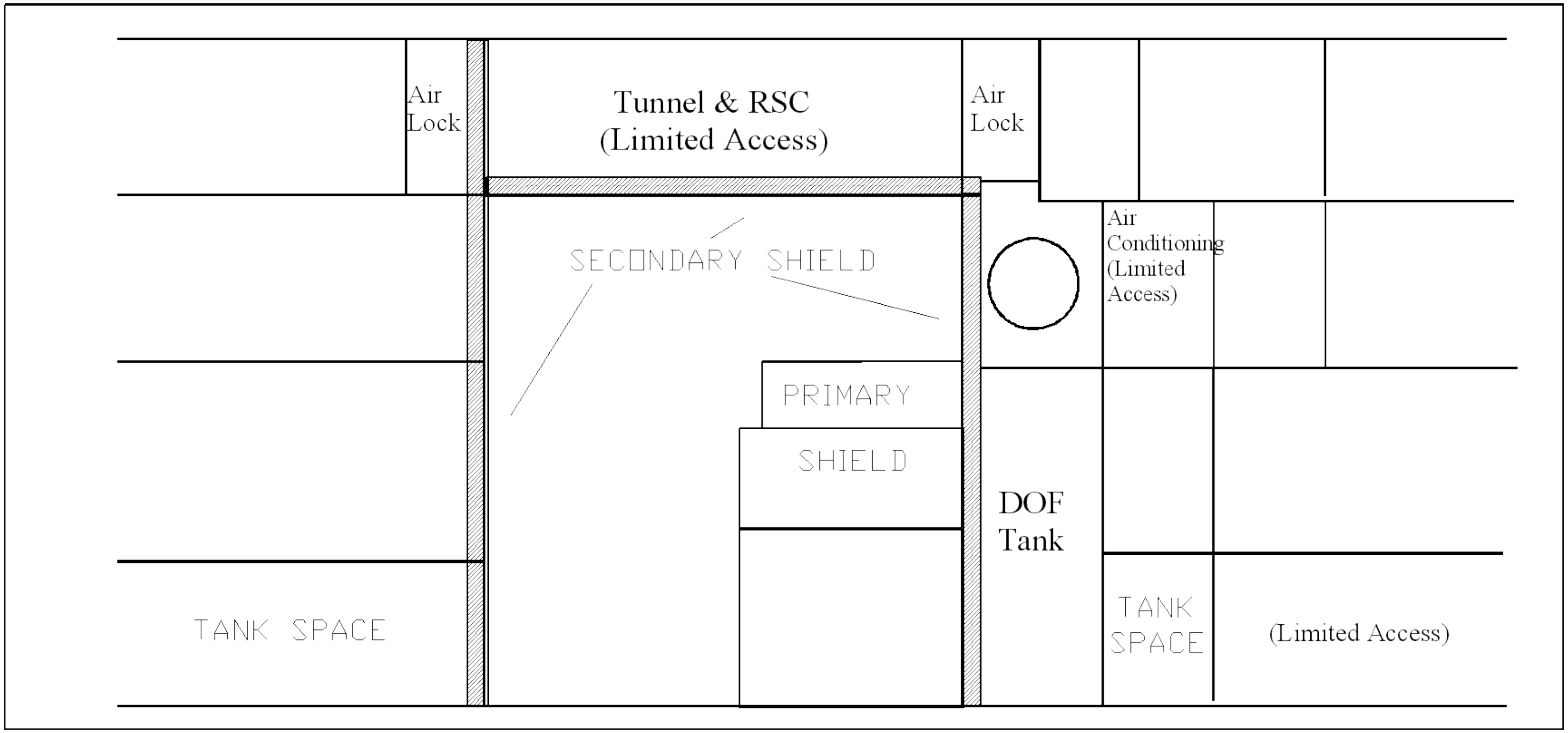
Dense hydrogenous materials are the most efficient neutron shields. Polythene is used extensively in the shielding

Submarine Reactor

- Neutron fluence is so high that the reactor has to be surrounded with shielding to bring flux down to levels that will ensure plant components are not activated
- The added shielding is still not sufficient to ensure that doserates outside the reactor compartment are low enough for general occupancy. Further neutron shielding must be added to reactor compartment bulkheads.



Submarine Radiation Shields



Radiation Transport Tools

- There are many different radiation transport tools available to the shield designer that use varied methods for calculating the radiation flux from a source after it has been attenuated by shield materials.
- Some popular methods are
  - Point kernel method for gamma calculations. This method approximates a volume source to several point sources (kernels) and uses the following equation to determine the doserate at a point.

$$Doserate = R_E \times Source \times BuildUp \times e^{-\mu t}$$

- Monte-Carlo statistical estimate for gamma and neutrons. In which particles are tracked across spatial volumes and interact with materials according to interaction probabilities. Random number generators are used to determine particle events using probability libraries of cross-sections.
- Discrete Ordinates methods used for gamma and neutron. This method applies transport equations across meshes overlaid on the spatial problem and discretises the angular variable.

Tools Used by Submarine Solutions

- PG2000 : Our main gamma calculation tool is an in-house code based on the Point Kernel method

- MCBEND : Our main neutron calculation tool supplied by ANSWERS of Serco, based on the monte-carlo method.

- MCNP : Another monte-carlo gamma and neutron code produced by Los Alamos in the USA

- SHOP/ASCOT : In-house shield panel configuration optimisation tools.

PG2000

- A Point Kernel code used because it is a quick & accurate method
- PG2000 is capable of modelling the coolant decay in the loops according to the volume of pipework and the flow rate of the coolant. It is updated regularly to keep it current and it has a combinatorial geometry modelling capability.
- It also forms an integral part of our dose/weight optimisation suite along with ASCOT.
- Comparisons with other codes have shown that PG2000 is very capable and compares well.

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MCBEND

- Monte Carlo codes are used because of the accuracy of the method. They are effectively a simulation of radiation behaviour. MCBEND is a QA'd tool with many useful features.
- Used since the Astute design as our neutron design code. It is capable of breaking down the problem into multiple stages, each of which can use different acceleration techniques.
- This code is also capable of calculating the source strength of gammas generated in materials as a result of neutron captures, i.e. Capture Gammas. It can then track the gammas to calculate capture gammas doserates. It is subject to an annual licence fee that also limits the number of machines it can run on.

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MCNP

- This code does not have the same ease of use and the extensive capabilities that MCBEND has but it does have the advantage that it is available for a one off fee and can run on any number of machines.
- It is also capable of running in a parallel mode across any number of processors.

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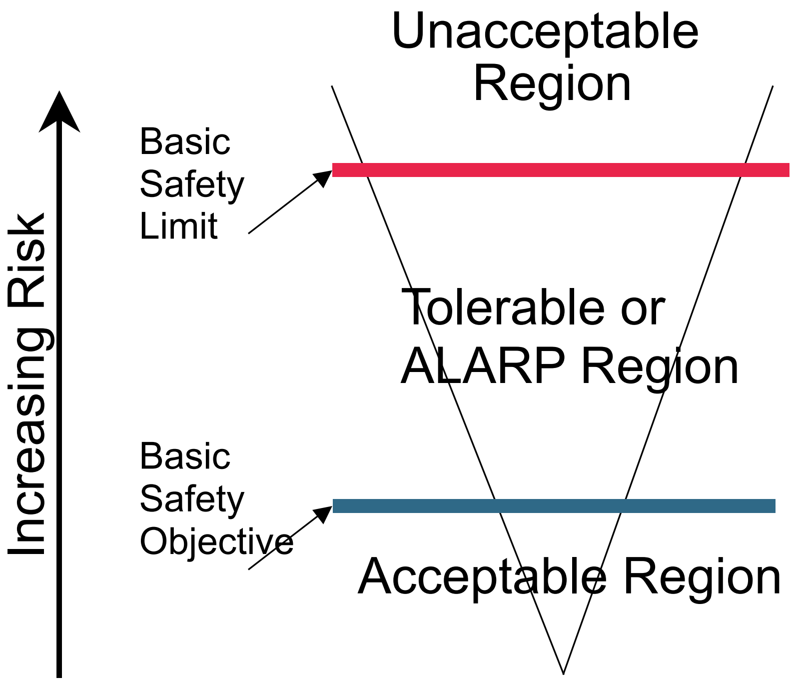
ASCOT

- This is not a radiation transport code.
- It is designed to work with PG2000 to calculate the optimum shield configuration to achieve the lowest dose for a given shield weight. Input 'dose objective' and it outputs shield weight.
- An early version (SHOP) was used to design the Secondary Shield for the Astute class.
- ASCOT is the successor to SHOP, designed to deal with the next generation of submarine reactors.

Requirements Criteria

- Astute brought a radical change
- Requirements criteria now dose based
- Requirement philosophy derived from the Tolerability of Risk work published in civil field by HSE
- Introduced concept of Basic Safety Limits and Objectives

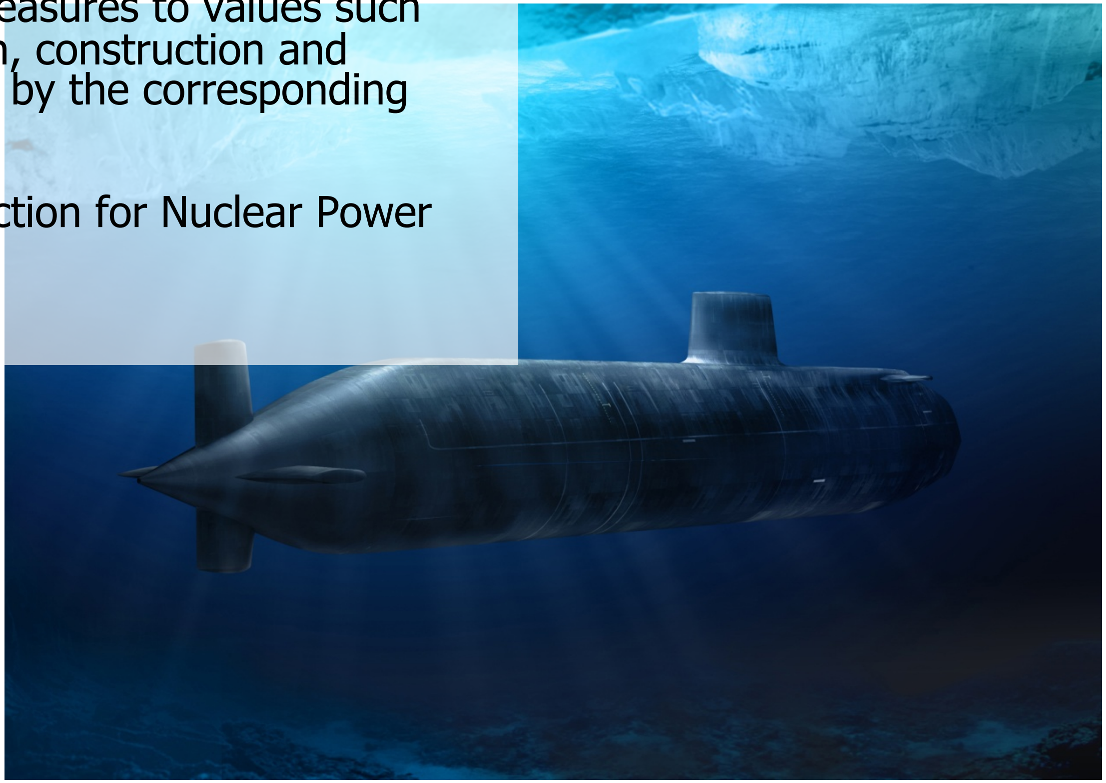


Requirements Criteria

ALARP

"The requirement to keep all exposures within prescribed limits and 'as low as reasonably practicable', economic and social factors being taken into account, implies that the radiation exposure resulting from a practice should be reduced by radiation protection measures to values such that further expenditure for design, construction and operation would not be warranted by the corresponding reduction in radiation exposure."

Design Aspects of Radiation Protection for Nuclear Power Plants.
IAEA Safety Series No. 50



Nuclear Safety Requirements for Astute

- Doserates specifications the same as previous class
- Basic Safety Limits & Objectives set for annual crew dose
- Normal Operation

  -Annual Collective Crew Dose Limit

  -Annual Individual Dose Limit
- No longer working to achieve doserates just outside the shield. Now have to calculate the expected dose for each crew member and make sure the shield design can achieve criteria.

Occupancy Model (1)

- For a given source of radiation, radiological safety is based on identification and control of the following quantities: Time, Distance & Shielding. Taking these in reverse order
  - Shielding is the quantity that is being designed but which is limited by weight considerations;
  - Distance is the position of each compartment relative to the source of radiation and is readily determined using the submarine General Arrangement;
  - Time is the fractional time spent by each individual in dose scoring compartments multiplied by the annual Effective Full Power Hours of reactor operation.
- Using these three quantities, a shield designer can calculate the annual Individual and Collective dose incurred by personnel onboard the submarine.
- The quantity Time has been incorporated into the shield design process in the form of an Occupancy Model.

Occupancy Model (2)

- A data file that cross-references each member of the crew against all the dose scoring compartments that he accesses
- In each case identifying the estimated fractional time per day spent within the respective compartments
- Derived from data obtained during crew monitoring trials carried out on in-service submarines
- Each trial was developed and conducted with the specific objective of quantifying the time an individual spent in dose scoring compartments and at the same time measuring their incurred dose
- The Occupancy Model is a combination of the trial data and the crew manning profile

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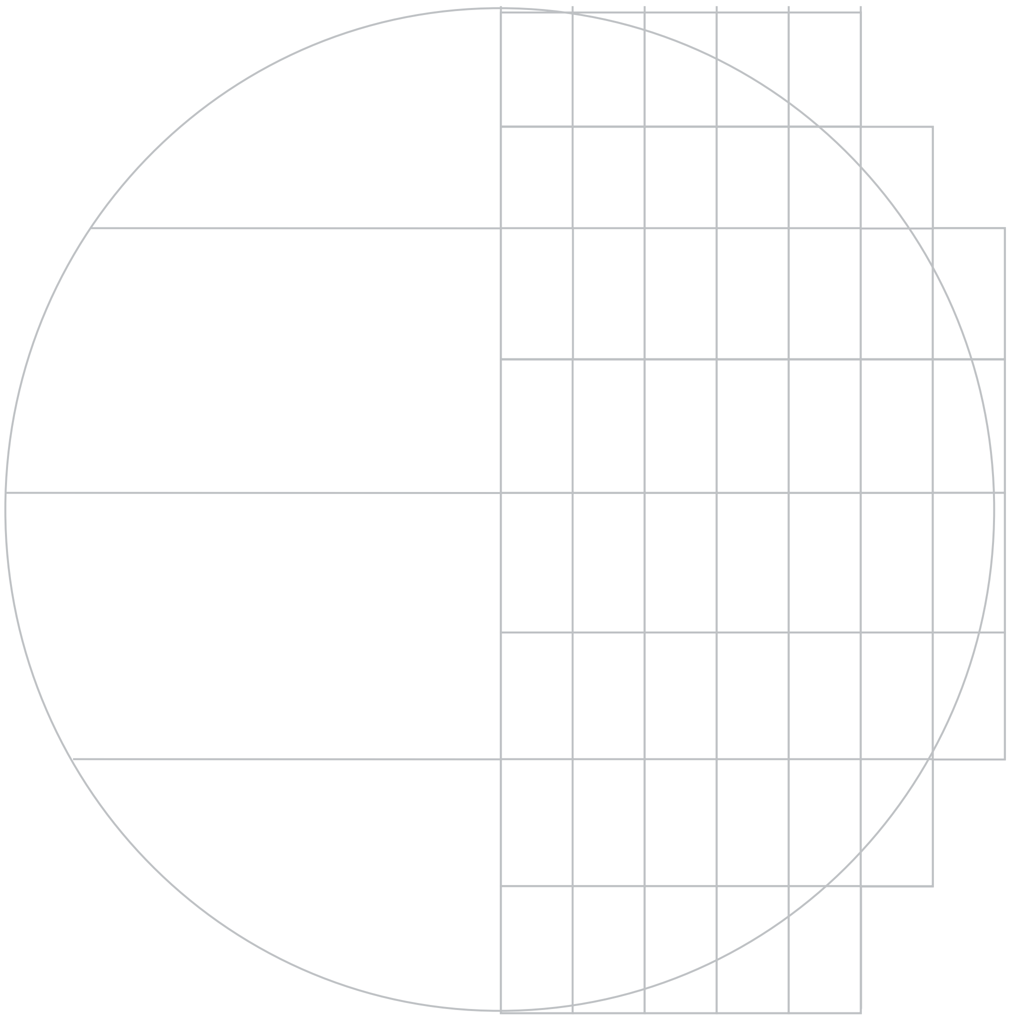
Shield Optimisation (ASCOT)



- ASCOT process evaluates the shield worth of each panel
- The efficiency of each panel is determined in isolation
- Efficiency is Dose/Weight
- Most efficient panel 'banked' in a stepwise process
- Results in a configuration that is optimised for gamma dose and weight

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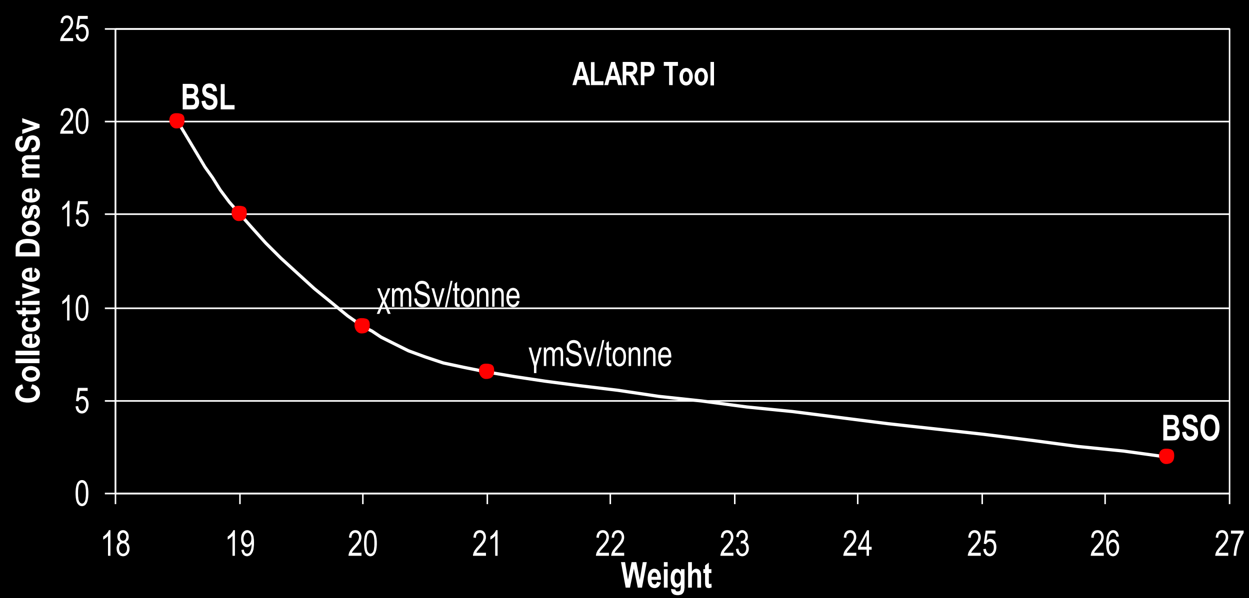
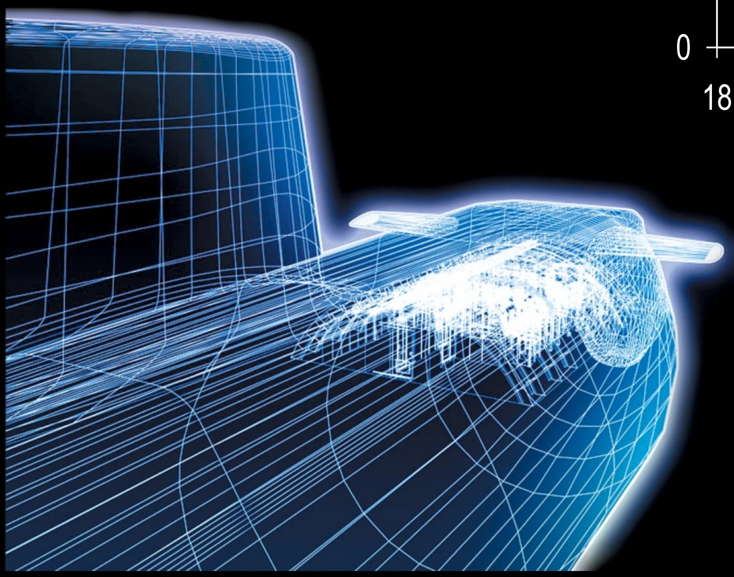
Design for ALARP





- ALARP tool used in decision making process
- Options can be ranked with risk/benefit analysis
- Cost of achieving BSO can be assessed to see whether the sacrifice is proportionate to the benefit

Neutron Shield Design Using MCBEND

- The model for the PG2000 calculations can be used directly by MCBEND in the neutron calculations
- Reactor sources are obtained from RRA and input into the model
- Calculations are performed in a 3 stage process as follows:-
    - Calculate from the sources to an interface file on each of the RC bulkheads
    - Using the interface file from the previous stage as a source calculations are performed through the shielded bulkhead to an interface file on external face of the bulkhead.
    - Using the interface file from the previous stage as a source calculations are performed throughout the compartments to determine doserates and doses.

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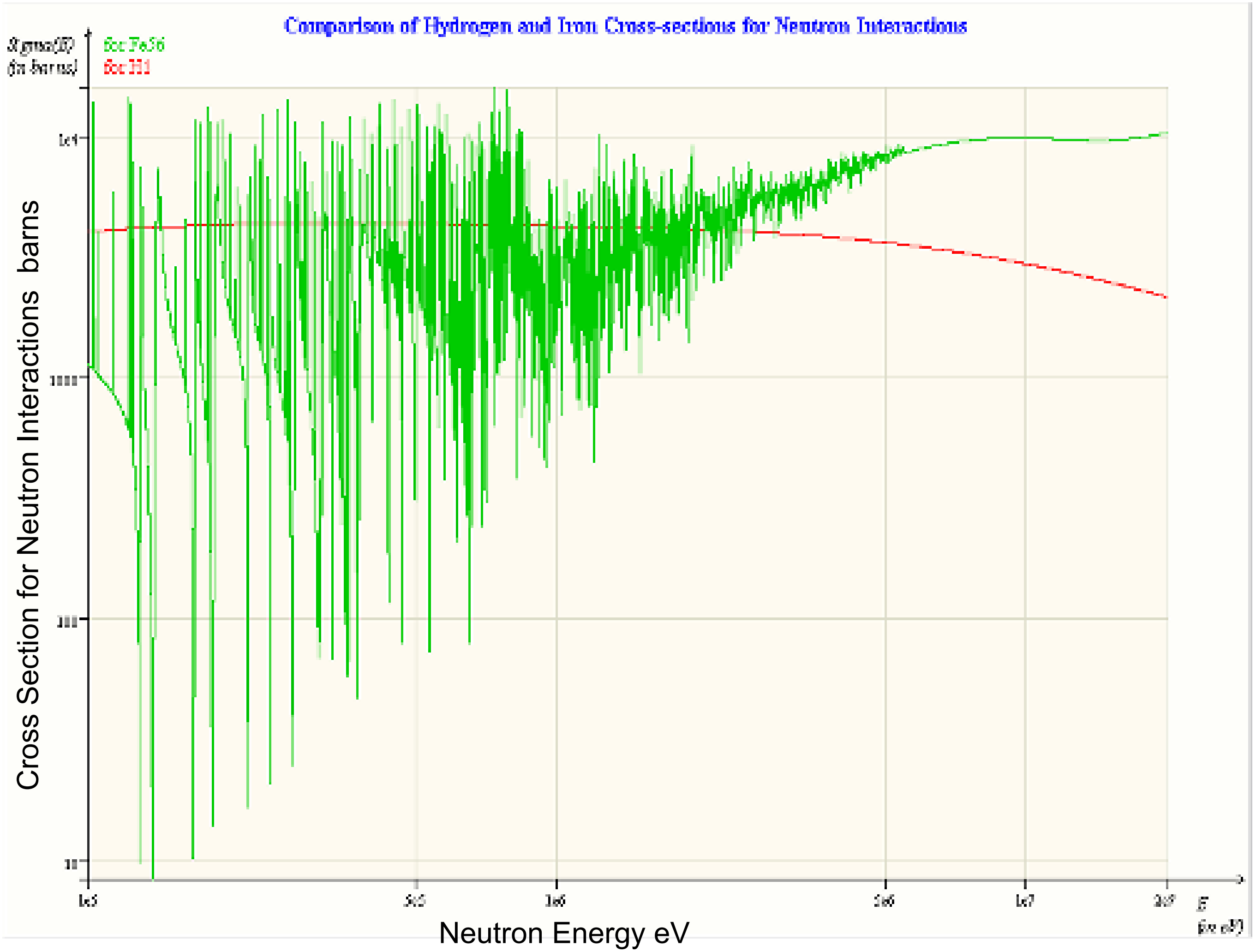
Hydrogen and Iron Cross-Sections for Neutron Interactions



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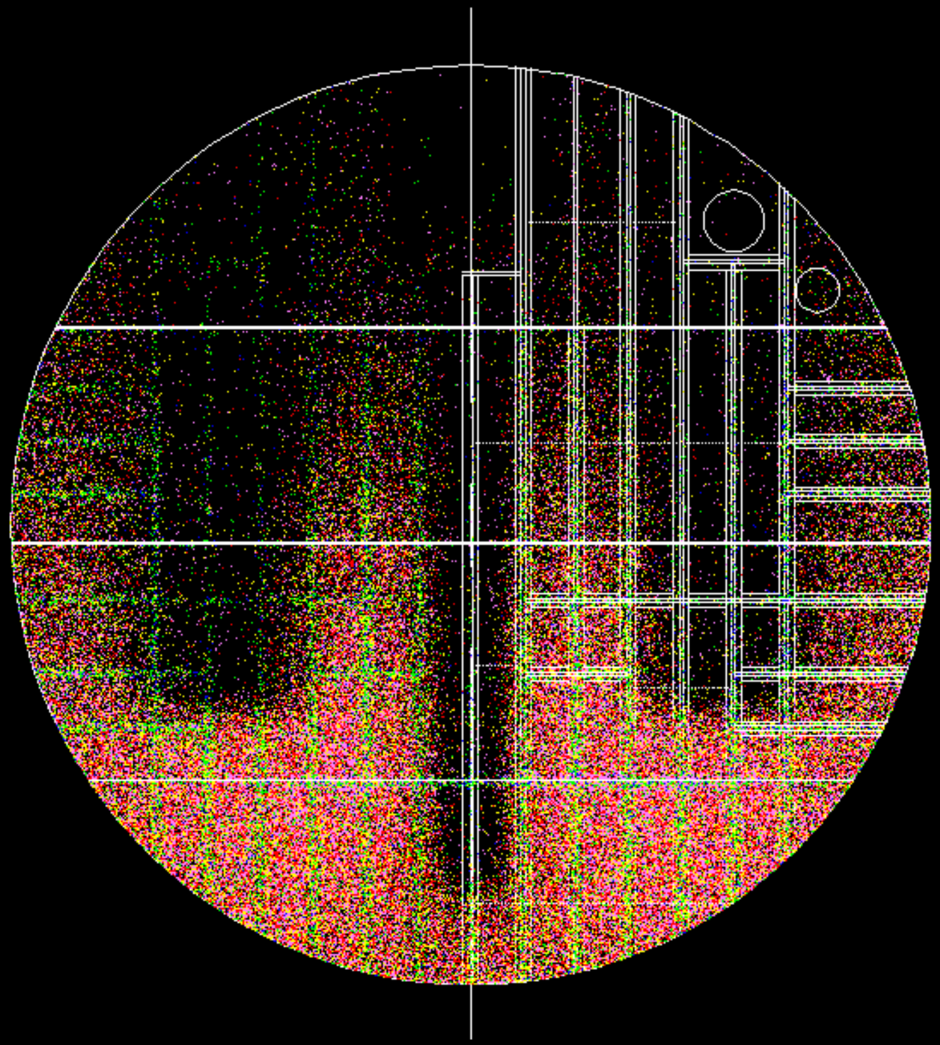
First Flight Source Out RC



Red :

14.0 - 4.72 MeV

Yellow :

4.72 - 0.60 MeV

Green :

600 - 67.4 keV

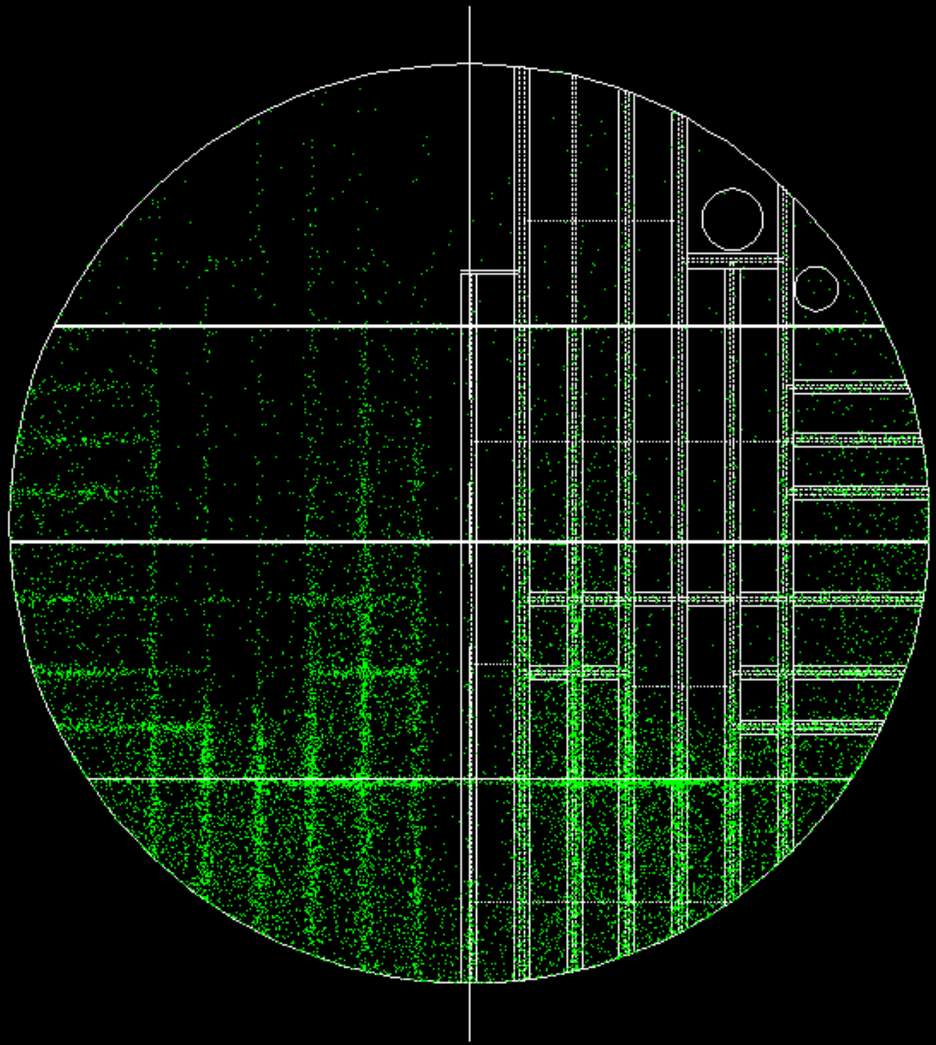
Blue :

67.4 - 9.12 keV

Purple :

9.12keV - Thermals

Neutrons Traveling Down Steel Penetrations



Green :

600 - 67.4 keV

Summary

- If Vanguard had used the optimisation suite the Collective Dose would be halved. Vanguard class submarine doses are so low that the dosimetry is struggling to measure them.
- Astute measured doserates are lower than Vanguard.
- Very little background radiation on a submarine underwater. Over 75% of Astute crew would get a bigger dose from background radiation staying ashore than they would get from the reactor while they were onboard.

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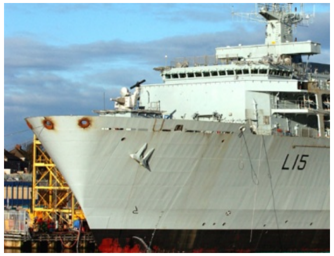

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