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V01	**25.08.2019**	Initial version (structure of document)
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List of symbols and abbreviations

DoA	Description of Action
EC	European Commission
PMT	Project Management Team
SG	Steering Group
QA	Quality Assurance
GT	Gross Tonnage
NAPA	Naval Architectural Package
MVZ	Main Vertical Zone
FEM	Finite Element Method
POB	Persons On Board
GAP	General Arrangement Plan
GM	Metacentric height
KG	vertical centre of gravity
VCG	vertical centre of gravity
LCG	longitudinal centre of gravity
FSM	free surface moment
DL	lightest service draught
DP	partial draught
DS	deepest subdivision draught
MER	main engine room

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1 EXECUTIVE SUMMARY

This report describes analysis of permeability of various categories of spaces.

1.1 Problem definition

- To achieve realistic research for the response to flooding events it is necessary to ensure that the basic input parameters are correct.
- For different categories of spaces default values are defined in SOLAS II/1.7-3. As some of these values originate from SOLAS48 and beyond a review of these figures is needed.
- For the assessment of a flooding event the amount of in flooded water may be essential for the result. If unrealistic values are used, it may result in strange design strategies, wrong judgment of an accident scenario and hence to wrong decision about abandonment of a passenger ship or not.
- As all tools to calculate any flooding event rely on the given default values for permeability the validation of these input parameters is essential.

1.2 Technical approach and work plan

- The work has been divided into three main parts. The calculation of permeability based on CAD models of built ships, the recording of stores and cargo hold onboard ships and the analysis of tank filling based on loading conditions collected in WP2.2

1.3 Results

- The analysis of the permeability has shown that the default values of SOLAS are in many aspects unrealistic and not appropriate. Only for the cargo hold of Ropax ships the SOLAS values have been confirmed.
- The permeability for stores, engine rooms and accommodation areas should be modified to a value of 0.9 to reflect a more realistic approach.
- The permeability of tanks in way of a probabilistic damage stability assessment as defined in SOLAS shows a very large deviation from the actual degree of filling. Two different proposals have been developed how this can be considered in a more realistic way.

1.4 Conclusions and recommendation

- The results for the permeability found in this work package should be considered in the further work of FLARE, in particular as input parameter for simulations, static stability assessment

- If the results of WP8 will show a new approach for the definition of a stability assessment after flooding together with a proposal for the corresponding requirements the new values for permeability should be included.
- In the meantime the results of this work package should be forwarded as separate submission to IMO as it contains substantive information for the application of SOLAS II-1.

2 INTRODUCTION

2.1 Task/Sub-task text

The amount of floodwater has a significant impact on the survivability after flooding. The current practice is to use standard values for the permeability as defined in SOLAS II-1, which may either be unrealistic or very conservative. For different categories of spaces, e.g. tanks, engine rooms, cabin areas, dry stores and provision stores, the actual permeability is to be assessed either by measurement on board or by detailed calculation. The work is distributed as follows:

- Measurement and/estimation of loaded stores onboard
- Measurement and/estimation of loaded stores and cargo onboard
- Calculation of engine rooms and cabin areas
- Averaged permeability of tanks

The collected data will be analyzed and compared with the SOLAS assumptions. Recommendations will be made which permeabilities should be used in the assessment of flooding events for different classes of spaces.

The objective of this work package is not to calculate the permeability down to the last digit, but to validate the SOLAS assumptions. As different designs or operational patterns may show a large variation of permeability and simultaneously the number of ships and spaces to be investigated Is limited only a coarse validation will be done.

3 DEFINITION OF PERMEABILITY

The permeability is the relation of the floodable volume and the total volume of a space.

PERM = (Total Volume – Volume of parts) / total volume

Total Volume: total moulded volume of room

Volume of parts: volume of non-floodable parts inside the room. E.g. steel structure, pipes, cables, furniture, machinery equipment, spare parts, trailer, cars etc.

The actual SOLAS convention handles this topic in a separate regulation. The permeability prescribed by SOLAS Ch.II-1 reg.7-3.1 for tanks intended for liquids is 0 or 0.95 whichever results in the more severe requirement but for cargo compartments SOLAS Ch.II-1 reg.7-3.2 defines a different permeability for each draught, as shown in the table.

In addition the default values (0.95 for accommodation, 0.6 for stores and 0.85 for machinery spaces) may be not realistic any more, as they are the same as in SOLAS48.

Regulation 7-3 - *Permeability*

1 For the purpose of the subdivision and damage stability calculations of the regulations, the permeability of each general compartment or part of a compartment shall be as follows:

Spaces	Permeability
Appropriated to stores	0.60
Occupied by accommodation	0.95
Occupied by machinery	0.85
Void spaces	0.95
Intended for liquids	0 or 0.95 footnote

2 For the purpose of the subdivision and damage stability calculations of the regulations, the permeability of each cargo compartment or part of a compartment shall be as follows:

Spaces	Permeability at draught d_s	Permeability at draught d_p	Permeability at draught d_l
Dry cargo spaces	0.70	0.80	0.95
Container spaces	0.70	0.80	0.95
Ro-ro spaces	0.90	0.90	0.95
Cargo liquids	0.70	0.80	0.95

3 Other figures for permeability may be used if substantiated by calculations.

Table 1 SOLAS II/1.7-3

Paragraph SOLAS II/1.7-3.3 allows explicitly to deviate from the default values if it can be substantiated by calculations.

4 ANALYSIS OF CAD MODELS

The chosen approach is the analysis of all parts in the investigated room using the CAD system. Special attention has been given to open ducts and pipes, e.g. HVAC ducts. These parts may be flooded and have been considered in a special way. Thin HVAC ducts may be disregarded, as the non-floodable volume is very small.

The non-flooded part of floodable equipment, like switchboards, furniture etc. has been estimated in a pragmatic way. For example the volume of the material of wooden furniture estimated from the weight and assuming a density for wood (e.g. 0.9)

4.1 Main Engine rooms

A number of engine rooms have been analyzed by the shipyards. Different ships have been used to understand the variety of results.

4.1.1 Main Engine Room #1

The engine room includes the main engines, other plants and systems, piping systems, control cabinets, equipment, electrical components, supply and discharge systems. The investigated space covers only the engine space which will have the same permeability as described in SOLAS. Other rooms, like switchboard rooms, which may be flooded separately, are excluded. The exact contour is marked in the following figure for each deck.

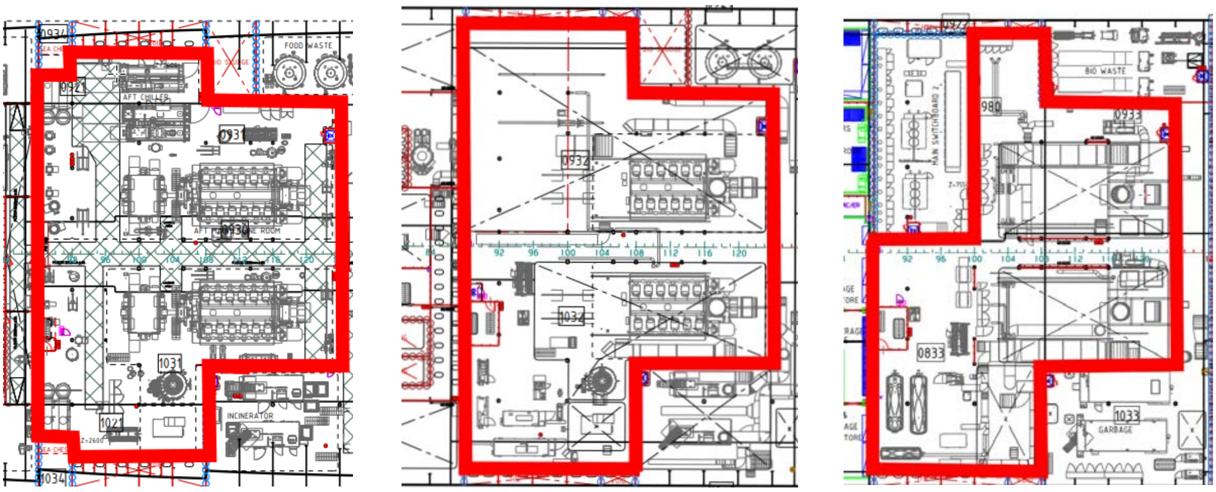


Figure 1 Contour of MER 1 for each deck

The total volume of the space, considering moulded lines and the previous description has been calculated based on the 3D model of NAPA.

The shape of the space is shown in the following figure, the volume is calculate as 6556 m^3.

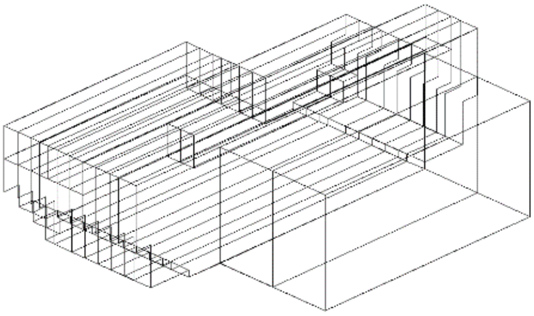


Figure 2 Shape of Main Engine Room 1 (front view)

In order to calculate the volume of the regarded components as precise as possible, a filter has been defined in the CAD system, which only shows the exact contour of volumes inside a before defined reference 3D-shape. The reference shape pictures the silhouette of NAPAs Main Engine Room to ensure a reasonable method.

Furthermore components which are completely floodable were not considered in the filter and therefore deleted from the list of displayed components. Such as non-waterproof exhaust gas ducts and air conditioning pipes.

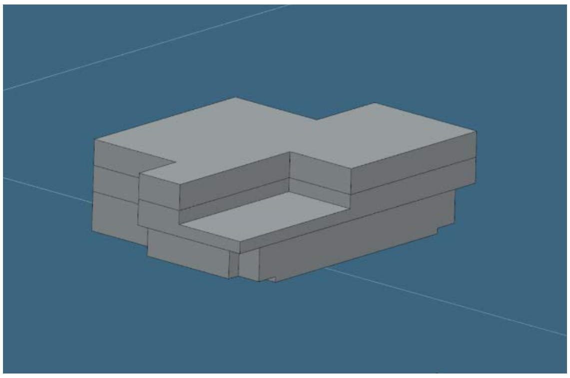


Figure 3 Reference 3D-shape of MER #1 (aft view)

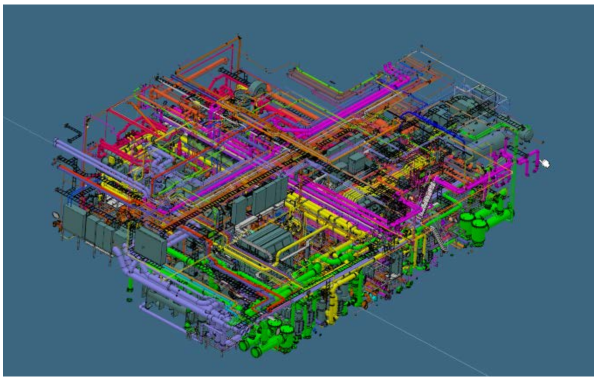


Figure 4 Components in MER #1 (aft view)

The filter shows the selection of parts for engine plants, piping, control cabinets, equipment and supply systems with a total volume of 494.24m³.

It should be noted that engines are assumed to be watertight, although it is obvious that engines may not sustain the water pressure during a long period of time.

The steel weight inside the defined room has been calculated by NAPA Steel.

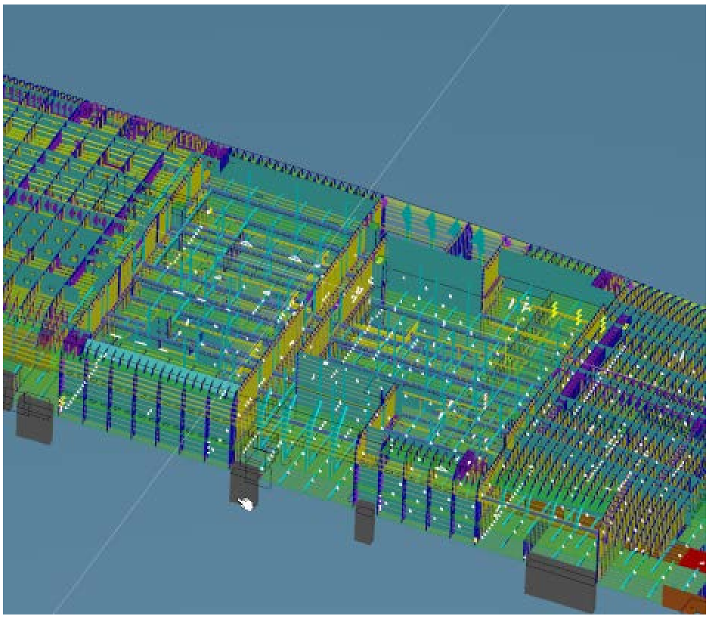


Figure 5 Steel structure of MER #1

Using the density of steel of approximately 8 t/m³ (including welding material, production tolerances and smaller parts) the volume of steel has been assessed to be 28 m3.

The volume of the applied fire insulation has been checked based on the structural fire protection plan and the used material. As the volume is very small, less than 0.5 m3, the insulation has been neglected in the calculation of permeability.

The table below shows the summary of MER#1:

Object	Volume [m³]
Total Room	6555.56
Steel structure	27.80
Engine plants, piping, control cabinets, equipment	494.24
Displaced Volume	522.04
Volume proportion	0.0796
Permeability of MER#1	0.92

Table 2 Summary MER #1

4.1.2 Main Engine Room #2

The investigated engine room is from medium sized Ropax ship. The engine room includes the main engines, other plants and systems, piping systems, control cabinets, equipment, electrical components, supply and discharge systems. The investigated space covers only the engine space which will have the same permeability as described in SOLAS. Other rooms, like switchboard rooms, which may be flooded separately, are excluded. Watertight Corridor located on deck 2 in centre line have been excluded from the total volume.
The exact contour is marked in the following figure for tank Top and Deck 2 (= deck below Car Deck).

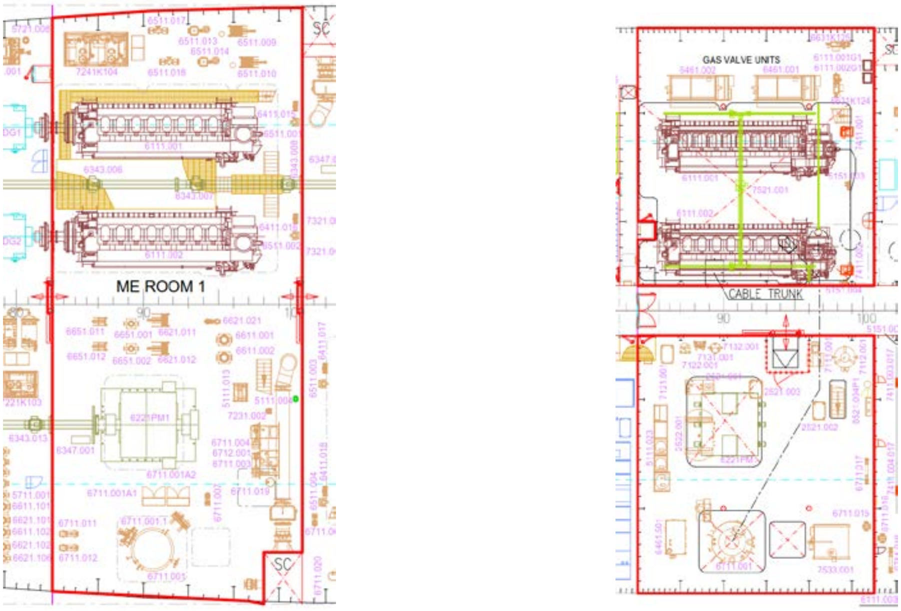


Figure 6 Contour of Aft Main Engine Room #2 for Tank Top and Deck 2

Figure 7 and Figure 8 present the shape of total volume calculated with NAPA. In Figure 9 and Figure 10 piping and different components are shown and in Figure 11 steel structure in Aft Main Engine Room.

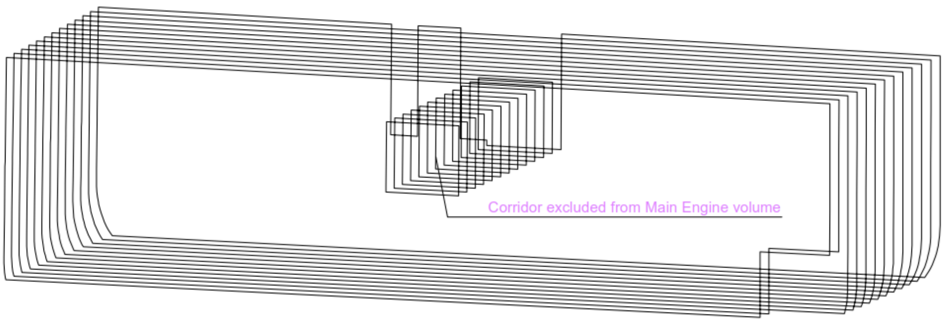


Figure 7 Shape of Main Engine Room #2 (aft view)

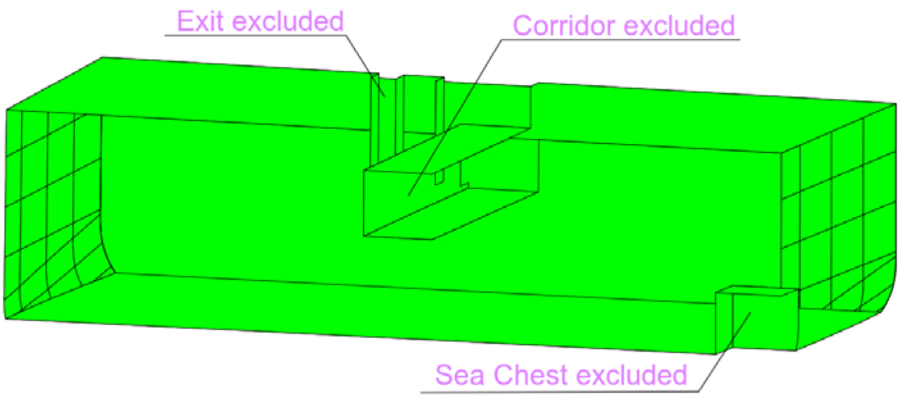


Figure 8 3D-shape of Main Engine Room #2 (aft view)

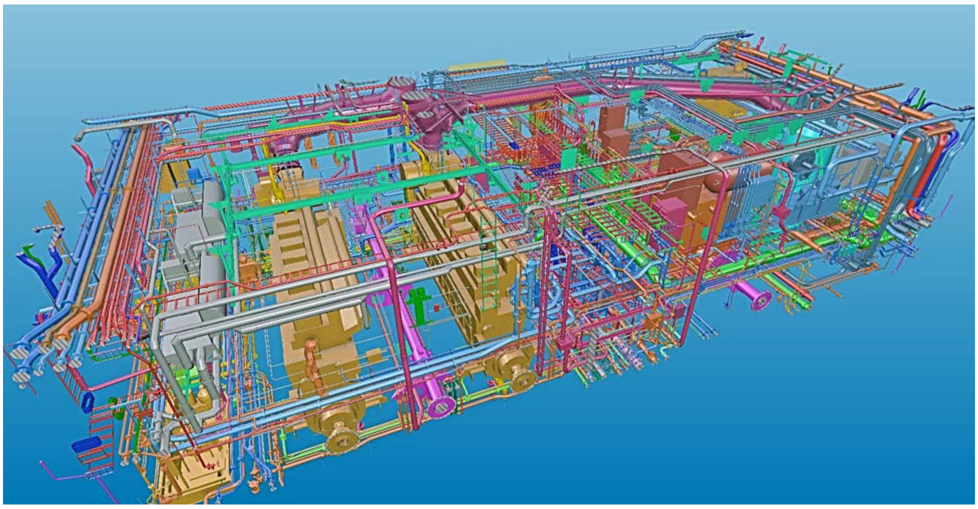


Figure 9 Components in Main Engine Room #2 (aft view)

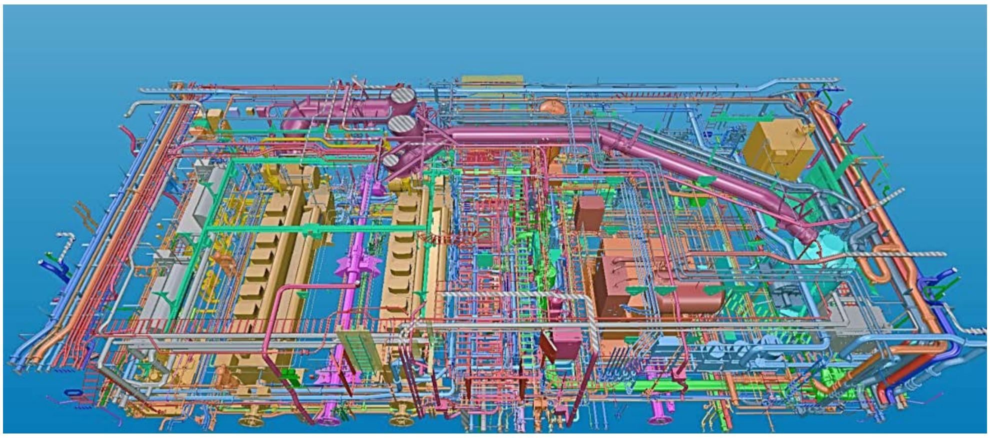


Figure 10 Components in Main Engine Room #2 (forward view)

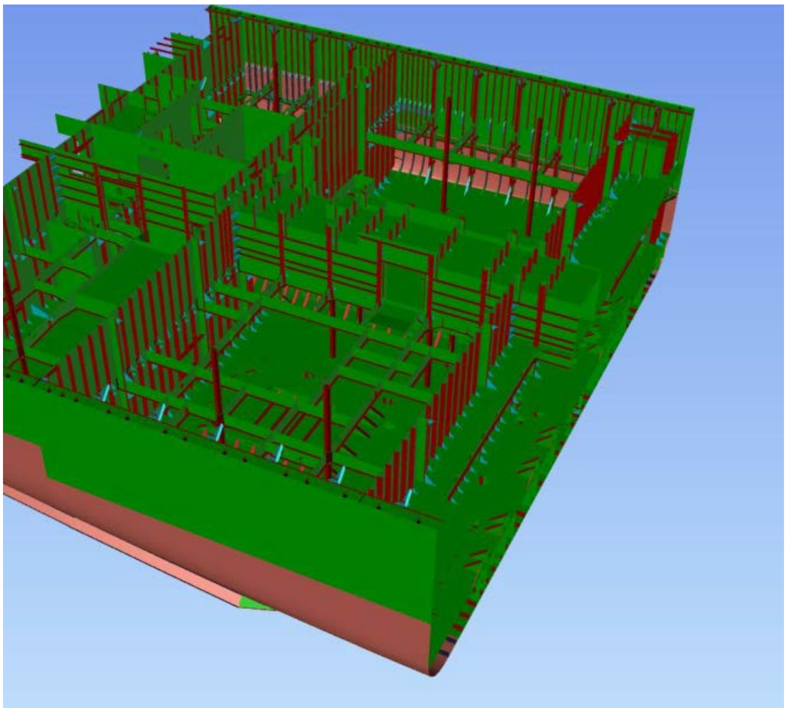


Figure 11 Steel structure of Main Engine Room #2

The total volume of the space, considering moulded lines and the previous description has been calculated based on the 3D model of NAPA.
The shape of the space is shown in Figure 7, the total volume is calculated as 3310 m^3.

Furthermore components which are completely floodable were not considered, such as non-waterproof exhaust gas ducts and air conditioning pipes.

The watertight volume for every machinery components has been calculated and is shown in Table 3. In addition the total volume of such components like main engine is shown.
The parts for engine plants, piping, control cabinets, equipment and supply systems with a total volume of 251.80 m^3.

The steel weight inside the defined room has been calculated and shown is in Table 4. The total volume of steel structure is 25.5 m^3.

The volume of the applied fire insulation has been checked based on the structural fire protection plan and the used material. Total volume has been calculated 1.50 m^3.

Component description	Volume Watertight (M3)	Volume Total (M3)
MAIN ENGINE 1	60.00	80.00
MAIN ENGINE 2	60.00	80.00
PROPULSION MOTOR	15.00	40.00
SHAFT AND BEARINGS	3.40	
AUX STEAM BOILER	22.00	
GAS VALVE UNIT, ME1	2.10	
GAS VALVE UNIT, ME2	2.10	
GAS VALVE UNIT, BOILER	3.00	
CONDENSE WATER TANK	3.50	
NITROGEN RECEIVER	5.10	
STARTING AIR RECEIVER	3.20	
WORKING AIR RECEIVER	0.60	
INSTRUMEN AIR RECEIVER	0.30	
NITROGEN GENERATOR	1.20	2.70
NITROGEN COMPRESSOR 1	0.50	1.00
NITROGEN COMPRESSOR 2	0.50	1.00
WORKING AIR COMPRESSOR	0.50	1.00
STARTING AIR COMPRESSOR	0.30	
LO SEPARATORS + TANK	3.00	
ME FW COOLERS 2PCS	1.60	
LUB OIL COOLERS 2 PCS	1.80	
WHR COOLERS 2PCS	1.00	
WASHING MACHINE TEIJO	0.80	8.00
ME PREHEATING UNITS 2 PCS	0.60	
PUMPS WITH EL MOTORS	0.80	
PLASTIC RECEIVERS (POTABLE WATER UNITS)	1.50	
EL CABINETS, SEVERAL	1.00	3.00
EXHAUST GAS PIPES	13.50	
LNG DOUBLE PIPES	3.00	
SEA WATER PIPES	10.50	
FW COOLING PIPES	1.50	
WHR PIPES	0.80	
FEED WATER AND STEAM	1.50	
FUEL OIL PIPES	0.50	
LUB OIL PIPES	2.50	
BILGE WATER	1.50	
BALLAST WATER	0.90	
AIR AND SOUNDING PIPES	2.50	
POTABLE WATER	2.20	

GREY WATER	0.50	
BLACK WATER	0.50	
FLOORS AND STAIRS	1.50	
LOOSE BEDS	1.00	
STRUCTURAL UNIT BEDS WITH FLOORS	1.20	
MAIN ENGINE AND PROP MOTOR BEDS	2.80	
CABLES	8.00	
Total Engine plants, piping, control cabinets, equipment	**251.80**	

Table 3 Machinery components in Main Engine Room #2

Component description	**Volume Watertight (M3)**
frame 83 plate	2.5800
stiffeners FR83	1.1129
webs at fr83	0.1872
stiffeners on deck 3	1.1017
long. girders on deck 3	0.5381
webs on deck 3	1.5050
steel above corridor	0.4340
stiffeners around the corridor	0.1382
pillars above deck 2	0.0594
webs in shellplating above deck 2	0.3069
long. girders on shell above deck 2	0.1856
stiffeners on shell above deck 2	0.6910
2. deck 5750 from BL	1.5897
2. deck 5550 from BL	0.3156
stiffeners on deck 2	0.3662
long. girders on deck 2	0.8174
webs on deck 2	0.9716
pillars below deck 2	1.7055
machine foundations	4.4301
webs in shellplating BELOW deck 2	0.3665
long. girders on shell BELOW deck 2	0.1435
stiffeners on shell below deck 2	0.4190
double bottom plate	5.5188
Total Steel structure	**25.4839**

Table 4 Volume of steel structure in Main Engine Room #2

The table below shows the summary of Aft Main Engine Room:

Object	Volume [m³]
Total Room	3310.40
Steel structure	25.48
Engine plants, piping, control cabinets, equipment	251.80
Fire insulation	1.50
Displaced Volume	278.78
Volume proportion	0.0842
Permeability of Aft Main Engine Room	**0.916**

Table 5 Summary Main Engine Room #2

4.1.3 Main Engine room #3

The engine room includes the main engines, other plants and systems, piping systems, control cabinets, equipment, electrical components, supply and discharge systems. The investigated space covers only the engine space which will have the same permeability as described in SOLAS. Other rooms, like switchboard rooms, which may be flooded separately, are excluded. The exact contour is marked in the following figure for each deck.

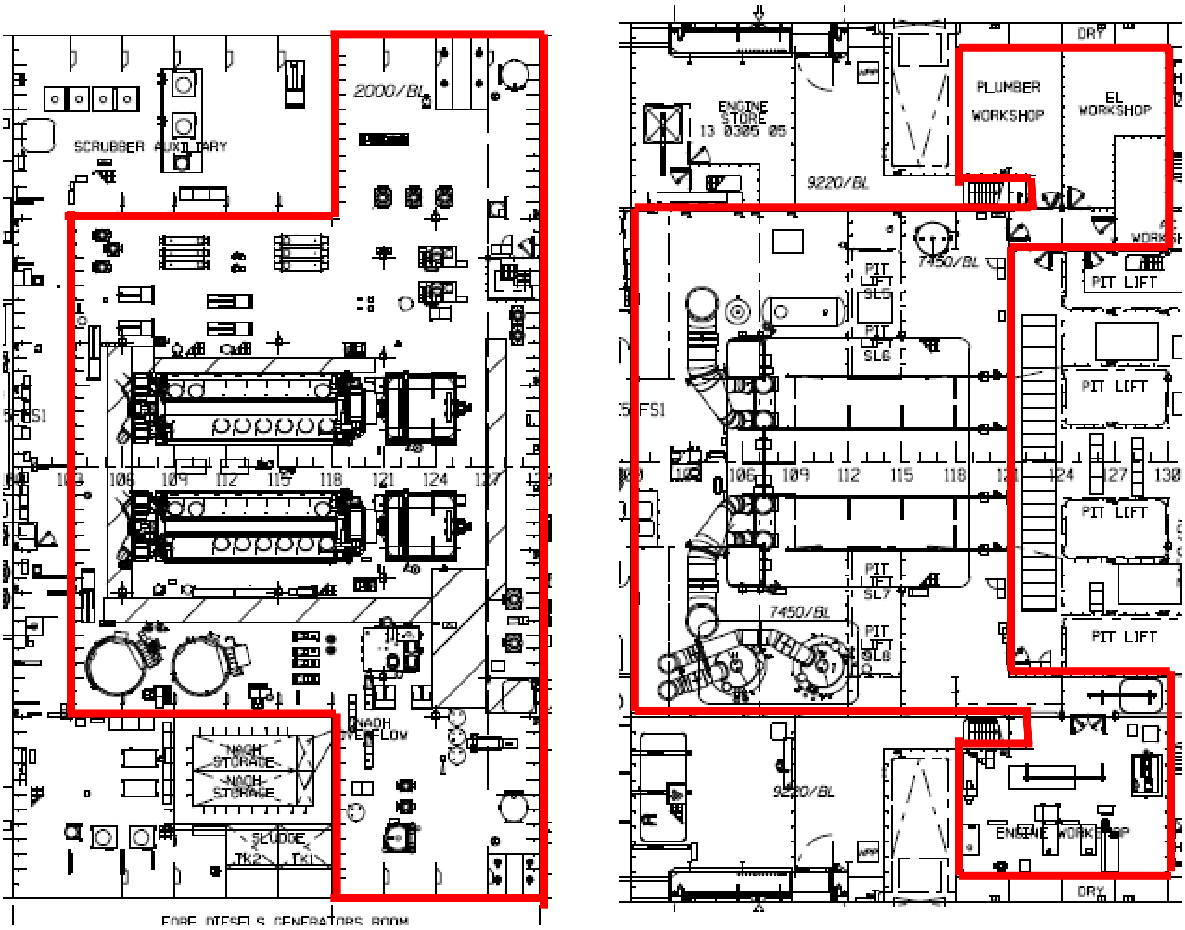


Figure 12 Contour of MER 3 for each deck

The total volume of the space, considering moulded lines and the previous description has been calculated based on the 3D model of NAPA.

The shape of the space is shown in Figure 13, the volume is calculated as 7008 m^3.

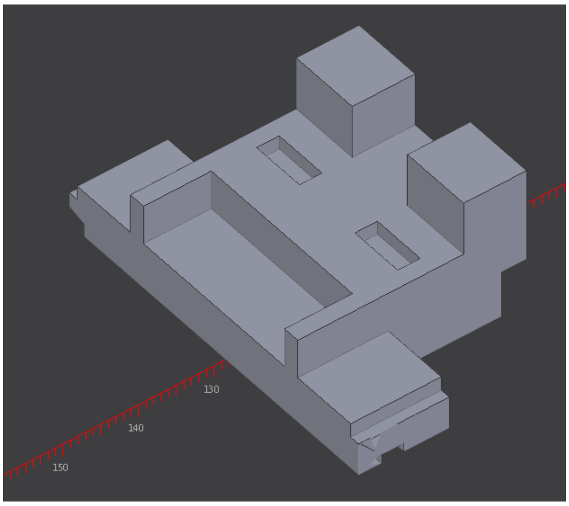


Figure 13 Reference 3D-shape of MER #3 (aft view)

In order to calculate the volume of the regarded components as precise as possible, an extraction has been performed from the pipe and equipment database, taking into account the boundaries of this 3D-shape.

Furthermore components which are completely floodable were not considered in the filter and therefore deleted from the list of displayed components. Such as non-waterproof exhaust gas ducts and air conditioning pipes.

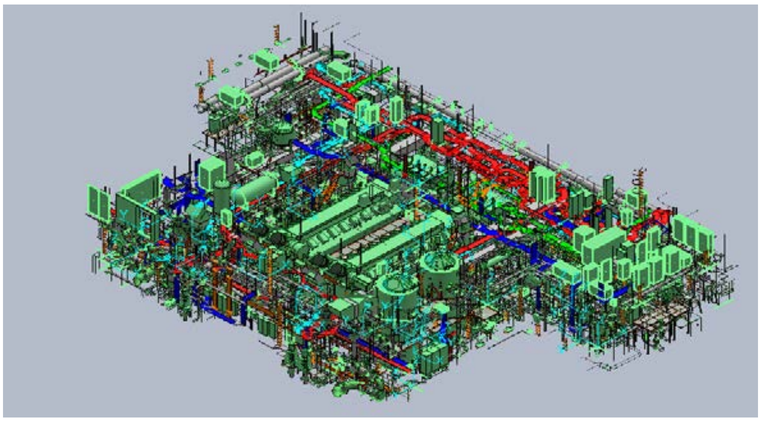


Figure 14 Components in MER #3 (aft view)

The figure shows the selection of parts for engine plants, piping, control cabinets, equipment and supply systems with a total volume of 172m³ (networks) + 505m³ (equipments).

The steel weight inside the defined room has been calculated using TRIBON. The figure below shows the entire fire zone but only the steel parts included in the selected 3D-shape have been taken into account in the calculation.

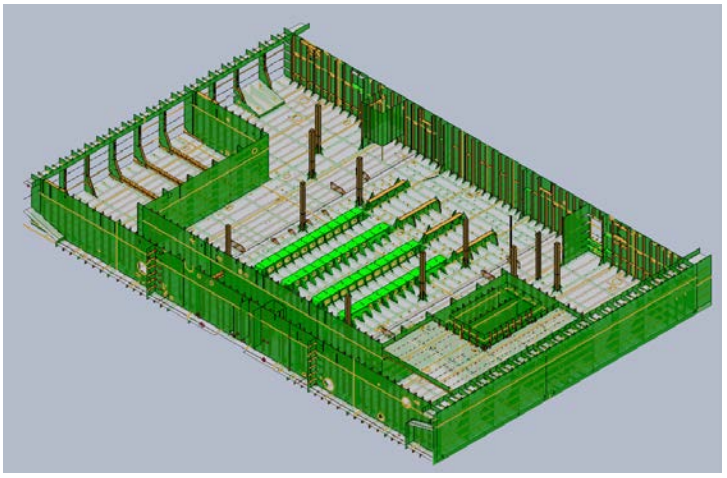


Figure 15 Steel structure of MER #3

Using the density of steel of approximately 8 t/m³ (including welding material, production tolerances and smaller parts) the volume of steel has been assessed to be 92 m³.

The volume of the pipes insulation has been checked based on the pipe networks breakdown. A total volume of 44.9m3 has been calculated, which corresponds to 0,6% of the total volume of the room. However, this insulation may be partially flooded or crushed. Therefore the remaining volume can be considered negligible in our calculation.

The volume of the applied fire insulation on bulkhead or below decks has been checked based on the structural fire protection plan and the used material. In this particular area, the volume of insulation is negligible.

The table below shows the summary of MER#3:

	Volume (m3)
Main Engine Room	7008.7
Piping, steel support	171.9
Engine, equipments…	504.9
Steel Structure	92.3
Displaced volume	769.1
Volume proportion	0.1097
Permeability	**0.890**

Table 6 Summary MER #3

4.2 Other machinery spaces

4.2.1 Aux Engine room #1

The engine room includes plants and systems, piping systems, control cabinets, equipment, electrical components, supply and discharge systems. The investigated space covers only the engine space which will have the same permeability as described in SOLAS. Other rooms, like switchboard rooms, which may be flooded separately, are excluded. The exact contour is marked in the following figure for each deck.

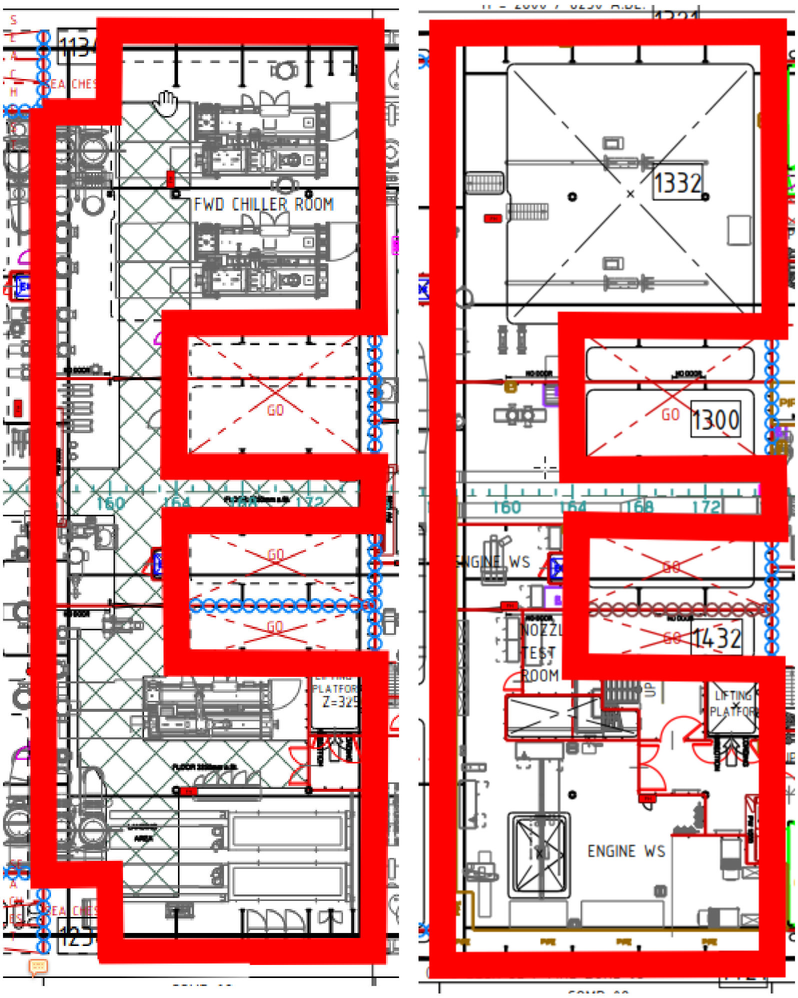


Figure 16 Contour of MER 1 for each deck

The total volume of the space, considering moulded lines and the previous description has been calculated based on the 3D model of NAPA.

The 3d-shape of the space is shown in the following figure; the volume is calculated as 6560m3.

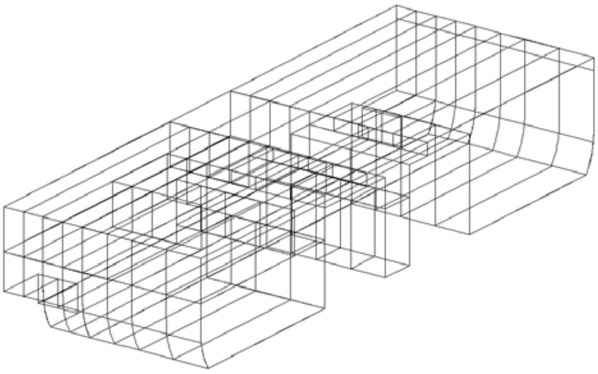


Figure 17 Shape of auxiliary engine room 1

In order to calculate the volume of the regarded components as precise as possible, a filter has been defined in the CAD system, which only shows the exact contour of volumes inside a before defined reference 3D-shape. The reference shape pictures the silhouette of NAPAs room to ensure a reasonable method.

Furthermore components which are completely floodable were not considered in the filter and therefore deleted from the list of displayed components. Such as non-waterproof exhaust gas ducts and air conditioning pipes.

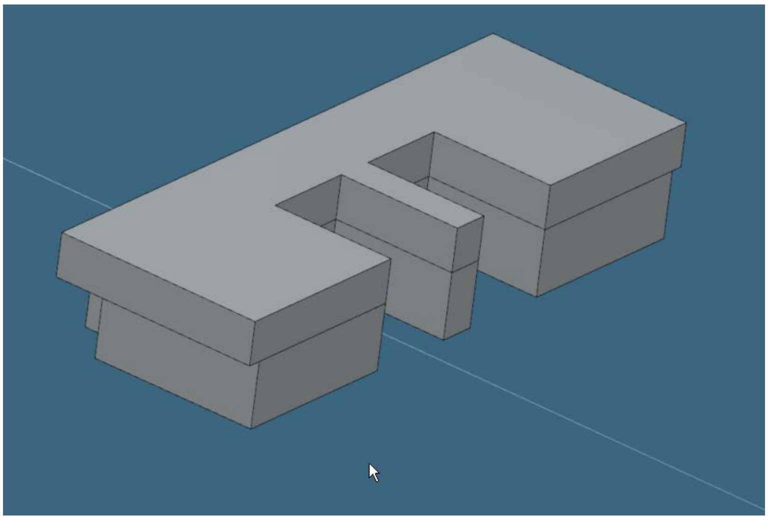


Figure 18 Reference 3D-shape of auxiliary engine room #1

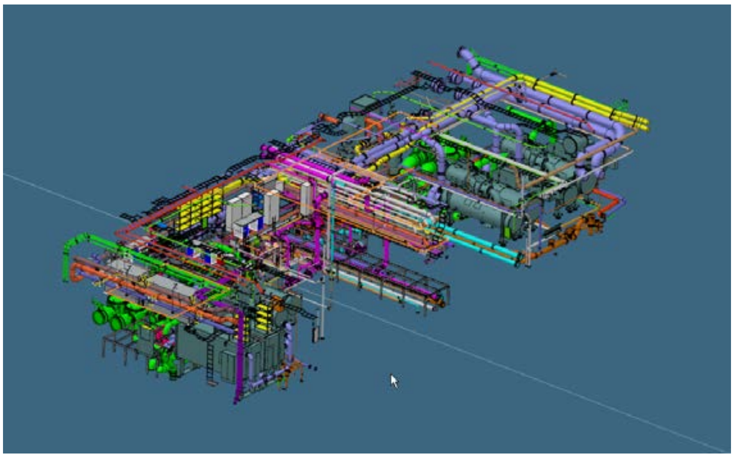


Figure 19 Components in auxiliary engine room #1

The filter selects a number of parts for engine plants, piping, control cabinets, equipment and supply systems with a volume of 527.44m³.

The steel weight inside the defined room has been calculated by NAPA Steel.

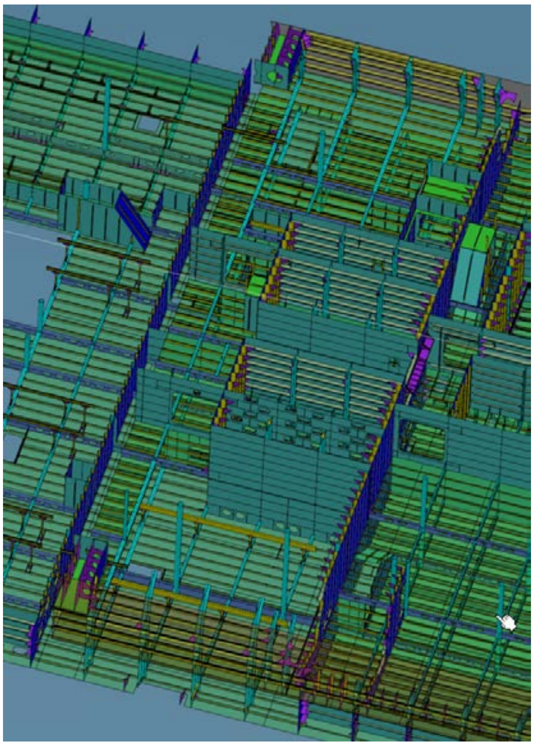


Figure 20 Steel structure of auxiliary engine room #1

Using the density of steel of approximately 8 t/m³ (including welding material. production tolerances and smaller parts) the volume of steel has been assessed to be 20 m³.

The volume of the applied fire insulation has been checked based on the structural fire protection plan and the used material. As the volume is very small, less than 0.5 m³, the insulation has been neglected in the calculation of permeability.

The table below shows the summary of auxiliary engine room #1:

Object	Volume [m^3]
Total Room	3171.40
Steel structure	20.00
Engine plants, piping, control cabinets, equipment	262.64
Displaced Volume	282.64
Volume proportion	0.089
Permeability	0.91

Table 7 Summary auxiliary engine room #1

4.2.2 Aux Engine room #2

The engine room includes plants and systems, piping systems, control cabinets, equipment, electrical components, supply and discharge systems. The investigated space covers only the engine space which will have the same permeability as described in SOLAS. Other rooms, like switchboard rooms, which may be flooded separately, are excluded. The exact contour is marked in the following figure for each deck.

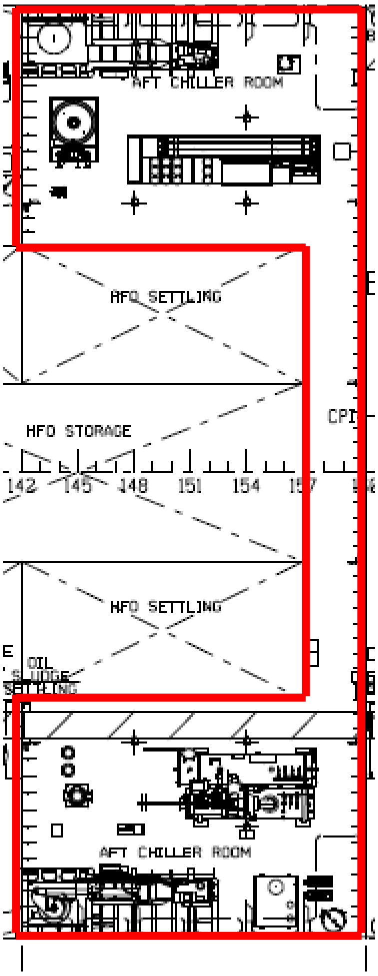


Figure 21 Contour of MER 2

The total volume of the space, considering moulded lines and the previous description has been calculated based on the 3D model of NAPA.

The 3d-shape of the space is shown in the following figure, the volume is calculated as 2077m^3.

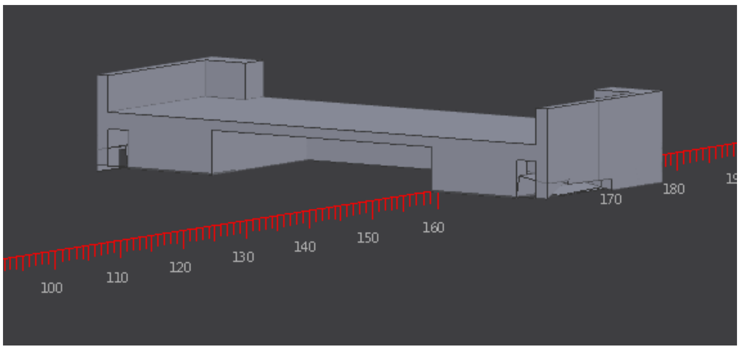


Figure 22 3D-Shape of auxiliary engine room #2

In order to calculate the volume of the regarded components as precise as possible, an extraction has been performed from the pipe and equipment database, taking into account the boundaries of this 3D-shape.

Furthermore components which are completely floodable were not considered in the filter and therefore deleted from the list of displayed components, such as non-waterproof exhaust gas ducts and air conditioning pipes.

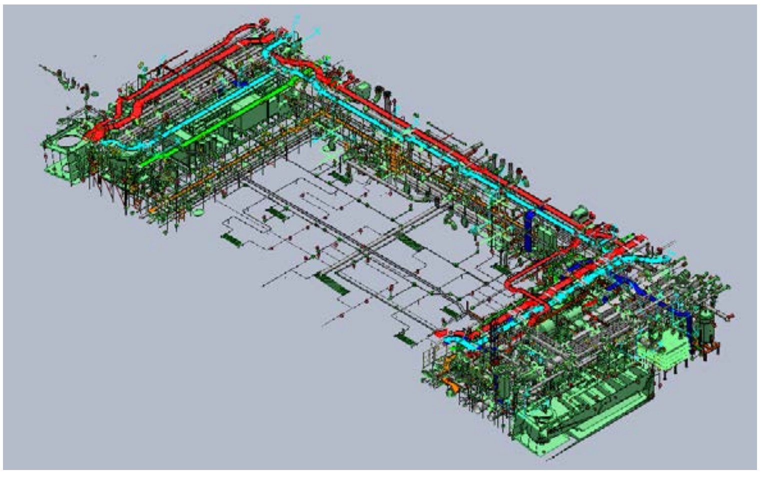


Figure 23 Components in auxiliary engine room #1

The figure shows the selection of parts for engine plants, piping, control cabinets, equipment and supply systems with a volume of 27.4 (pipes) + 57.5 (equipments) = 82.9m³. Please note that the stabilizers are not part of the investigated room but visible in Figure 23.

The steel weight inside the defined room has been calculated using TRIBON. Only the steel parts included in the selected 3D-shape have been taken into account in the calculation, although the tanks are also depicted on the below figure.

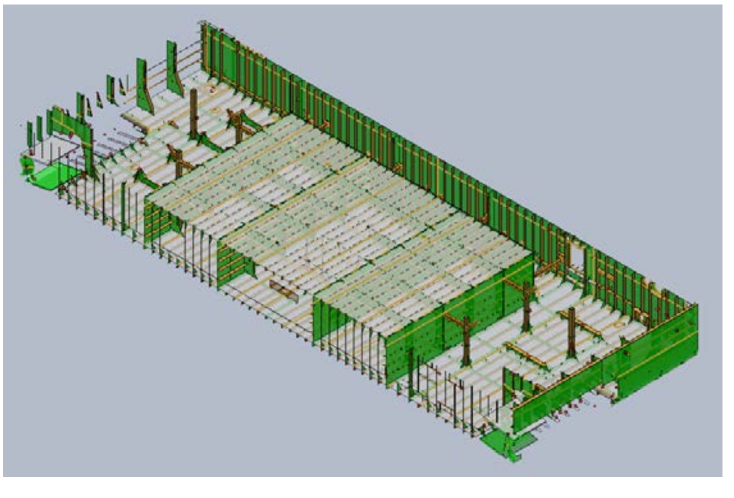


Figure 24 Steel structure of auxiliary engine room #2

Using the density of steel of approximately 8 t/m³ (including welding material. production tolerances and smaller parts) the volume of steel has been assessed to be 45.9 m3.

The volume of the pipes insulation has been checked based on the pipe networks breakdown. A volume of 6.3m3 has been calculated. This insulation may be partially flooded or crushed. Therefore the remaining volume can be considered negligible in our calculation.

The volume of the applied fire insulation on bulkhead or decks has been checked based on the structural fire protection plan and the used material. In this particular area, the volume of the hard floor insulation installed above the HFO tanks is significant and has been retained in the calculation.

The table below shows the summary of auxiliary engine room #2:

	Volume (m3)
Auxiliary Engine Room	2077.3
Piping	25.4
Hard floor above HFO tanks	10
Equipments	57.5
Steel Structure	45.9
Total	138.8
Permeability	**0.933**

Table 8 Summary auxiliary engine room #2

4.3 Cabin Areas

The permeability of cabin area has been calculated in a similar way as for engine rooms. However the displaced volume of the cabins itself have been calculated using the different components in the cabin. As the space consists of similar sized cabins the displaced volume of the parts will be very similar for all cabins. Therefore only one cabin has been analyzed in detail.

4.3.1 Cabin area #1

The investigated cabin area consists mainly of crew cabins and corridors.

Figure 25 Cabin area #1

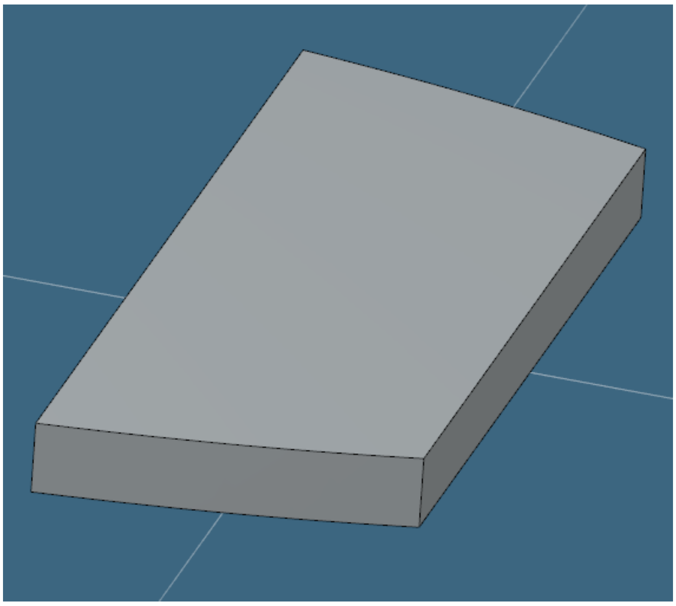


Figure 26 3D shape of cabin area #1

The figure below shows the layout of a typical crew cabin.

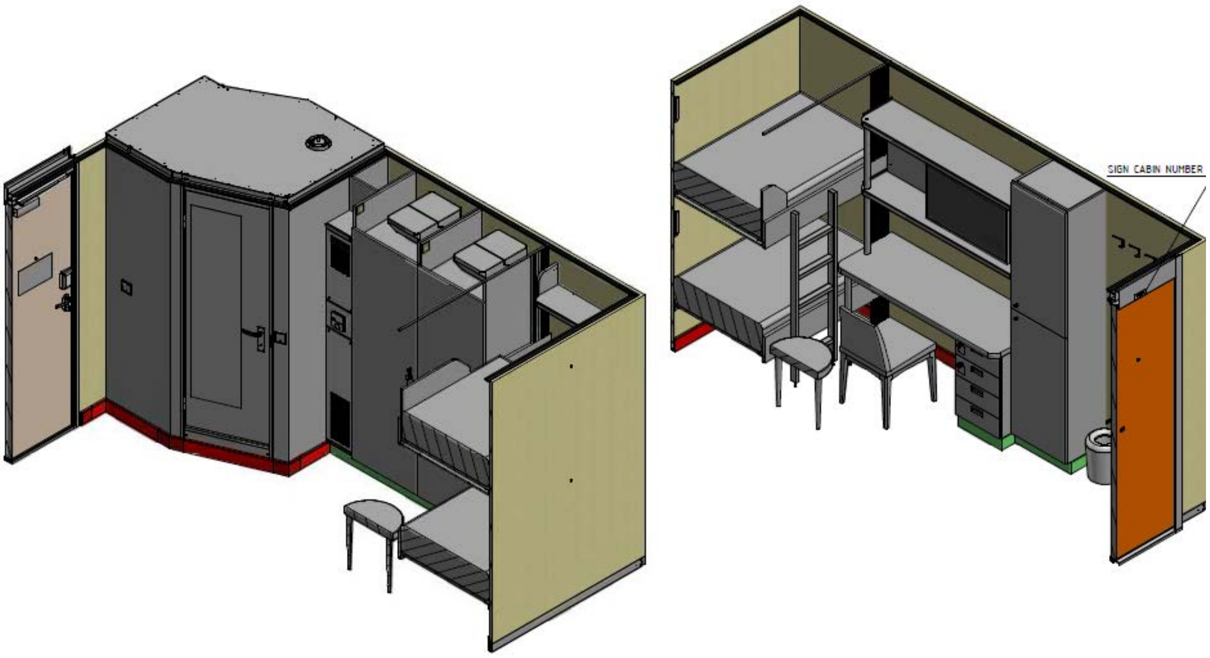


Figure 27 cabin layout

The displaced volume for one typical cabin has been calculated by summing up each part in the cabin. For some parts, like mattresses or wall panels a permeability of that part has been estimated.

internal parts	displaced Volume	assumed permeability
bed	0.1025	
bed linen	0.0001	
matrasses	0.3520	0.5
bed ware	0.0014	0.8
TV set	0.0125	
desk	0.0907	
chair	0.0122	
wardorbe	0.4071	
waste bin	0.0002	
cloth hangers	0.0009	
side table	0.0115	
lamps	0.0034	
mirror	0.0021	
carpet	0.0300	0.8
luggage	0.1288	

Cabin boundaries	displaced Volume	assumed permeability
profiles	0.0059	
wall panel	0.4660	0.9
door and frame	0.0364	
ceiling	0.2698	0.9
floor construction	0.1012	0.9
support	0.0357105	0.05
Total	**0.9150**	

bathroom unit	displaced Volume	assumed permeability
floor construction	0.0280	0.15
door and frame	0.0333	
wall panel	0.1920	
corne piece	0.0036	
flooring	0.0148	

desk chair	0.0099	
small parts	0.0015	
wardrobe	0.2463	
curtains	0.0050	0.92
AC duct	0.0314	0.05
phone	0.0007	
safe	0.0057	
skirting	0.0011	
Total	**1.4570**	

insulation	0.1293	
WC	0.0229	0.9
shower	0.0005	0.92
shower curtain	0.0006	
small equipment	0.0002	
mirror and cabinet	0.0103	
outer cladding	0.0039	
wash basin	0.0138	
waste bin	0.0001	
ceiling	0.0370	
Total	**0.4903**	

Total displaced volume for one cabin	2.86	m3
Total volume cabin	20.09	m3
permeability of cabin	0.8575	

Table 9 Volume of parts of one cabin

For the calculation of the permeability of the whole space the displaced volume of steel, piping and ducting and the cabins has been added.

Object	**Volume [m^3]**
Total Room	1480
Steel structure	6.54
Piping and ducting	14.84
28 Cabins	80.08
Displaced Volume	101.46
Volume proportion	0.069
Permeability	0.93

Table 10 Summary cabin area #1

4.3.2 Cabin area #2

The investigated cabin area consists mainly of crew cabins and corridors.

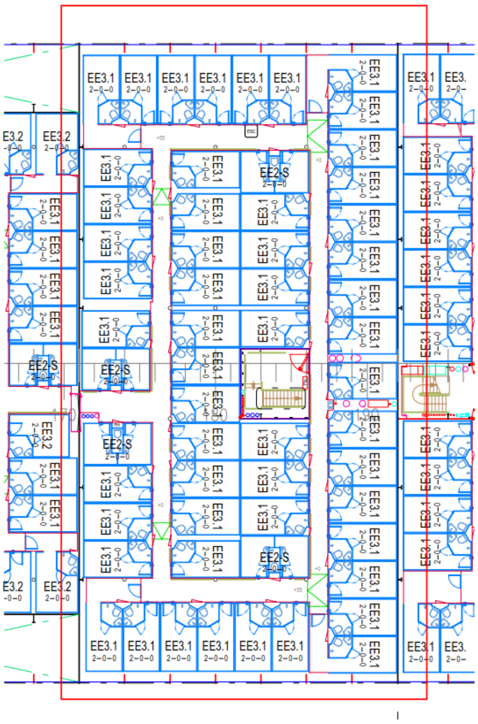


Figure 28 Cabin area #2

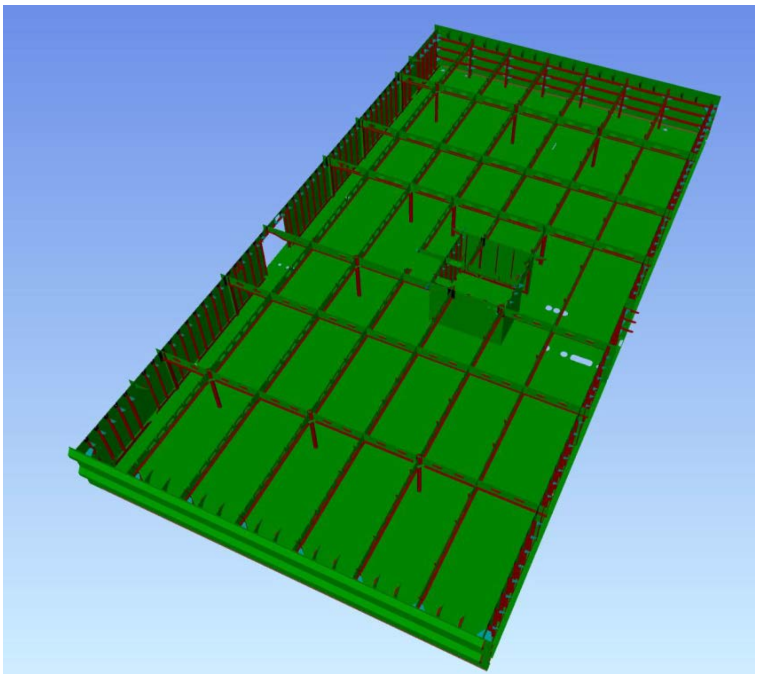


Figure 29 Cabin area #2 steel structure

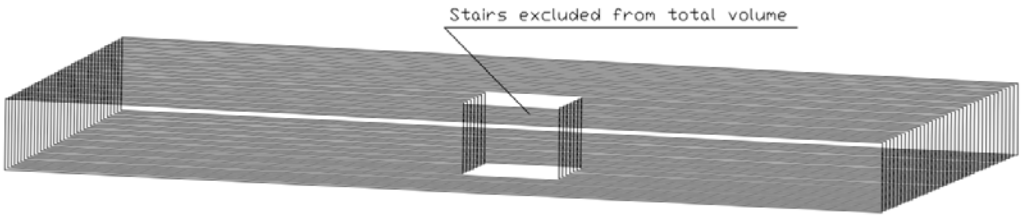


Figure 30 3D shape of cabin area #2

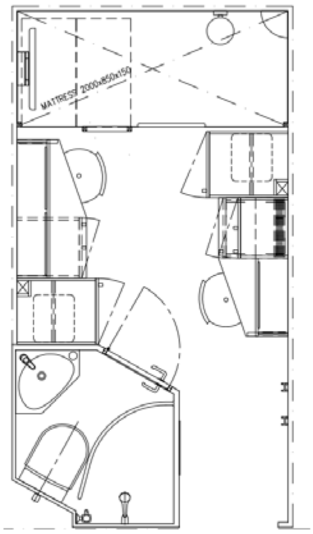


Figure 31 cabin layout type EE3.1

The displaced volume for one typical cabin has been calculated by summing up each part in the cabin. For some parts, like mattresses or wall panels a permeability of that part has been estimated.

internal parts	displaced Volume	assumed permeability
bunk beds	0.1025	
bed linen	0.0001	
matresses	0.2400	0.5
bed ware	0.0014	0.8
TV set	0.0251	
desk	0.1550	
chairs	0.0243	
cabinet	0.1600	
waste bin	0.0002	
cloth hangers	0.0009	

Cabin boundaries	displaced Volume	assumed permeability
profiles	0.0047	
wall panel	0.4691	0.9
door and frame	0.0364	
ceiling	0.2754	0.9
floor construction	0.0836	0.9
support	0.0357	0.05
Total	**0.9049**	

bathroom unit

lamps	0.0034	
mirror	0.0030	
carpet	0.0255	0.8
luggage	0.1288	
desk chair	0.0198	
small parts	0.0015	
wardrobe	0.4136	
AC duct	0.0314	0.05
phone	0.0007	
safe	0.0057	
skirting	0.0011	
Total	**1.3440**	

floor construction	0.0332	0.15
door and frame	0.03328	
wall panel	0.2454	
flooring	0.0175	
insulation	0.1987	
WC	0.0229	0.9
shower	0.0005	0.92
shower curtain	0.0006	
small equipment	0.0002	
mirror and cabinet	0.0103	
wash basin	0.0138	
waste bin	0.0001	
ceiling	0.0438	
Total	**0.6203**	

Total displaced volume for one cabin	2.87	m3
Total volume cabin	17.52	m3
permeability of cabin	**0.8362**	

Table 11 Volume of parts of one cabin Type EE3.1

internal parts	displaced Volume	assumed permeability
bunk beds	0.1025	
bed linen	0.0001	
matresses	0.2400	0.5
bed ware	0.0014	0.8
TV set	0.0251	
desk	0.1550	
chairs	0.0243	
cabinet	0.1600	
waste bin	0.0002	
cloth hangers	0.0009	
lamps	0.0034	
mirror	0.0030	
carpet	0.0255	0.8

Cabin boundaries	displaced Volume	assumed permeability
profiles	0.005	
wall panel	0.458	0.9
door and frame	0.036	
ceiling	0.230	0.9
floor construction	0.086	0.9
support	0.036	0.05
Total	**0.8507**	

bathroom unit		
floor construction	0.0332	0.15
door and frame	0.0333	
wall panel	0.2454	

luggage	0.1288	
desk chair	0.0198	
small parts	0.0015	
wardrobe	0.4136	
AC duct	0.0314	0.05
phone	0.0007	
safe	0.0057	
skirting	0.0011	
Total	**1.3440**	

flooring	0.0175	
insulation	0.1987	
WC	0.0229	0.9
shower	0.0005	0.92
shower curtain	0.0006	
small equipment	0.0002	
mirror and cabinet	0.0103	
wash basin	0.0138	
waste bin	0.0001	
ceiling	0.0438	
Total	**0.6203**	

Total displaced volume for one cabin	2.82	m3
Total volume cabin	17.52	m3
permeability of cabin	**0.8393**	

Table 12 Volume of parts of one cabin Type EE2-S

For the calculation of the permeability of the whole space the displaced volume of steel, piping and ducting and the cabins has been added.

Object	**Volume [m³]**
Total Room	1760
Steel structure	8.94
Piping and ducting	2.28
54 pcs Cabins Type EE3.1	152.28
8 pcs Cabins Type EE2-S	22.96
Displaced Volume	186.46
Volume proportion	0.106
Permeability of Cabin area	**0.894**

Table 13 Summary cabin area #2

4.3.3 Cabin area #2

The investigated cabin area consists mainly of crew cabins and corridors.

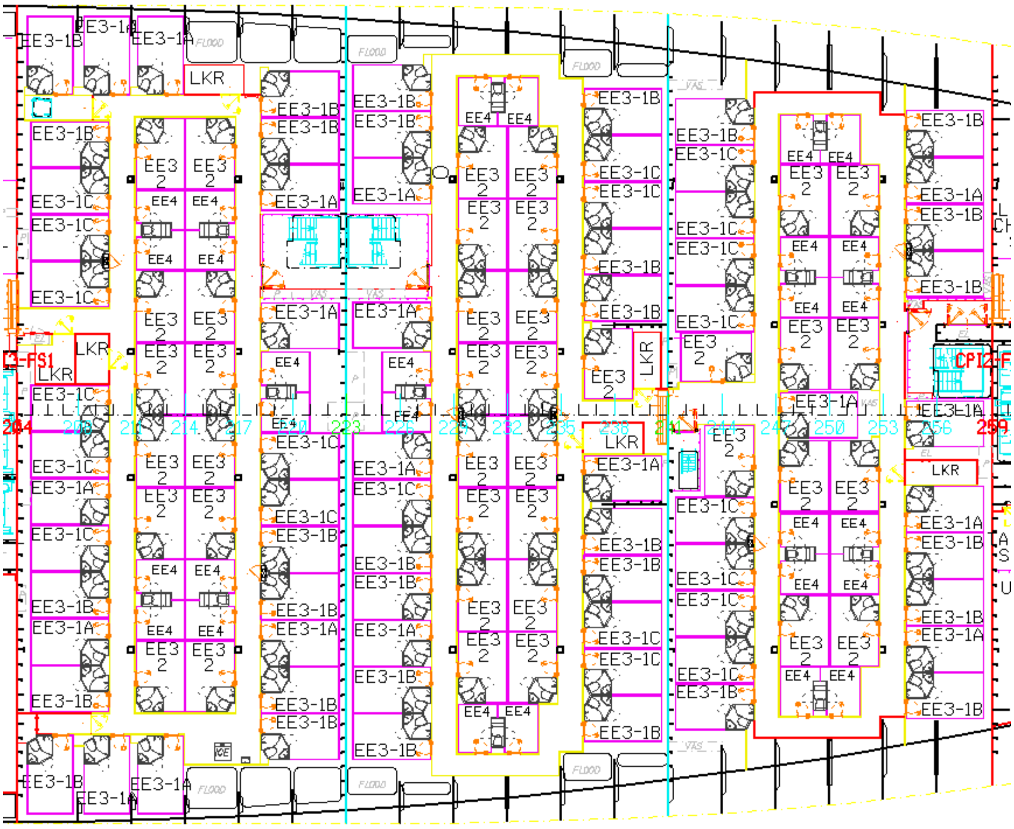


Figure 32 Cabin area #3

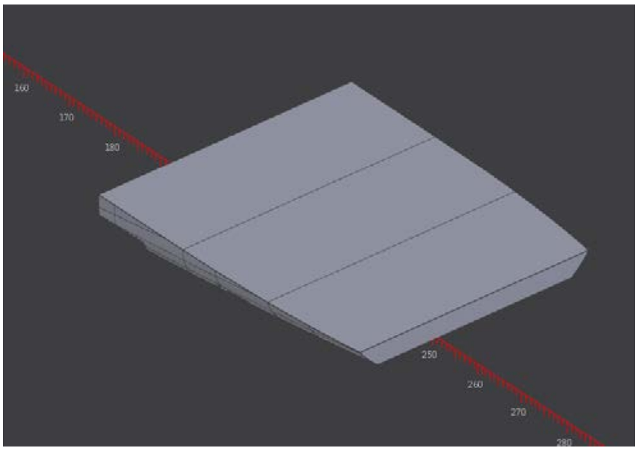


Figure 33 3D shape of cabin area #3

The figure below shows the layout of a typical crew cabin.

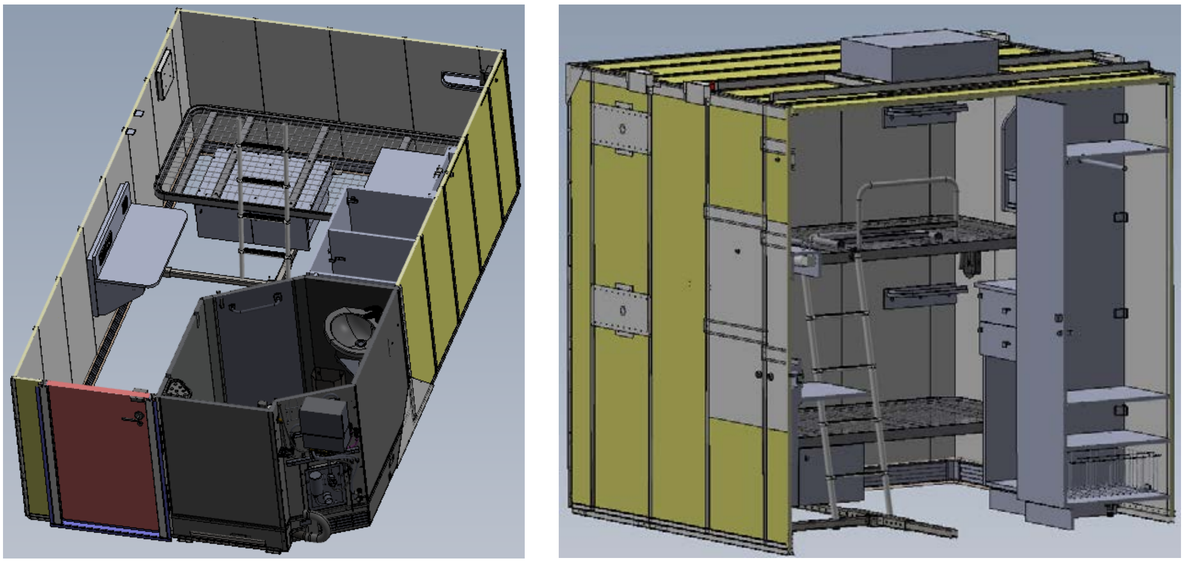


Figure 34 cabin layout

The displaced volume for one typical cabin has been calculated by summing up each part in the cabin. For some parts, like mattresses or wall panels a permeability of that part has been estimated. The “displaced volume” column takes into account the selected permeability.

	CABIN BOUNDARIES	
	Displaced volume	Assumed Permeability
Wall panel	0.46413	0.9
Reinforcements/Profiles	0.00821	
Door & Frame	0.08223	
Floor	0.04960	
Ceiling	0.21170	0.9
Skirting	0.00822	
HVAC	0.04500	
TOTAL	**0.86908**	

	INTERNAL PARTS	
	Displaced volume	Assumed Permeability
Wardrobe	0.1471	
Desks	0.0857	
Electrical strip	0.0036	
Shelves	0.0429	
Plinth kit	0.0129	
Mirror	0.0023	
Caisson bed	0.0186	
Matrasses	0.3420	0.5
Bed	0.0109	
Bed curtains	0.0006	0.8
Bed linen	0.0001	
Bed ware	0.0014	0.8
TV set	0.0125	
Chair	0.0122	
Waste bin	0.0001	
Clothes hooks	0.0010	
Global ligthing	0.00324	
Fridge	0.03	
Safe	0.0248	
Luggage	0.1288	
Phone	0.0007	
TOTAL	**0.8814**	

	BATHROOM UNIT	
	Displaced volume	Assumed Permeability
Floor construction	0.044	
Door and frame	0.026	
Wall panel + insulation	0.34056	0.9
WC	0.02083	
Wash basin	0.0125	
Ceiling	0.0396	
TOTAL	**0.48349**	

Total displaced volume for one cabin	2.2339	m3
Total volume cabin	16.4994	m3
Permeability of the cabin	0.8646	

Table 14 Volume of parts of one cabin

For the calculation of the permeability of the whole space the displaced volume of steel, piping and ducting and the cabins has been added. The piping networks and steel parts have been calculated on a similar way as for the engine rooms.

The volume of the applied fire insulation has been checked based on the structural fire protection plan and the used material. The volume of thermic insulation applied mainly on the shell has been retained in the calculation.

Object	**Volume [m³]**
Total Room	4924.5
Steel structure	54.1
Thermic Insulation	39
Piping and ducting	2.8
124 Cabins	277
Displaced Volume	**372.9**
Volume proportion	**0.0757**
Permeability	**0.924**

Table 15 Summary cabin area #3

5 MEASURED PERMEABILITY

The basic approach used to estimate the permeability is based on the data recorded on board the ships.

Information which has been provided by operators:

- Inventory list for each store (weight, contents but not a list of each individual part)
- Photos of the store at current inventory list status
- GAP showing dimensions of the investigated stores

For provision stores the situation at the begin and end of a typical round trip

- Cargo loading condition of cargo/RoRo deck
- GAP showing dimensions of the cargo area

The analysis follows the approach to calculate the gross volume of the space, estimate the volume to be deducted of any fixed equipment; calculate the non-flooded volume of the cargo or stores content based on the weight and reasonable assumptions.

5.1 Stores

The permeability of stores has been calculated based on the weight allocated for each store. For different types of stores an averaged density has been assumed to calculate the displaced volume.

Type of stores	Average density
Engine stores	5 t/m³
Electric stores	2 t/m³
Dry stores, provision stores, paint stores etc	1 t/m³

Table 16 Average density of store types

For the steel structure an analysis of a comparable part of a ship has been made to calculate the steel weight per volume. This constant value has been applied on all stores. For some Ropax vessels the stores have been investigated based on the data received from the operator and the volume of the space. For installed equipment and steel a mean percentage has been used. Photos of the stores can be found in the appendix.

No	Name	Type of store	Gross Volume	Weight	density	volume of contents	Volume of structure	Volume of equipment	Total non flooded volume	Permeability
			m3	t	t/m3	m3	m3	m3	m3	
1	Tax free dk2	dry store	152.07	6.43	1.00	6.43	0.91	1.52	8.86	0.94
2	carpet store	dry store	98.80	1.26	1.00	1.26	0.59	0.99	2.84	0.97
3	paint store	dry store	3.42	0.33	1.00	0.33	0.02	0.03	0.39	0.89
4	carpenter store	dry store	98.80	0.60	1.00	0.60	0.59	0.99	2.18	0.98
5	chemical store	dry store	37.81	0.44	1.00	0.44	0.23	0.38	1.05	0.97
6	el store	dry store	69.39	1.90	2.00	0.95	0.42	0.69	2.06	0.97
7	el store	dry store	84.95	3.40	2.00	1.70	0.51	0.85	3.06	0.96
8	engine store	engine store	88.15	7.42	5.00	1.48	0.53	0.88	2.89	0.97
9	deck store	dry store	122.39	2.06	1.00	2.06	0.73	1.22	4.02	0.97
10	el store	dry store	90.42	1.00	1.00	1.00	0.54	0.90	2.45	0.97
11	engine store	engine store	217.24	4.25	5.00	0.85	1.30	2.17	4.33	0.98
12	carpenter workshop	dry store	165.11	0.83	1.00	0.83	0.99	1.65	3.47	0.98
13	paint store	dry store	51.65	2.69	1.00	2.69	0.31	0.52	3.52	0.93
14	boatswain store	dry store	183.02	1.73	1.00	1.73	1.10	1.83	4.66	0.97
15	el store	dry store	165.91	2.85	2.00	1.43	1.00	1.66	4.08	0.98
16	hotel store	dry store	79.67	5.99	1.00	5.99	0.48	0.80	7.26	0.91
17	chemical store	dry store	73.70	4.12	1.00	4.12	0.44	0.74	5.30	0.93
18	linen store	dry store	61.89	1.73	1.00	1.73	0.37	0.62	2.72	0.96
19	chemical store	dry store	59.22	3.40	1.00	3.40	0.36	0.59	4.35	0.93
20	engine store	engine store	217.95	1.73	1.00	1.73	1.31	2.18	5.22	0.98

21	engine store	engine store	367.88	3.67	5.00	0.73	2.21	3.68	6.62	0.98
22	provision stores	cold room	257.76	14.21	1.00	14.21	1.55	2.58	18.34	0.93
23	provision stores	dry store	100.99	4.92	1.00	4.92	0.61	1.01	6.53	0.94
24	provision stores	cold room	721.74	20.17	1.00	20.17	4.33	7.22	31.72	0.96
25	beverages	dry store	63.00	3.20	1.00	3.20	0.38	0.63	4.21	0.93
26	beverages	dry store	59.07	4.50	1.00	4.50	0.35	0.59	5.45	0.91
27	provision stores	cold room	166.24	3.19	1.00	3.19	1.00	1.66	5.85	0.96

Table 17 Stores Ropax

A similar approach has been done for a cruise vessel of about 45,000 GT.

No	Name	Type of store	Gross Volume	Weight	density	volume of contents	Volume of structure	Volume of equipment	Total non flooded volume	Permeability
			m3	t	t/m3	m3	m3	m3	m3	
28	hotelstore dk5	dry store	996.20	14.28	2.00	7.14	5.98	9.96	23.08	0.98
29	uniform store dk 4	dry store	308.65	3.57	1.00	3.57	1.85	3.09	8.51	0.97
30	chemical store dk2	dry store	142.27	3.78	1.00	3.78	0.85	1.42	6.06	0.96
31	consumable locker dk2	dry store	264.55	30.03	2.00	15.01	1.59	2.65	19.25	0.93
32	beverage 4 Dk2	dry store	168.13	14.28	1.00	14.28	1.01	1.68	16.97	0.90
33	beverage 2 - dk2	dry store	94.15	8.96	1.00	8.96	0.56	0.94	10.47	0.89
34	beverage 5 dk2	dry store	110.65	10.50	1.00	10.50	0.66	1.11	12.27	0.89
35	milk box dk3	dry store	61.28	7.07	1.00	7.07	0.37	0.61	8.05	0.87
36	dry store 2 dk2	dry store	83.22	10.42	1.00	10.42	0.50	0.83	11.75	0.86
37	dry store 3 dk2	dry store	121.89	16.39	1.00	16.39	0.73	1.22	18.34	0.85
38	meat box dk3	ref store	117.80	9.86	1.00	9.86	0.71	1.18	11.74	0.90
39	fish box dk3	ref store	102.48	6.69	1.00	6.69	0.61	1.02	8.33	0.92
40	poultry box dk3	ref store	116.33	5.13	1.00	5.13	0.70	1.16	6.99	0.94
41	fresh fruit dk3	ref store	83.41	11.57	1.00	11.57	0.50	0.83	12.91	0.85
42	frzn fruit&veg dk3	ref store	92.46	7.46	1.00	7.46	0.55	0.92	8.94	0.90

Table 18 Stores cruise ship

The mean value for the permeability is 0.936 for all these stores, with a standard deviation of only 0.039.

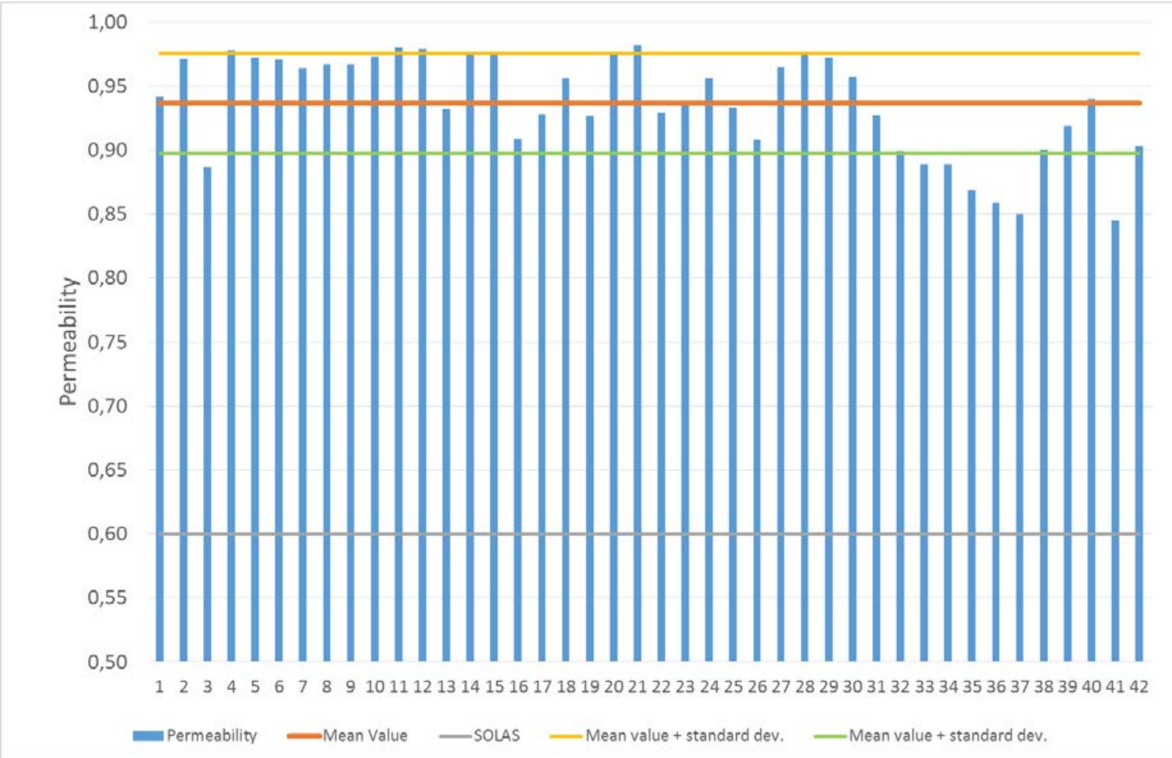


Figure 35 Permeability of stores

Based on these results it can be concluded that the value for permeability of stores as given in SOLAS with 0.6 does not reflect the reality on passenger ships. A more realistic value would be 0.9, considering the standard deviation and the mean value.

5.2 Cargo Holds

For the calculation of the permeability of roro spaces following approach has been used.

1. Analysis of loading conditions of two ships for one whole year. Extracting the weight and number of units from stored loading conditions
2. Estimating the displaced volume for each unit, based on available information and an estimated density of the material mix.
3. Assuming 2% volume reduction due to steel, equipment, pining etc.
4. Calculating the permeability for each space for each loading condition

5.2.1 Assumptions

For the different types of cargo following assumptions with regard to the unit density has been made.

Trailers: For normal trailer the displaced volume has been based on the weight of the trailer and the truck as well as the average permeability of container [Mallet, 1976], which should be thesame for trailer cargo.

	Mass	Density	displaced Volume
Trailer base	6.3 t	7.0 t/m3	0.9 m3
truck	8.2 t	5.0 t/m3	1.6 m3
total			2.5 m3
	Volume	Permeability	
Cargo based on 2TEU	76.6 m3	0.77	17.6 m3
Total			20.2 m3

Table 19 Displaced volume of trailers

Cars: For cars the material mix [Volkswgen AG, 2011] has been used to estimate teh displaced volume. A standard weight of 2.5t for each car has been assumed.

Material		density
Steel	55%	7.9 t/m3
Plastic	15%	1.0 t/m3
Aluminium	10%	2.7 t/m3
other metal	6%	9.0 t/m3
miscellanous	14%	1.0 t/m3
	Total density	5.4 t/m3
	chosen density	5.0 t/m3
	Weight	2.5 t
	Displ Vol	0.5 m3

Table 20 Displaced volume of car

Busses: For busses a unit weight of 12 t has been applied, the average density assumed to be the same as for cars, as the material mix is similar.

Motorhomes / Caravans: For this cargo a reduced density has been assumed to reflect the higher amount of wood and plastic. The chosen density is 3.5t/m^3.

Other cargo: For other kind of cargo which may appear in a negligible amount a constant density of 5t/m^3 has been assumed.

5.2.2 Results

The analysis has been made for two different ships. Both ships have several cargo spaces but no significant difference has been found. The following diagram shows the distribution of permeability versus the nominal draught (0 = lightest subdivision draught DL, 1 = deepest subdivision draught DS). Also shown is the permeability as defined in SOLAS.

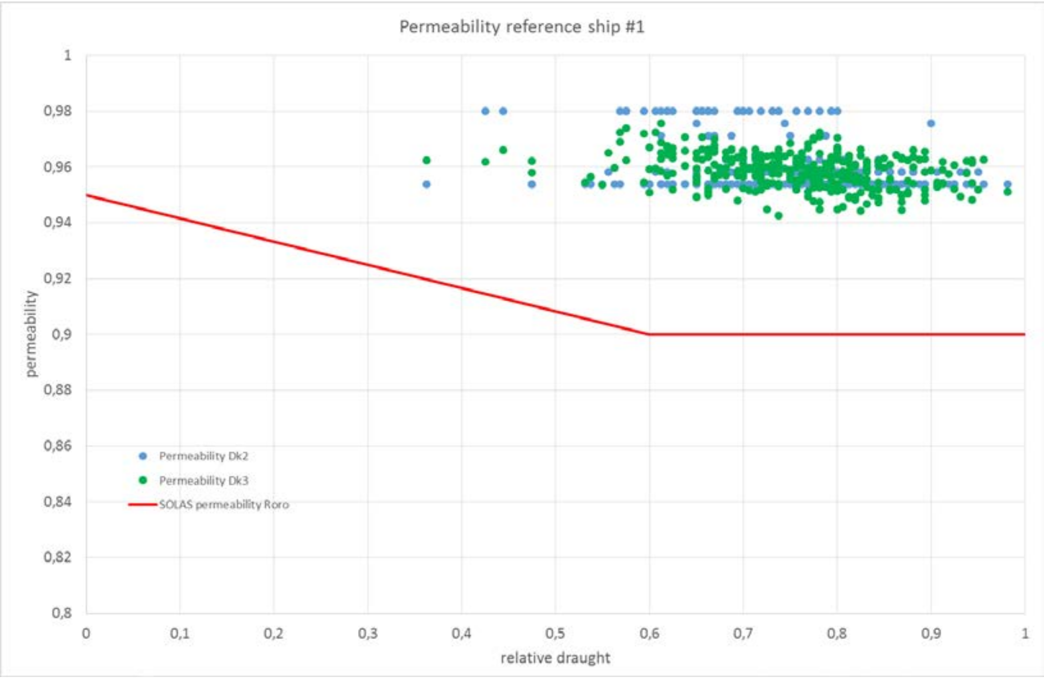


Figure 36 Permeability cargo hold ship #1

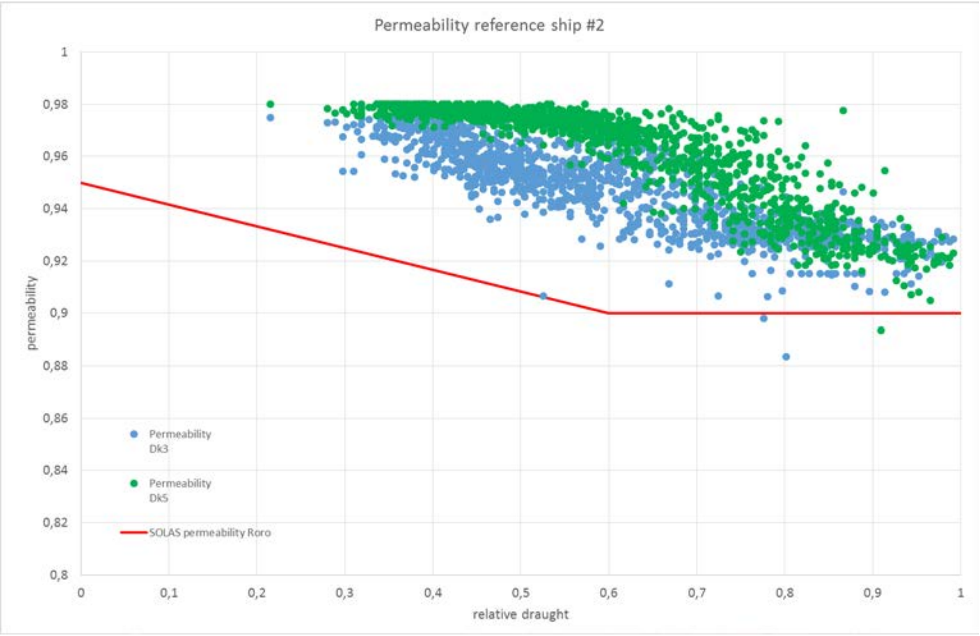


Figure 37 Permeability of cargo holds ship #2

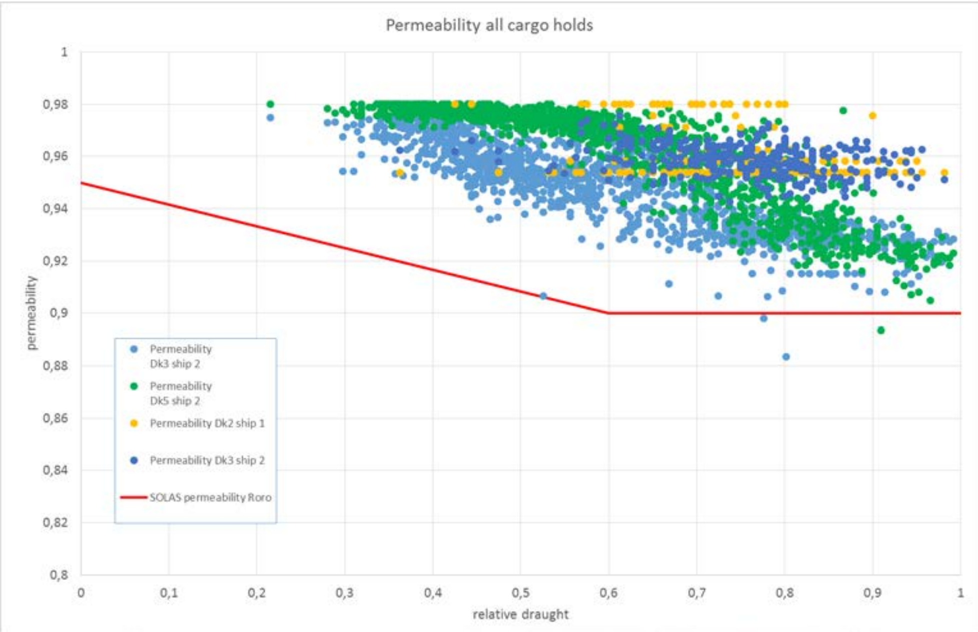


Figure 38 Permeability all cargo holds

It can be seen that the actual permeability is slightly higher than the default values from SOLAS but still quite close to it.

As the calculation of the permeability is based on a number of estimation, a sensitivity check has been made. If all assumed density of cargo types will be reduced by 30% the overall mean value for permeability changes significantly downwards, but is still in the region of the SOLAS default values.

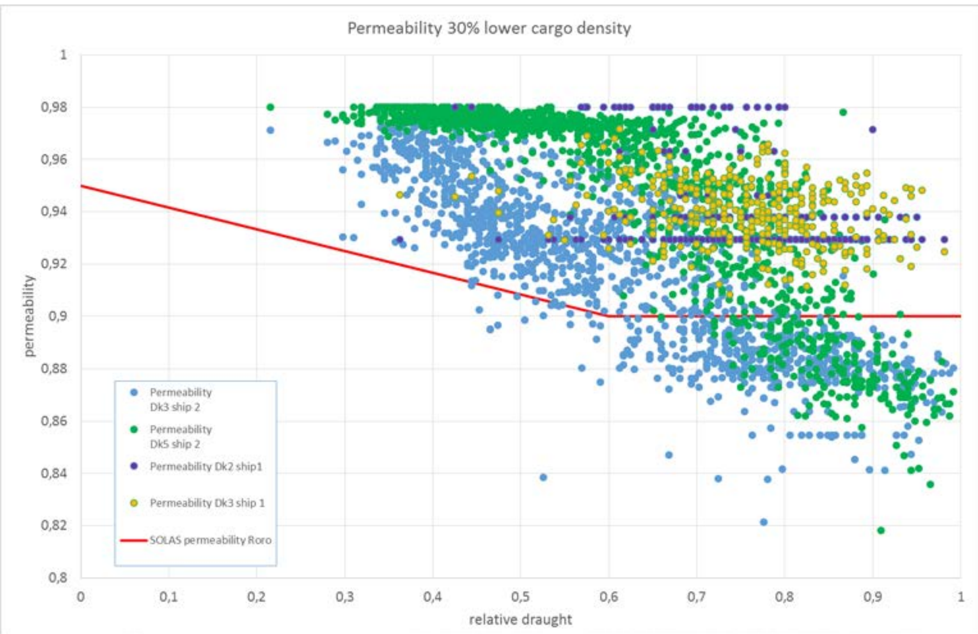


Figure 39 permeability of cargo holds with 30% lower density

It can be concluded that the SOLAS default values are somewhat conservative for RoRo cargo spaces, but taking into account the uncertainty of the calculation and the variety of cargo and ship designs there is no need to change the SOLAS default values.

6 PERMEABILITY OF TANKS

The eSAFE project showed that the permeability of tanks for cruise ship is very far from value prescribed by SOLAS (0 or 0.95 whichever results in the more severe requirement). The loading conditions data collected in this WP permit to study further the tanks permeability of cruise ships and to investigate the tanks permeability of Ropax ships.

6.1 Actual global tanks permeability for cruise ships

In this project the real loading cases of 27 existing cruise ships have been investigated and the loading conditions recorded on board have been collected.

Then all the conditions recorded have been examined to assess that all needed data to investigate tanks permeability were available.

In particular it has been verified that the following data were available at least:

- Aft and fore draught for each loading condition
- Potable Water tanks filling and total capacity
- Water Ballast tanks filling and total capacity
- Fuel tanks filling and total capacity
- Waste water tanks filling and total capacity
- Miscellaneous tanks filling and total capacity
- Draught range (minimum and maximum draught according to the Loading manual)

As an outcome of that assessment 6 cruise ships have been excluded due to missing or inconsistent data (see Table 21).

Ship n.	Max Draft	Min Draft	Year	GT	Operating Area	Note on tanks loading
1	9.2	7.7	2001	137000	Caribbean and US East Coast	Used
2	8.6	8.12	2010	122000	Caribbean, Europe and South America	Used
~~3~~	~~8,60~~	~~8.24~~	~~2009~~	~~122000~~	~~Caribbean~~	~~Displacement N/A and draughts out of range~~
4	9.00	8.45	2005	156000	Caribbean	Used
~~5~~	~~9.3~~	~~8.33~~	~~2016~~	~~227000~~	~~Caribbean~~	~~PW not available~~
6	9.024	8.65	2008	154000	Caribean and Europe	Used
7	5.95	5.51	2000	30000	Asia, Europe and Caribbean	Used
8	9.1	8.6	2003	138000	Asia and Caribbean	Used
9	7.85	7.53	1992	74000	Caribbean	Used
10	8.3	7.3	2014	100000	Caribbean, Europe, Middle East and Asia	Used
11	8.25	7.4	2015	100000	Europe middle East	Used
12	8.25	7.95	2016	99000	Middle East, europe and Ceribbean	Used
13	8.26	6.82	2017	99000	Caribbean and Europe	Used
~~14~~	~~7.3~~	~~6.11~~	~~1990~~	~~49000~~	~~Caribbean~~	~~Displacement and Draughts not available~~
15	8.8	8.1	2016	167000	Asia and Alaska	Used
16	8.8	7.892	2014	169000	Asia	Used

~~17~~	-	-	~~2000~~	~~30000~~	~~Caribbean, Europe and Middle East~~	~~Draught range not available~~
18	8.6	8.3	2001	90000	Alaska and Australia	Used
19	8.6	8.152	2012	128000	Caribbean and Europe	Used
20	7.9	7.38	1997	78000	Caribbean and Europe	Used
21	8.6	8.201	2011	122000	Caribbean and Europe	Used
22	8.6	8.3	2008	122000	Asia and Alaska	Used
23	8.596	7.091	2003	90000	Caribbean, East Coast and Europe	Used
~~24~~	~~7.8~~	~~7.712~~	~~1988~~	~~73000~~	~~Europe and South america~~	~~Displacement and Draughts not available~~
25	7.9	7.32	1998	78000	europe and US	Used
26	9.1	8.54	1999	137000	Asia	Used
~~27~~	-	-	~~1992~~	~~47000~~	~~Europe~~	~~Draught range not available~~

Table 21 List of cruise ships used/excluded from the tanks permeability assessment

21 cruise ships satisfied the minimum required data, as explained above, therefore they have been selected for tanks permeability investigation and a diagram with Gross Tonnage (GRT) versus year of built is shown in Figure 40. Cruise ships selected for tanks permeability assessment.

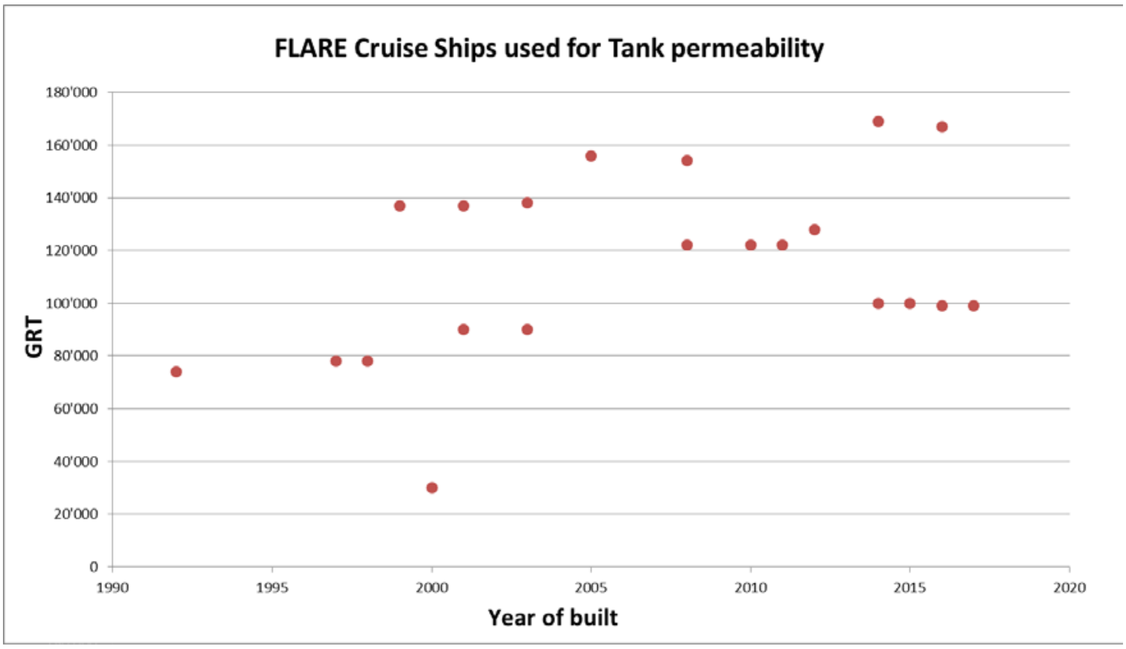


Figure 40 Cruise ships selected for tanks permeability assessment

It appears evident that the range of ships, in terms of dimension and year of built, is wide and a huge number (11354) of loading conditions has been recorded for these selected vessel. Therefore it can be concluded that the collected data permit to have a wide picture of the real tanks permeability of cruise ships.

In order to calculate the real tank permeability the following general data have been selected for each ship:

- $\boldsymbol{Ts}$ Maximum draught [m] (corresponding to deepest subdivision draught for ships built under SOLAS 2009)
- $\boldsymbol{Tl}$ Minimum Draught [m] (corresponding to light service draught for ships built under SOLAS 2009)
- $\boldsymbol{CBLW}$ max. capacity black water [m^3]
- $\boldsymbol{CGW}$ max. capacity grey water [m^3]
- $\boldsymbol{CDO}$ max. capacity marine gas oil/diesel oil [m^3]
- $\boldsymbol{CTFW}$ max. capacity technical fresh water [m^3]
- $\boldsymbol{CFO}$ max. capacity fuel oil [m^3]
- $\boldsymbol{CLO}$ max. capacity lubricating oil [m^3]
- $\boldsymbol{CMIS}$ max. capacity miscellaneous tanks [m^3]
- $\boldsymbol{CPW}$ max. capacity potable water [m^3]
- $\boldsymbol{CWB}$ max. capacity ballast water [m^3]

And the following data have been selected for each loading condition:

- $\boldsymbol{Tf}$ Draught fore [m]
- $\boldsymbol{Ta}$ Draught aft [m]
- $\boldsymbol{LBLW}$ total mass of black water [t]
- $\boldsymbol{LGW}$ total mass of grey water [t]
- $\boldsymbol{LDO}$ total mass of MGO/DO loaded [t]
- $\boldsymbol{LTFW}$ total mass of technical fresh water[t]
- $\boldsymbol{LFO}$ total mass of fuel oil loaded [t]
- $\boldsymbol{LLO}$ total mass of lubrication oil loaded [t]
- $\boldsymbol{LMIS}$ total mass of liquid loaded within miscellaneous tanks[t]
- $\boldsymbol{LPW}$ total mass of potable water loaded [t]
- $\boldsymbol{LWB}$ total mass of ballast water loaded [t]

Heeling water tanks are not included in that analysis as they have been treated separately due to their different scope.

For the permeability calculation it is assumed that the liquid loaded within the damaged tanks is totally replaced by sea water. Therefore the actual global tanks permeability is obtained from the following equation:

$$\sum_{i=1}^{n}(\rho \cdot c_i - m_i) = \rho \cdot tperm \cdot \sum_{i=1}^{n} c_i \qquad (1)$$

Where

$i = tank$

$\rho = sea\ water\ density\ 1.025\ {}^{t}/_{m^3}$

$c_i = capacity\ of\ the\ tank$

$m_i = mass\ of\ liquid\ within\ the\ tank$

$$tperm = actual\ global\ tanks\ permeability$$

It follows that:

$$tperm = 1 - \frac{\sum_{i=1}^{n} m_i}{\rho \cdot \sum_{i=1}^{n} c_i} \tag{2}$$

Based on the data collected on board the actual global tanks permeability becomes:

$$tperm = 1 - \frac{LBLW + LGW + LDO + LTFW + LFO + LLO + LMIS + LPW + LWB}{1.025 * (CBLW + CGW + CDO + CTFW + CFO + CLO + CMIS + CPW + CWB)} \tag{3}$$

It has to be noted that the data have been collected for all tank purposes therefore the outcome of this study may be applied to any structural tank.

Then for each loading condition the normalized draught (dn) has been calculated with the following formula:

$$dn = \frac{Tm - Tl}{Ts - Tl} \tag{4}$$

where

$$Tm = \frac{Ta + Tf}{2}$$

An overview of the calculated data is presented in Figure 41 to Figure 43 where diagrams with actual global tanks permeability (tperm) vs normalized draught (dn) are shown ship by ship. From the diagrams it becomes evident that there is a good correlation between tank permeability and normalized draught.

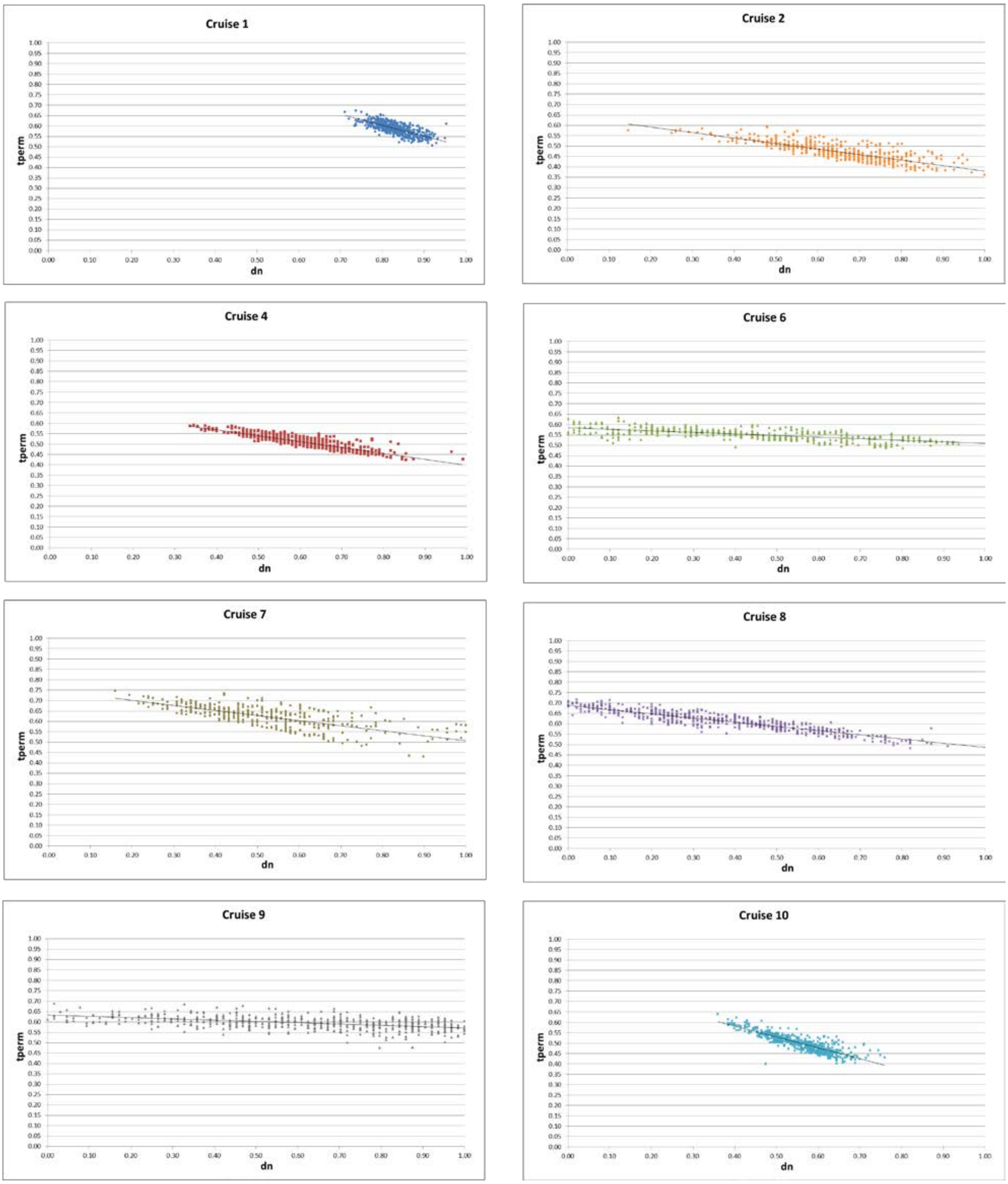


Figure 41 Actual global tanks permeability vs Normalized Draught (cruise ships 1 – 10)

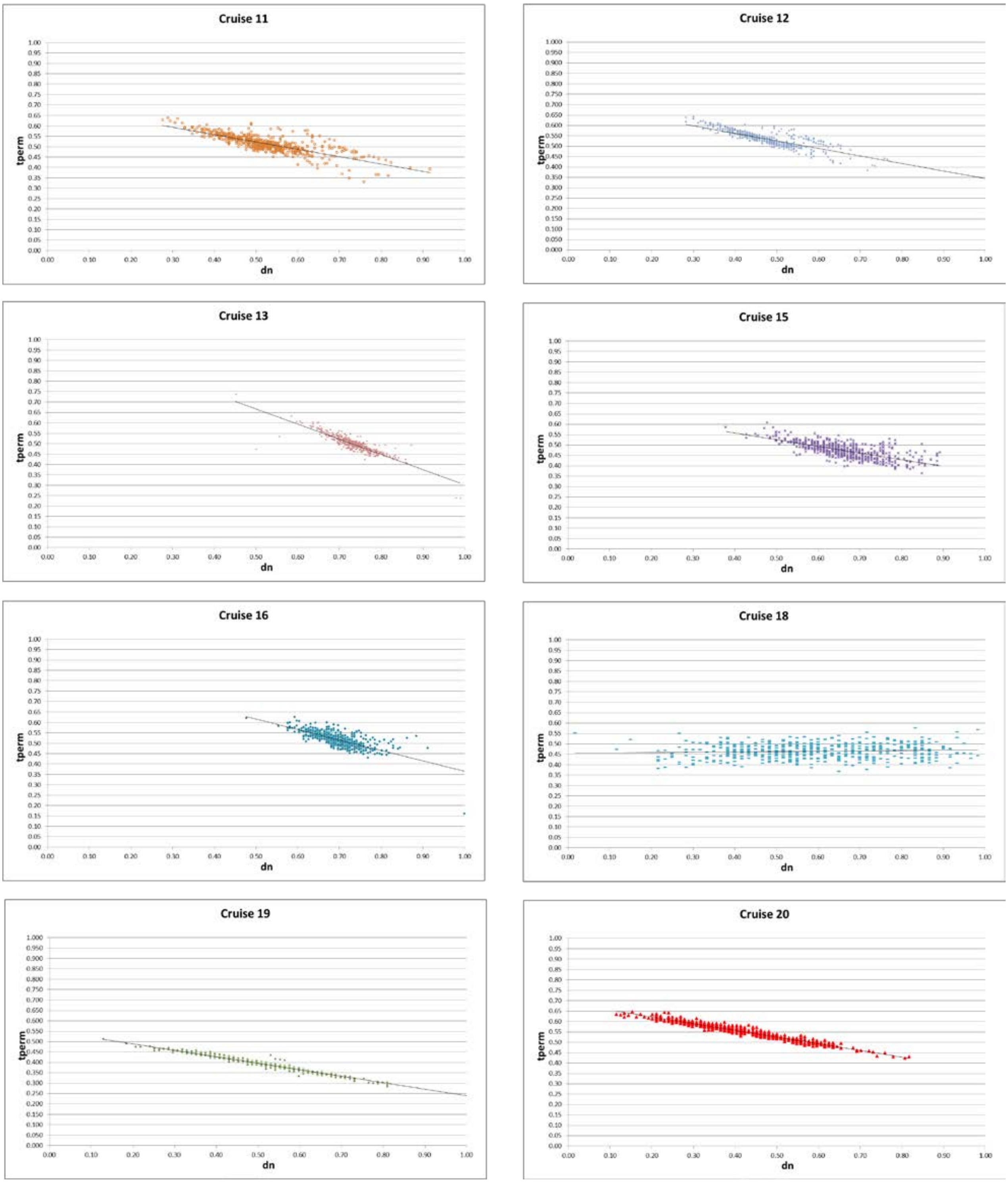


Figure 42 Actual global tanks permeability vs Normalized Draught (cruise ships 11 – 20)

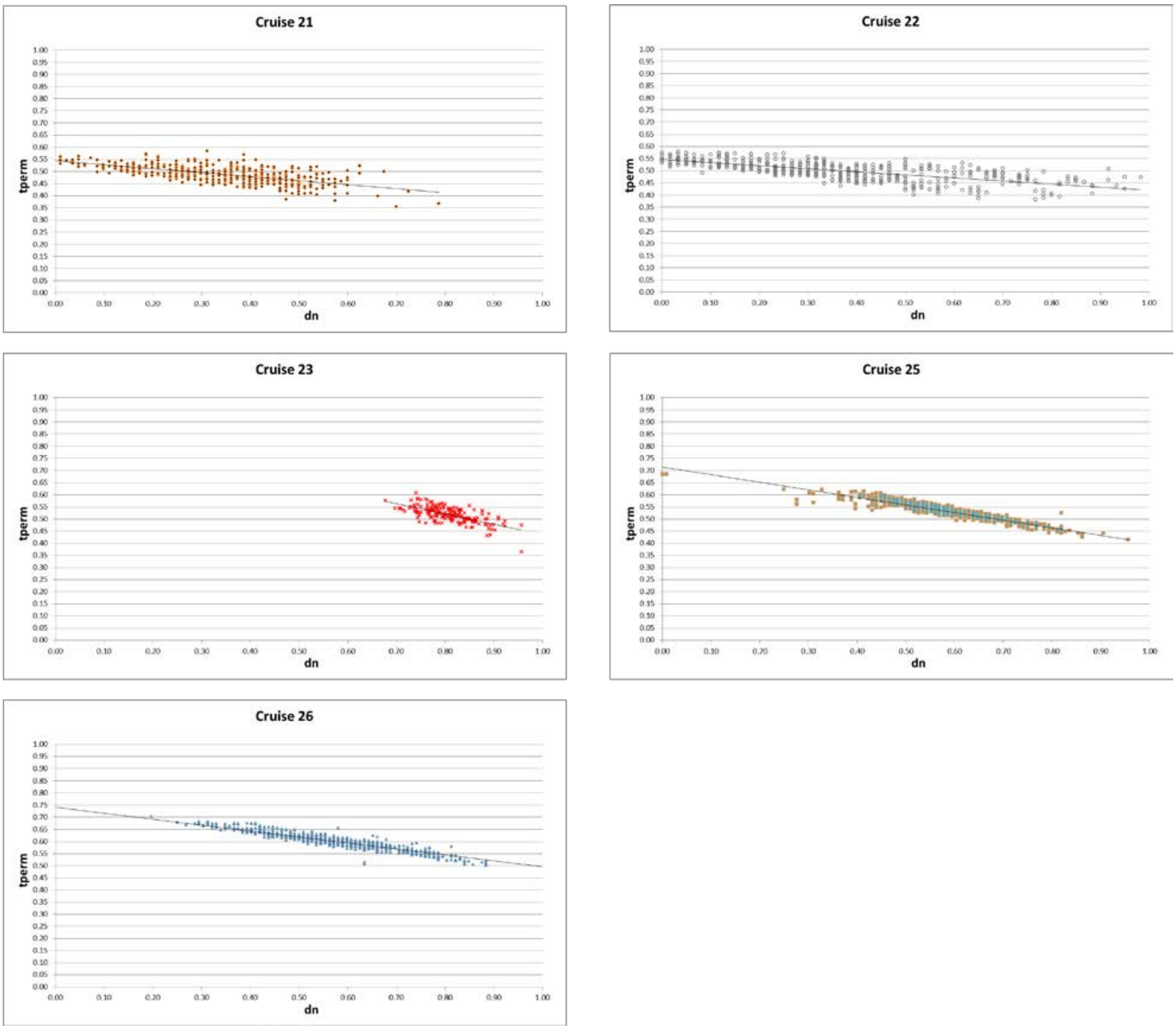


Figure 43 Actual global tanks permeability vs Normalized Draught (cruise ships 21 – 26)

Then in Figure 44 the data for all ships are collected in the same graph. Looking at that graph we can realize that the SOLAS permeability for tanks is not realistic and too conservative.

According to the scope of the FLARE WP2 a new permeability for tanks of cruise ships is proposed. Based on the approach used in SOLAS Ch.II-1 reg.7-3.2 for dry cargo spaces, container spaces, ro-ro spaces, cargo liquids a similar formula can be used for permeability of tanks intended for liquids on cruise ships (instead of 0 or 0.95) since the calculations of real permeability with results shown in Figure 41 to Figure 44 are sufficient to justify such different approach.

In Figure 45 a linear regression is used to define the permeability of tanks as a function of the normalized draught.

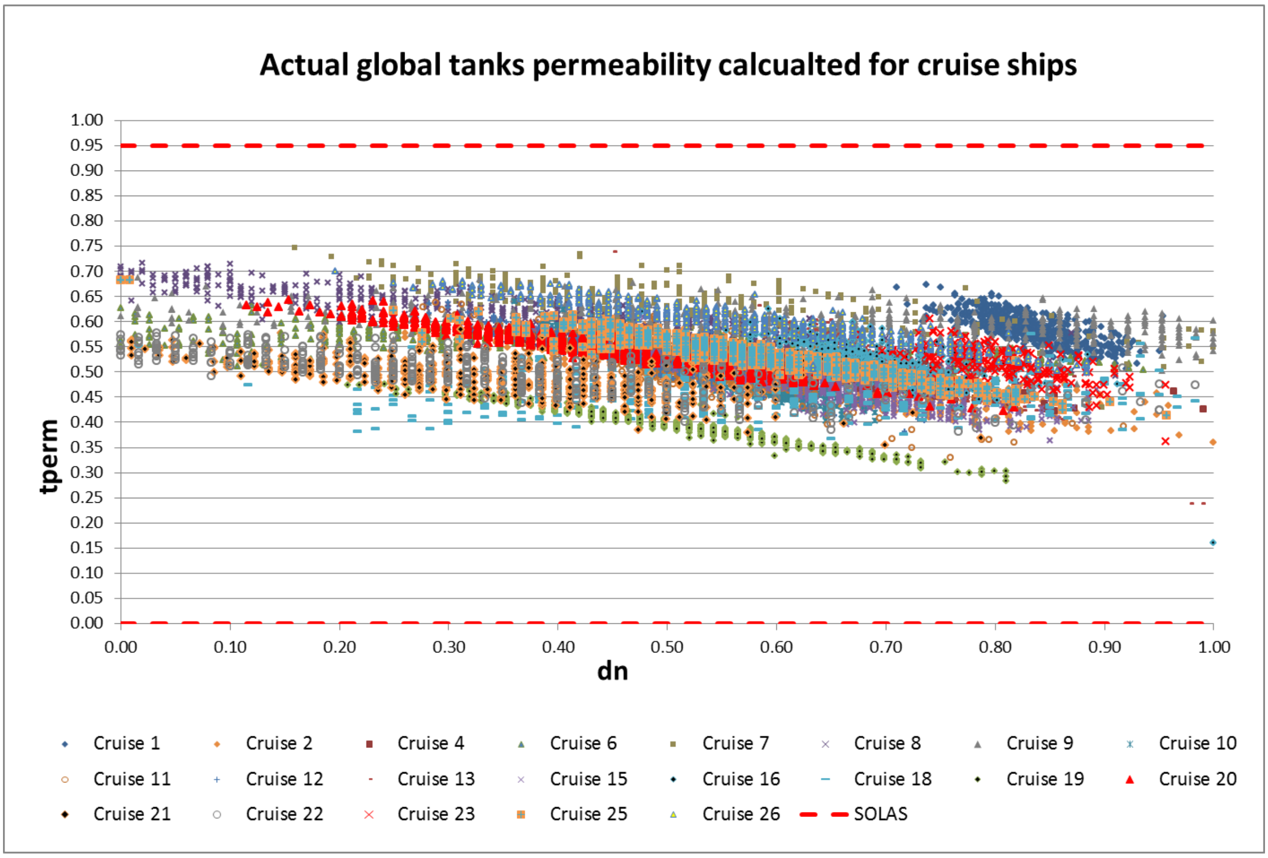


Figure 44 Actual global tanks permeability vs Normalized Draught (all cruise ships)

The proposed formulation takes the following analytical form:

$$Tperm = 0.59 - 0.11 \cdot \frac{T - T_{min}}{T_{max} - T_{min}} \quad (5)$$

Where

$T = Mean\ draught\ of\ the\ init\ condition\ to\ be\ calculated$;

$Tperm\ = Tanks\ permeability\ obtained\ with\ linear\ regression;$

$T_{min} = Minimum\ draught\ according\ to\ stability\ booklet$

$(corresponding\ to\ light\ service\ draught\ for\ ships\ built\ under\ SOLAS)$;

$T_{max} = Maximum\ draught\ according\ to\ stability\ booklet$

$(corresponding\ to\ deepest\ subdivision\ draught\ for\ ships\ built\ under\ SOLAS)$;

The notation *Tperm, with capital "T"*, is used in formula above to differentiate between the permeability directly determined from the on-board data (*tperm*) and the permeability from the regression.

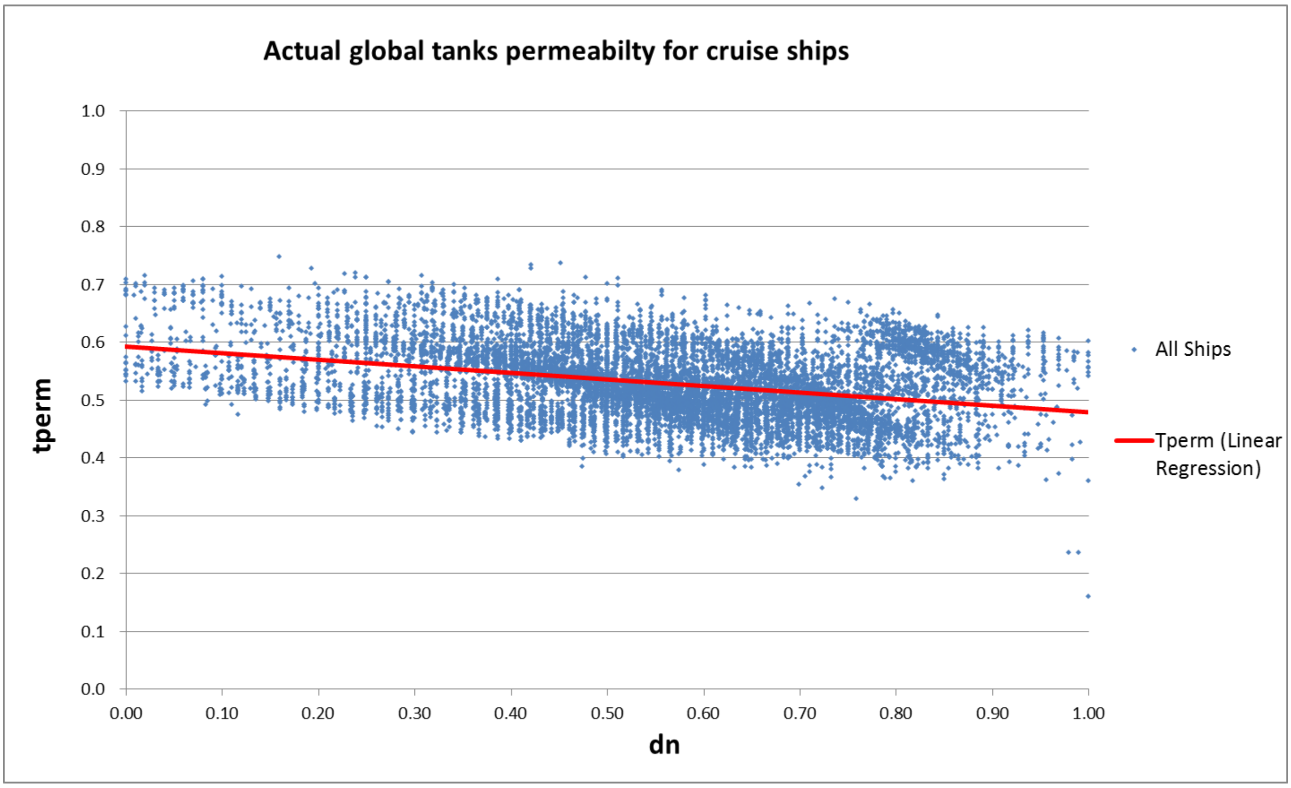


Figure 45 Tanks permeability proposal

To apply this proposal in damage stability calculation, as prescribed in SOLAS, Part B, Ch.II-1, the following values are to be used for the three initial draughts:

- Tperm=0.59 at lightest service draught (dl)
- Tperm=0.52 at partial subdivision draught (dp)
- Tperm=0.48 at deepest subdivision draught (ds)

The filling level of heeling tanks was available for eleven cruise ships from the collected data. These tanks are always filled about 50% on both sides and, depending on the asymmetry of the ship, the water is shifted from one side the other. So the filling of a heeling tank in a case of damage may vary between 0.1 and 0.9 as the tanks usually cannot be emptied totally.

From the probabilistic perspective it has to be considered that the average filling level for Heeling tanks is generally close to 50%. Therefore considering that fresh water is used for these tanks the formula (1) takes the following analytical form:

$$\sum_{i=1}^{n}(\rho \cdot c_i - 0.5 \cdot \rho_F \cdot c_i) = \rho \cdot HWTperm \cdot \sum_{i=1}^{n} c_i \quad (6)$$

Substituting the Heeling tanks capacity $HCap = \sum_{i=1}^{n} c_i$ in (6) it results in:

$$HCap \cdot (\rho - 0.5 \cdot \rho_F) = \rho \cdot HWTperm \cdot HCap \quad (7)$$

Thus, the Heeling Water Tanks permeability is given as:

$$HWTperm = 1 - \frac{0.5 \cdot \rho_F}{\rho} = 0.51 \quad (8)$$

Where:

i = tank

ρ = sea water density $1.025\, {}^{t}/_{m^3}$

ρ_F = fresh water density $1.0\, {}^{t}/_{m^3}$

$HCap$ = Heeling tanks capacity

$HWTperm$ = global permeability for heeling tanks

The obtained value is close to the actual values calculated for the real loading conditions as shown in Figure 46.

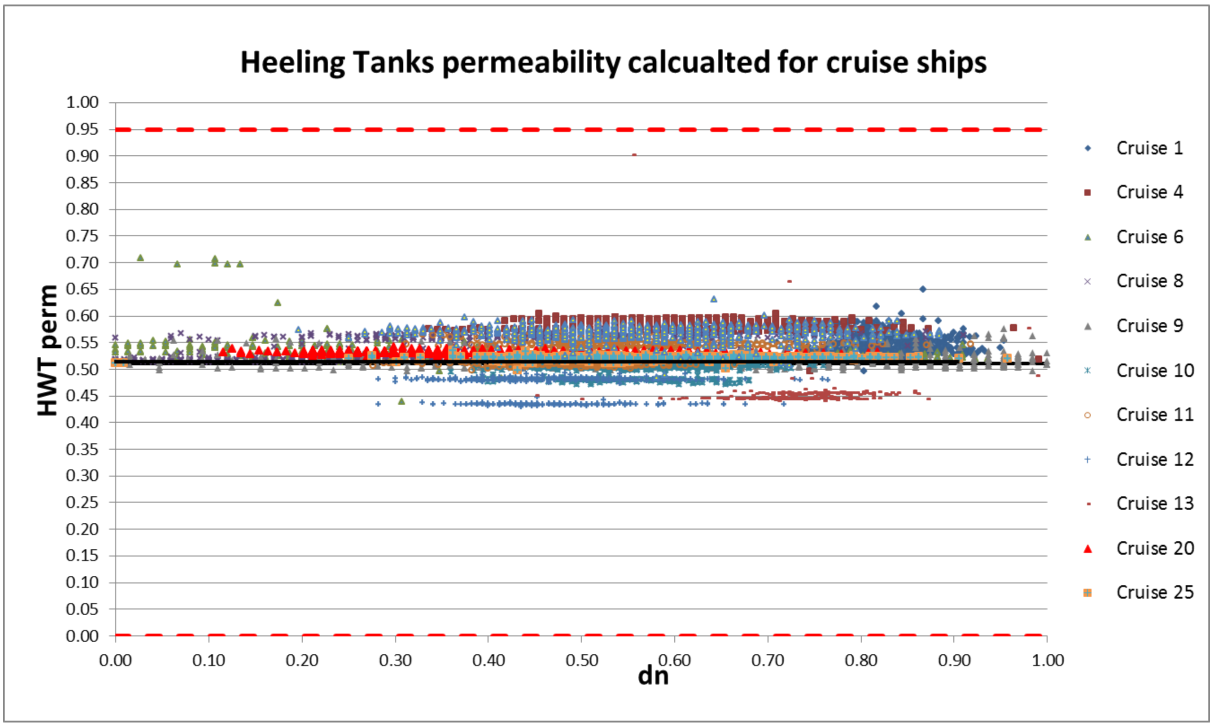


Figure 46 Actual Heeling Tanks permeability (HWTperm) vs Normalized draught (dn)

6.2 Mathematical approach for cruise ships

The formulation proposed in (5) is a good step forward to calculate an average value of the tank permeability for cruise ships. With the aim to further reduce the gap between real permeability and calculated value a mathematical approach has been investigated.

The total deadweight of a cruise ship may be written with the following equation:

$$DWT = T_{DWT} + HWM + O_{DWT} \quad (9)$$

Where:

DWT = Total deadweight

T_{DWT} = mass of liquid loaded within tanks (heeling tanks excluded)

HWM = mass of water loaded within heeling tanks

O_{DWT} = remaining part of the deadweight (e.g. pax, crew, pools, stores, etc.)

Thus the following equation may be derived for the ship displacement:

$$Disp = LWT + T_{DWT} + HWM + O_{DWT} \quad (10)$$

Where:

Disp = Intact displacement

LWT = Lightship weight

T_{DWT} may be obtained from equation (1):

$$T_{DWT} = \sum_{i=1}^{n} m_i = \sum_{i=1}^{n} \rho \cdot c_i \cdot \ (1 - tperm) \quad (11)$$

Thus using the total tank capacity "*Tcap*" (excluding heeling water) the equation (11) becomes:

$$T_{DWT} \ = \sum_{i=1}^{n} m_i = \ \rho \cdot Tcap \ \cdot (1 - tperm) \quad (12)$$

And substituting equation (12) within equation (10) it follows that:

$$Disp = LWT + \rho \cdot Tcap \cdot (1 - tperm) + HWM + O_{DWT} \quad (13)$$

Thus the tanks permeability takes the following analytical form:

$$Tperm = 1 - \frac{Disp \ - \ LWT \ - HWM \ - O_{DWT}}{\rho \ \cdot \ TCap} \quad (14)$$

As already explained, the total filling level of heeling tanks is always about 50% considering both sides. Then, considering that in the cruise vessels the value of $_{DWT}$ is very low and it may be assumed abt. 4% of the total displacement, the tanks permeability is provided from the following equation:

$$Tperm = 1 - \frac{0.96 \cdot Disp \ - \ LWT \ - 0.5 \cdot HCap}{\rho \ \cdot \ TCap} \quad (15)$$

The obtained formula has been validated on cruise vessels mentioned in Table 21. Not all the data required by equation (15) were available and reliable on those ships therefore 17 cruise ships have been selected for that validation.

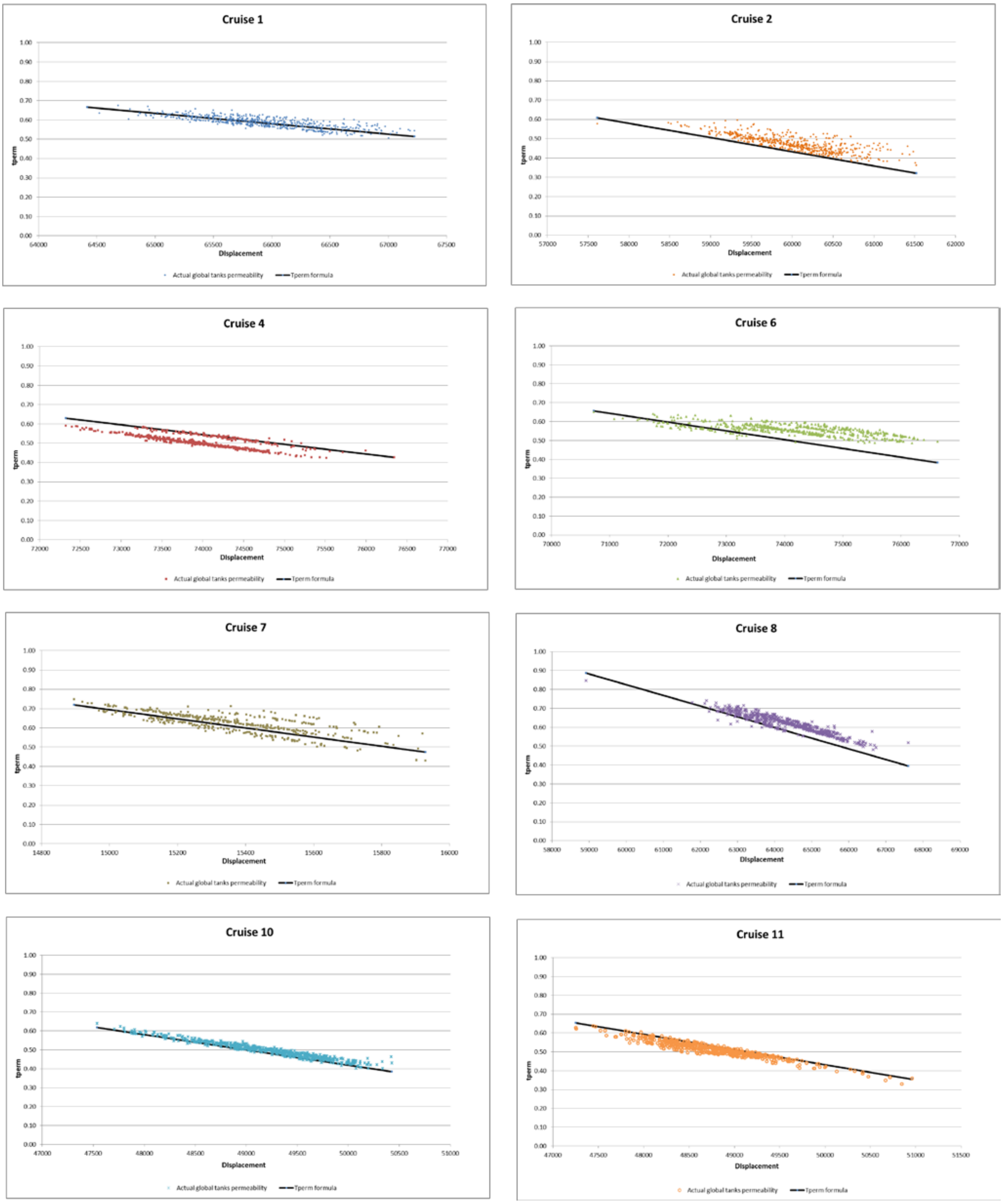


Figure 47 Actual global tanks permeability vs Displacement (cruise ships 1 – 11)

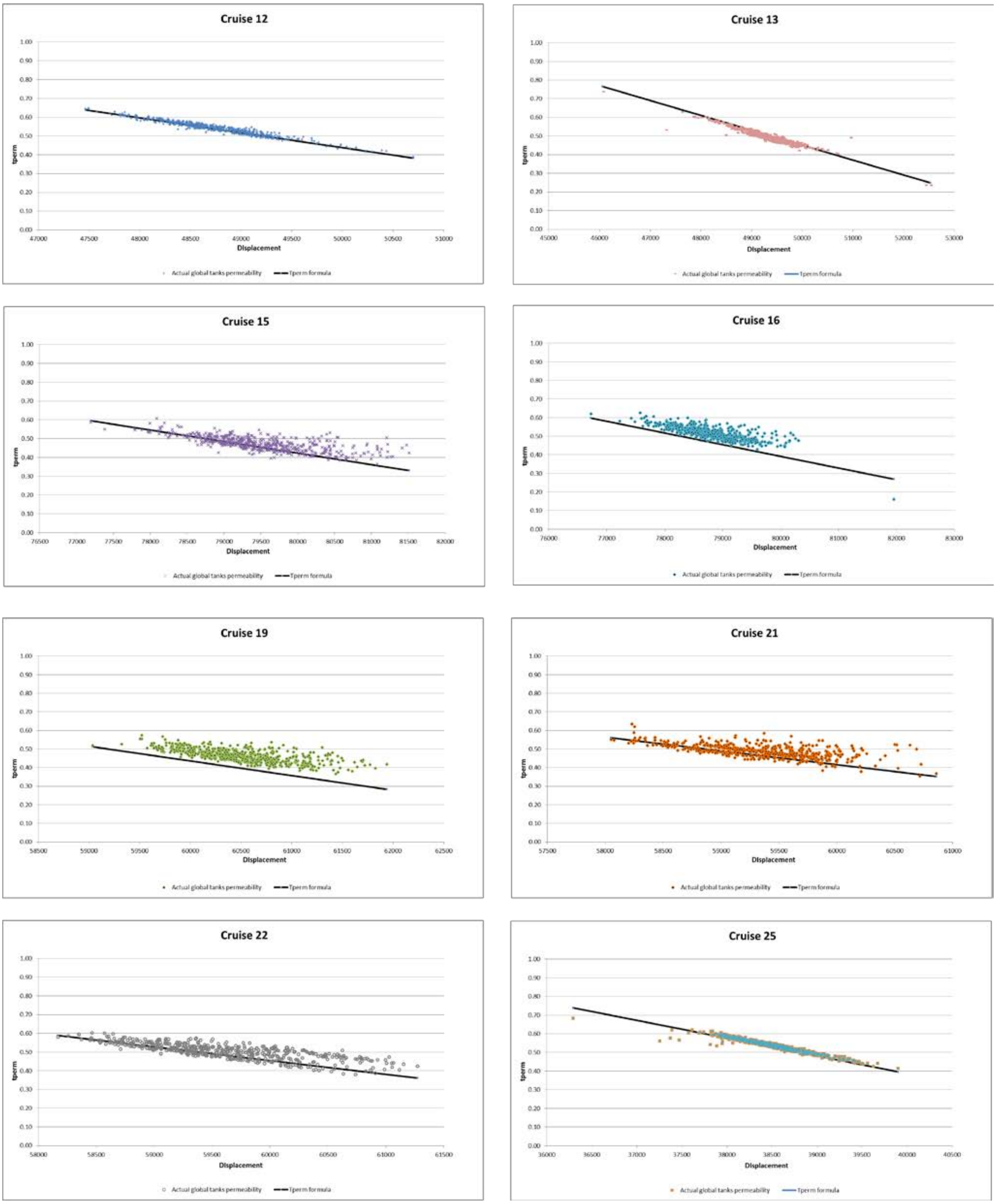


Figure 48 Actual global tanks permeability vs Displacement (cruise ships 12 – 25)

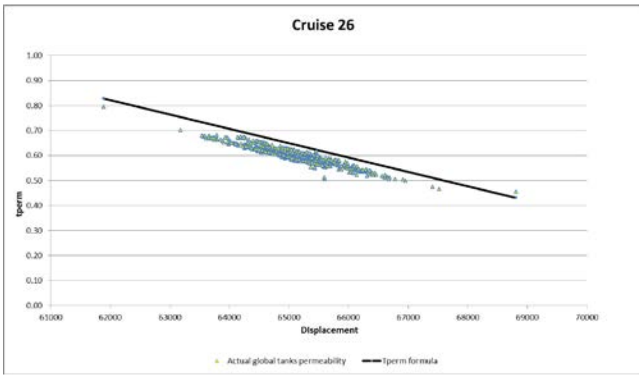


Figure 49 Actual global tanks permeability vs Displacement (cruise ship 26)

In Figure 47 to Figure 49 the diagrams comparing the actual global tanks permeability with the formula for $Tperm$ (15) are shown.

From the results in the above figures it can be concluded that there is a very good correlation between actual global tanks permeability and the value calculated with formula (15).

6.2.1 Linear regressiom vs Mathematical formula

A clear measure of the reliability of different formulation is shown in Table 22 where the standard deviations from real permeability are calculated for the different formulas (using all the available loading conditions) presented in this deliverable for cruise ships.

Description	Formula	STANDARD DEVIATION from real permeability calculated for FLARE Loading conditions
SOLAS permeability	0 or 0.95 whichever results in the more severe requirement	**0.42**
FLARE Linear Regression	$Tperm = 0.59 - 0.11 \cdot \frac{T - T_{min}}{T_{max} - T_{min}}$	**0.06**
FLARE Mathematical Formula	$Tperm = 1 - \frac{0.96 \cdot Disp - LWT - 0.5 \cdot HCap}{\rho \cdot TCap}$	**0.04**

Table 22 Standard deviation of different formulas from real permeability

The standard deviation between real value and SOLAS values is huge (0.42) and it confirms that SOLAS approach is not reliable for tanks permeability on cruise ships. That deviation can be reduced a lot using the simple formula obtained by linear regression. If further precision is needed the mathematical formula may be used.

Using the formula (15) the actual global tanks permeability is evaluated with better accuracy as the three main parameters, affecting the tanks permeability, are taken into account:

- Displacement
- Lightship weight
- Tanks capacity

While the formula (5) takes into account just the displacement by means of the normalized draught.

On the other hand it should be noted that during design phase the lightship weight is estimated by the builder but the real value is not available before the inclining test. Furthermore that value is going to increase during the ship's life due to the growth therefore it has to be updated after each weight survey.

Thus it is quite easy to calculate the value *Tperm* by formula (15) for built cruise ships but it may be difficult to establish a correct value for design calculation.

To solve that problem a suitable approach may be to use a conservative lightship weight including a growth margin of 2% (see example Figure 50). This will ensure that the permeability used at an anticipated design stage is not lower than the value calculated when the final lightship weight is available and it permits to keep the calculation valid even if the weight is increasing due to the growth. The limit of 2% is chosen to meet the same limit for a lightweight increase as defined in SOLAS II-1/5.2 and 5.5. An update of the permeability values is to be required together with a new inclining test and new stability documents when the lightship weight exceeds the value assumed in the relevant calculations.

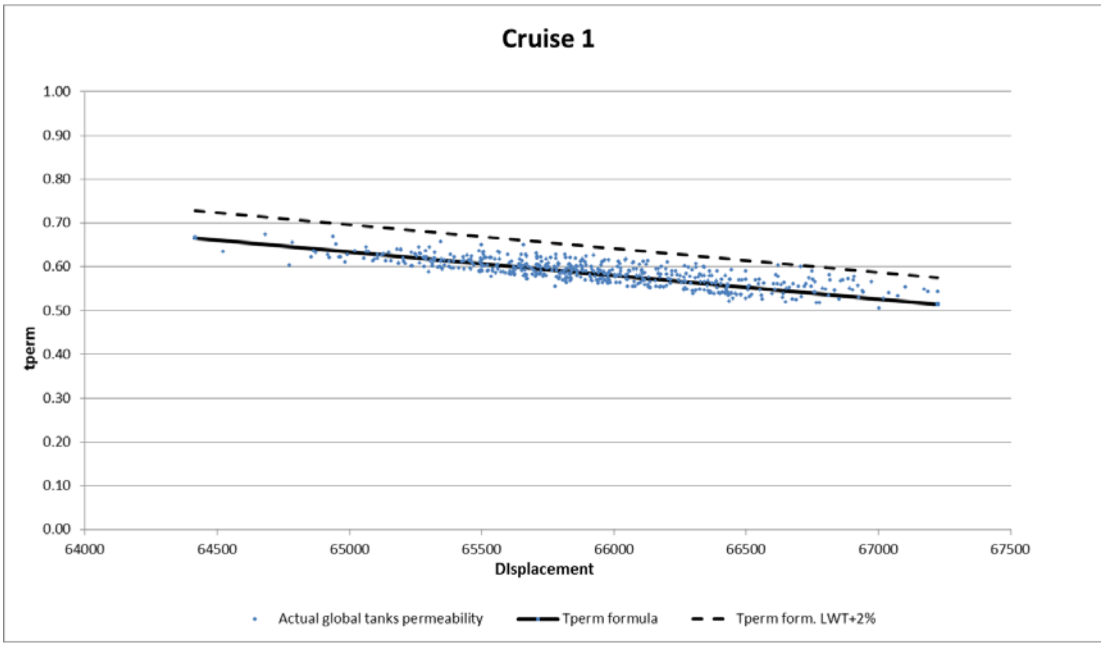


Figure 50 Tanks permeability calculated with Mathematical formula and 2% Lightweight margin

The proposed process seems not so difficult in fact it should be noted that stability calculations for cruise ships are normally re-executed when the increase of lightship weight leads to an increased subdivision draught.

In any case it can be concluded that both proposed formula may be used on cruise ships and they are almost closing the gap between actual global tanks permeability in real loading conditions and values used in damage stability calculations.

6.3 Actual global tanks permeability for RoPax ships

The methodology applied in chapter 6.1 for the calculation of the actual global tanks permeability of cruise ships has been repeated here for RoPax vessels.

In this case the real loading conditions recorded on board for nine existing RoPax ships have been analysed (see table 23).

The recorded data for some of them did not include data about waste water and/or potable water; anyway all the ships have been included in the investigation due to limited number of vessels.

Ship n.	Max Draft	Min Draft	Year	GT
1	7	6.2	2007	75000
2	5.64	5.1	1985	19700
3	6.7	5.54	2007	33500
4	6	5.09	1996	29700
5	5.86	4.75	2001	19700
6	6.3	5.04	2011	55000
7	6.5	5.02	1998	42700
8	6.6	5.77	2001	30300
9	6.8	5.8	2011	38800

Table 23 List of RoPax ships used for the tanks permeability assessment

Furthermore the diagram with Gross Tonnage (GRT) versus year of built is shown in Figure 51.

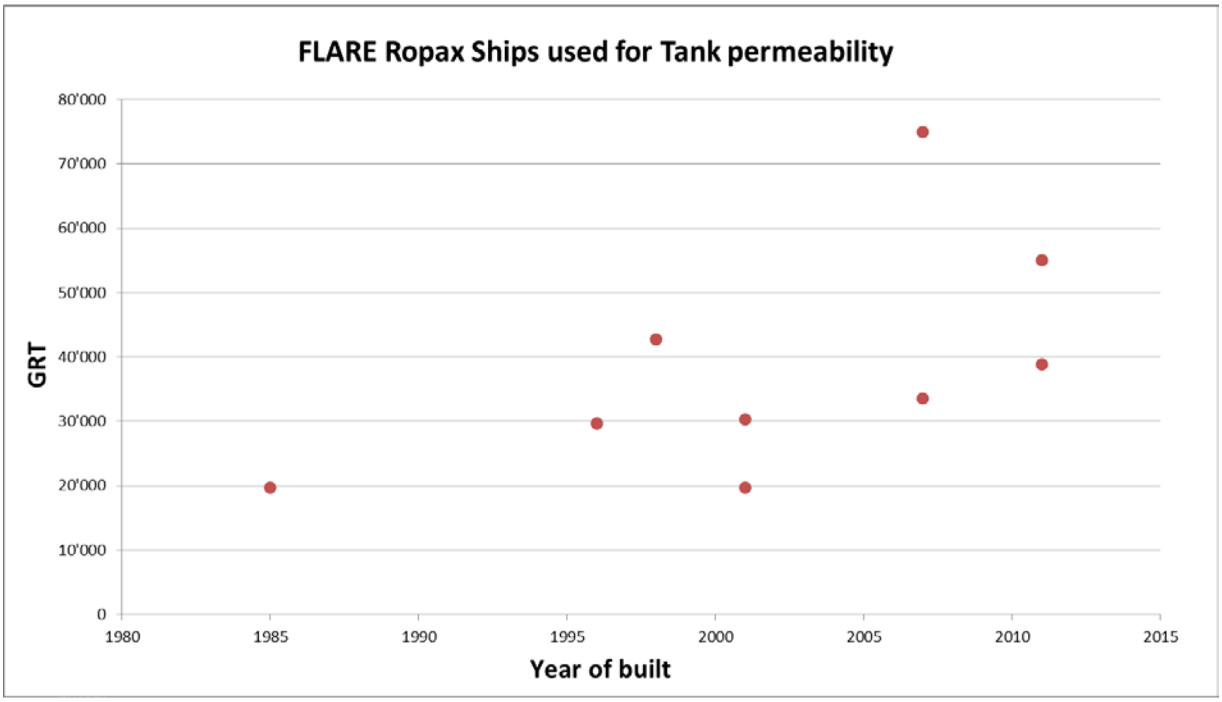
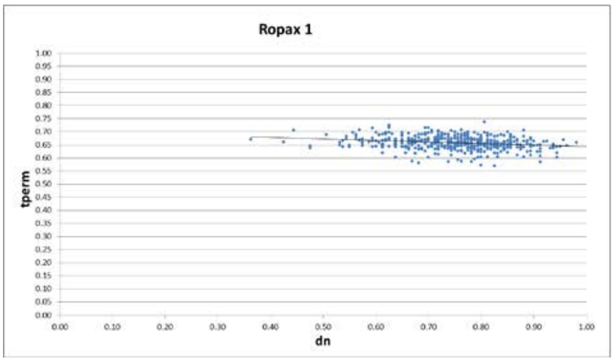


Figure 51 RoPax ships selected for tanks permeability assessment

The total number of loading conditions recorded for these selected vessels is 9731.

Based on the formula from (1) to (4), already applied for cruise vessels, the actual global tanks permeability has been calculated for Ropax ships but different results have been obtained. In fact from Figure 52 and Figure 53 it can be concluded that for these ships there is no correlation between normalized draught and *tperm*.

Furthermore the analysis shows in Figure 54 a wide spread of permeability (between 0.25 and 0.85) therefore a formula obtained by linear regression may be not put forward.



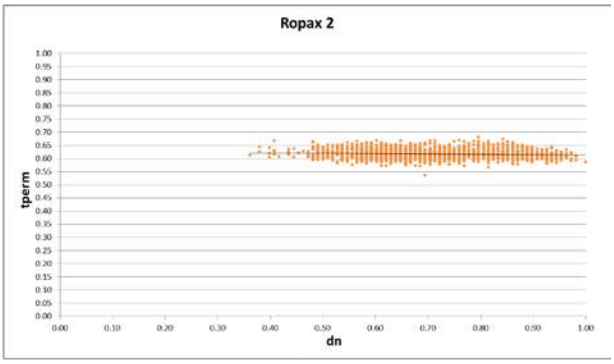


Figure 52 Actual global tanks permeability vs Normalized Draught (ropax ships 1 - 2)

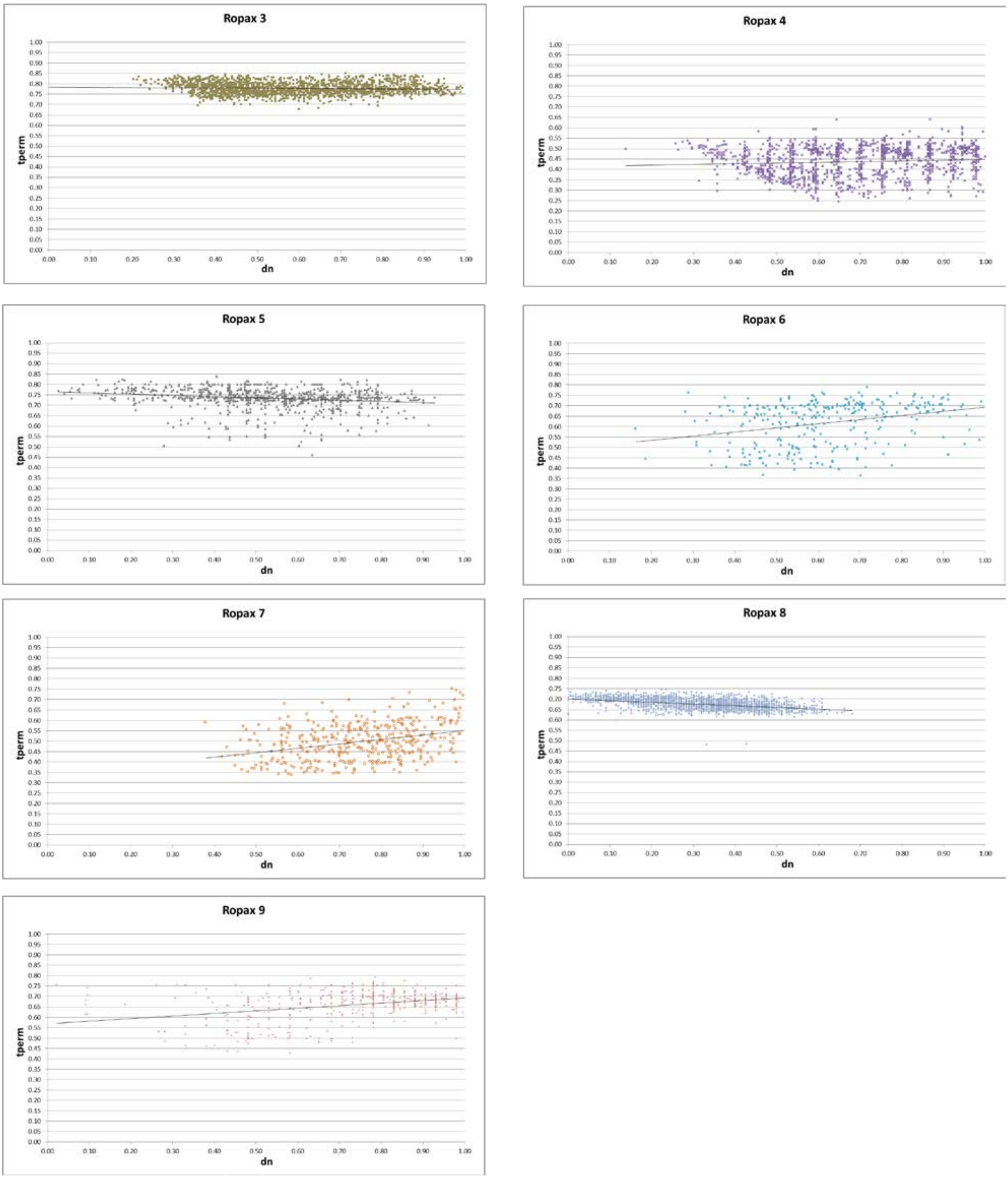


Figure 53 Actual global tanks permeability vs Normalized Draught (ropax ships 3 - 9)

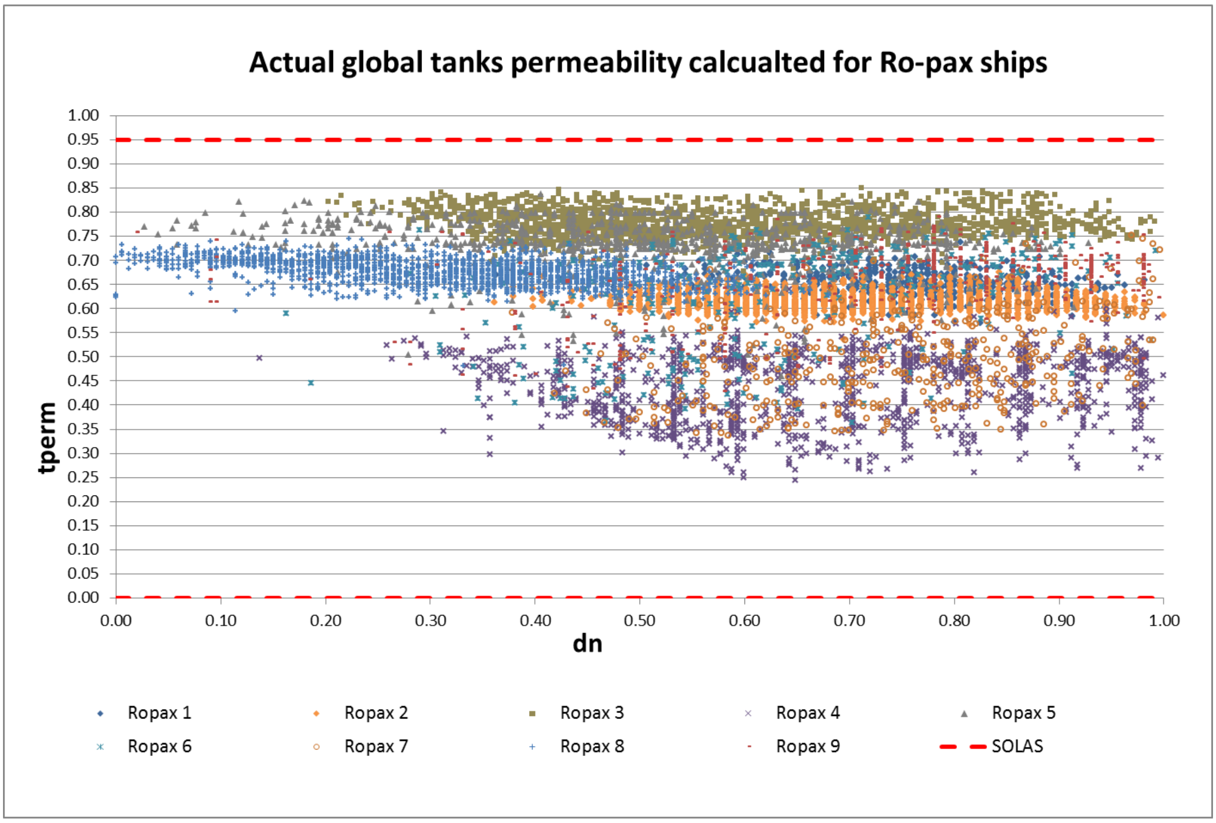


Figure 54 Actual global tanks permeability vs Normalized Draught (all ropax ships)

The mathematical approach is not applicable too as the weight of cars/trailers on these type of vessel is not a limited portion of the displacement therefore no assumption may be made in order to calculate the tanks permeability with a formula similar to (15).

For heeling tanks instead the formula derived for cruise vessels is still valid therefore the proposed value of 0.51 may be used for these ships too, as confirmed by Figure 55.

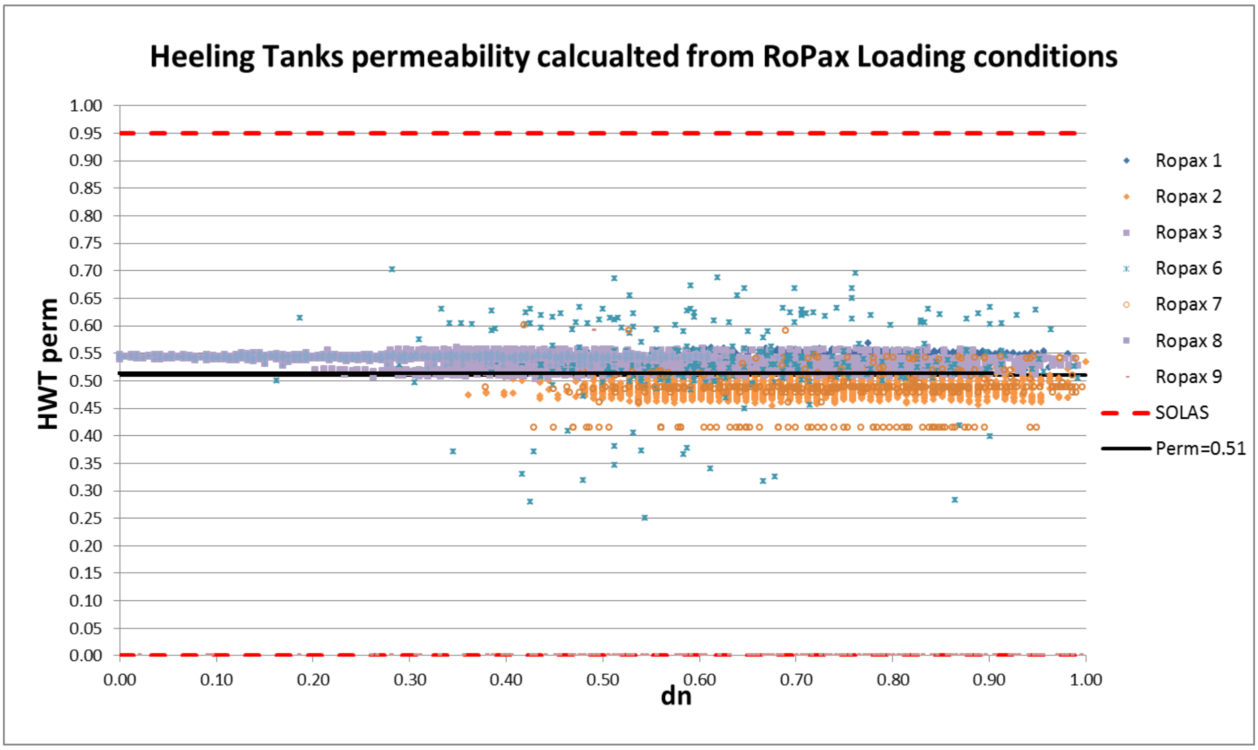


Figure 55 Actual global tanks permeability for Heeling tanks (ropax ships)

7 SUMMARY OF RESULTS

The assessment of permeability shows that the default values defined in SOLAS may not be appropriate anymore.

For engine rooms the calculated permeability is shown in Table 24

Machinery spaces SOLAS	0.85
Main Engine room #1	0.920
Main Engine room #2	0.916
Main Engine room #3	0.910
Aux. Engine room #1	0.910
Aux. Engine room #2	0.933
Mean value	0.918
Standard deviation	0.008
Bandwidth +standard dev	0.926
Bandwidth -standard dev	0.909

Table 24 Summary Machinery Spaces

The variation is rather small, although different sizes of ships have been investigated. Keeping in mind that also those components which are not considered as they may be flooded will contribute to the displaced volume and as smaller ships may have more dens engine room designs as a conclusion a permeability of 0.9 should be applied for machinery spaces considering also the bandwidth of ± standard deviation around the mean value.

Table 25 shows the results for cabin areas with a similar tendency, although the variation of the results is somewhat higher. In any case the assumed permeability in SOLAS is too high and also a value of 0.9 should be used considering the standard deviation.

Cabin area SOLAS	0,95
Cabin area #1	0,930
Cabin area #2	0,894
Cabin area #3	0,924
Mean value	0,916

Standard deviation	0,016
Bandwidth +standard dev	0,932
Bandwidth -standard dev	0,900

Table 25 Summary cabin areas

The assessment of permeability of stores shows a very large difference to the default values of SOLAS. Although the mean value of the stores investigated results in a permeability of 0.936 a slightly lower permeability is proposed, as there is some uncertainty in the variability of store on different ships. Hence also a value of 0.9 is recommended to be used.

For the permeability of cargo holds of Ropax ships it has been confirmed that the values defined in SOLAS reflect quite well the situation on board. Due to the uncertainties in the assessment of the permeability of cargo it is recommended not to change the permeability of cargo holds with 0.9 at the partial draught DP and the maximum draught DS, and with 0.95 at the lightest service draught DL.

For the tanks permeability it has been confirmed that the values defined in SOLAS is not realistic for both cruise ships and for Ropax. The analysis done on about eleven thousands loading conditions of cruise ships permitted to generate two different formulas to be used for tanks of this ship type (heeling tanks excluded):

- Formula based on mathematical approach that permits to calculate the global permeability with higher accuracy but it requires that the Lightship weight is available

$$Tperm = 1 - \frac{0.96 \cdot Disp\ - LWT\ - 0.5 \cdot HCap}{\rho\ \cdot TCap}$$

- Formula from linear regression that is easier to use but less accurate than the mathematical one

$$Tperm = 0.59 - 0.11 \cdot \frac{T - T_{min}}{T_{max} - T_{min}}$$

No proposal may be put forward for Ropax vessel due to spread of permeability between 0.25 and 0.85.

A constant value of 0.51 has been proposed for permeability of heeling tanks for both cruise and Ropax ships.

8 CONCLUSIONS AND RECOMMENDATIONS

The results for the assessment of permeability of stores, engine rooms and accommodation areas show that the default values on SOLAS are not appropriate and do not reflect the reality. As the investigated spaces show only a very small variation of permeability a common value of 0.9 is proposed.

The analysis of cargo spaces of Ropax vessels show that the current values in SOLAS reflect the actual permeability quite good and hence these defaults values should be kept.

The proposed way to apply a mean permeability for tanks requires a new mind set for the stability assessment. In this case it is obviously that for cruise ships the main driver for the draught is the filling of tanks. For forensic or deterministic damage stability assessments the proposed way may not be suitable, however for the calculation of an averaged survivability index, like the attained subdivision index A, the permeability of tanks should be considered in the proposed way.

To achieve a way of calculation as close as possible to reality all new permeability values are to be considered in the simulations, in static damage stability calculations and also in the work of WP7 and WP8. As this approach, in particular the permeability of tanks differs significantly from the previous approach special attention should be given to an early involvement of the relevant stakeholders in class societies and administrations. A separate IMO submission is recommended.

9 REFERENCES

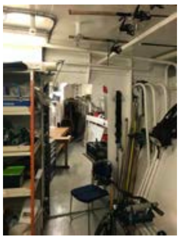
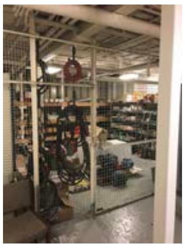
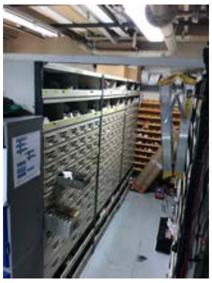
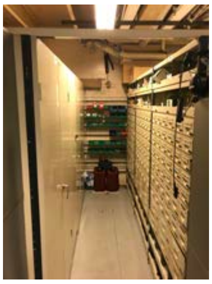
[1] D.T. Mallet, Study of the permeability of cargo ships, Washington DC, 1976

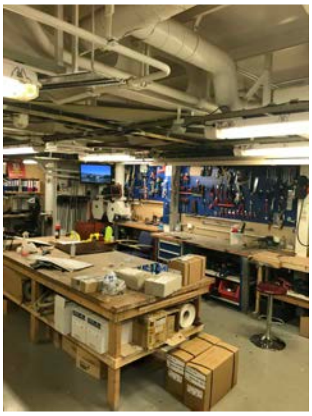
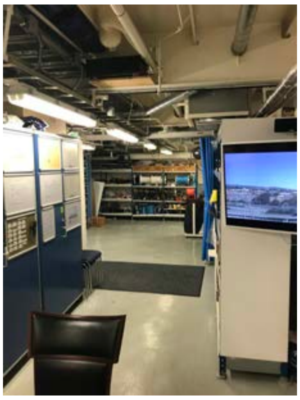
[2] Volkswagen AG, Viavision 04/2011, Wolfsburg 2011

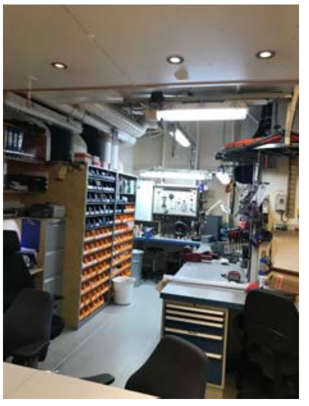
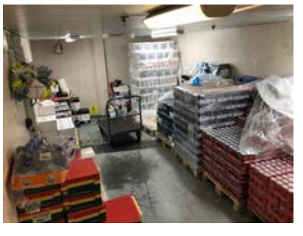
[3] H. Luhmann, G. Bulian, D. Vassalos, O. Olufsen, I. Seglem, J. Pöttgen, eSAFE-D4.3.2 – Executive summary, Joint Industry Project “eSAFE - enhanced Stability After a Flooding Event – A joint industry project on Damage Stability for Cruise Ships”, Oslo 2018

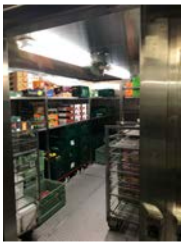
[4] M. Cardinale, A. Routi, H. Luhmann, R. Bertin, Permeability of tanks intended for liquids in cruise vessels, Proceedings of the 17th International Ship Stability Workshop, Helsinki 2019

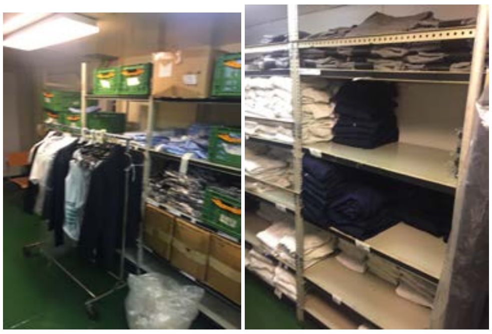
10 Annex 1 Photographs of stores

1 tax free	
3 deck store	
4 carpenter store	
6 Electrical store	
7 electrical store	 

9 deck store	 
10 electrical store	 
11 stores shop	 
12 Carpenter store	
14 Boatswain workshop	

15 Electric store	
16 Hotelstore	
17 Chemical store	
19 chemical store	
20 Engine store	 

22 provision stores	
23 provision stores	
24 provision stores	  
27 hotel stores	
28 hotel store	

29 uniform store	
30 chemical store	
31 consumable locker	
32 beverage 4	
33 beverage 2	

34 beverage 5	
35 milk box