SAFETY EQUIVALENCE – MEANING AND IMPLEMENTATION

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SUMMARY

Deriving motivation from the recent IMO Resolution MSC.99(73) on "Alternative Design and Arrangements" for fire safety and of new proposals at SLF 44 concerning other ship hazards, this paper focuses on the safety equivalence issue, which is at the heart of these exciting new developments. In this respect, it presents an analysis on the level of safety portrayed by current regulatory instruments on assessing damage stability, aiming to demonstrate and quantify the link between deterministic and probabilistic damage stability regulations and performance-based standards. To this end, survivability test results of a representative sample of Ro-Ro passenger vessels, which were model tested according to Stockholm Agreement Resolution 14, are used to provide a reference level against which all other instruments pertinent to damage survivability are tested.

NOMENCLATURE

A	Attained Index of Subdivision
R	Required Index of Subdivision
γ	Peakness parameter
H_s	Significant wave height [m]
s_i	Probability of a ship surviving a specific damage case in a given sea state
p_i	Probability that the compartment(s) under consideration is flooded
s_w	Probability of a ship surviving collision damage with large scale flooding on deck
s_a	Probability of a ship surviving collision damage considering all effects other water accumulation on deck
SEM	Static Equivalent Method
SLF	Sub-committee on Stability and Load Lines and on Fishing Vessels Safety under Marine Safety Committee (MSC) at the International Maritime Organisation (IMO)
T_p	Peak period [sec]
T_0	Zero-crossing period [sec]

1. INTRODUCTION

In the wake of recent shipping casualties involving Ro-Ro ferries, which resulted in severe loss of life, standards for Ro-Ro ship configuration, construction and operation have come under close scrutiny and new legislation has been put into place aimed at improving the safety of these vessels, notably SOLAS '90 as the new global standard for all existing ferries. Furthermore, concerted action to address the water-on-deck problem following the *Estonia* tragedy led to new requirements for damage stability agreed among North West European Nations to account for the risk of accumulation of water on the Ro-Ro deck, known as the *Stockholm Agreement*. Furthermore, in view of the uncertainties in the state of knowledge concerning the ability of a vessel to survive damage in a given sea state, an alternative route has also been allowed which provides a non-prescriptive way of ensuring compliance, through the "*Equivalence*" route, by performing model experiments in accordance with the Model Test Method of SOLAS '95 Resolution 14.

Deriving from systematic research over the past 14 years, numerical simulation models have been developed capable of predicting with good engineering accuracy the capsizal resistance of a damaged ship, of any type and compartmentation, in a realistic environment whilst accounting for progressive flooding. With considerable justification, this approach may be considered as another alternative to complying with Resolution 14, the so-called "*Numerical Equivalence*" route.

The tightening of legislation described above is coupled with serious considerations at IMO for regular application of risk assessment methods, for example, the *Formal Safety Assessment*. In this context, considerable attention has been focusing on the application of probabilistic procedures of damage stability assessment for the evaluation of Ro-Ro vessels and it appears more than likely that developments in the foreseeable future will most certainly adopt a framework of a probabilistic description. The regulatory regime described in the foregoing with respect to assessing the damage survivability of passenger/Ro-Ro vessels has understandably left the shipping industry in a state of confusion and uncertainty concerning the available options, approaches and optimum choice to ensure compliance and to ascertain the level of safety attained with regard to any such choice. Stated specifically, a ship owner today is faced with the following choices concerning damage stability-related standards:

Deterministic Regulations
- SOLAS'90, [1]
- Stockholm Agreement, [2]

Performance-Based Standards
- Numerical Simulations, [3]
- Model Experiments, [4]

Probabilistic Procedures
- Index-A calculations, IMO Resolution A.265(VIII), [5]

- ❖ Index-A calculations, IMO Draft Harmonised Regulations (SLF-42), [6]
- ❖ Index-A calculations, Nordic Project probabilistic framework with water on deck, [7]

Standards in each group are assumed to ensure an "equivalent" level of safety, correspondingly, whilst a summary of the only serious attempt to demonstrate such equivalence among instruments of the first two groups was reported in [8]. The methodology adopted there considers performance-based standards as derived from model experiments and numerical simulations to form a basis against which all other instruments are compared.

When it comes, however, to direct comparisons between deterministic and probabilistically regulations there is an added complication concerning difficulties in finding a common ground. For example, whilst the first deals with prescribed damages, the second deals with the whole range of possible damage scenarios. Notwithstanding this, it is simply amazing that in the 27 years since the introduction of the probabilistic regulations for subdivision and stability of passenger ships as an equivalent to Part B of Chapter II of SOLAS '74, no reported evidence exists of any attempt to establish quantitatively a relationship between probabilistic and deterministic instruments. This paper claims a first in attempting to provide meaningful comparisons for elucidating, for example, what level of the Attained Index A for a given ship would ensure the same level of damage survivability as that deriving from SOLAS considerations.

2. COMPARATIVE ASSESMENT METHODOLOGY

The search in establishing the meaning of the Attained Index and its equivalence to SOLAS standards (in this case SOLAS '90 two-compartment standards) could again be dealt best by considering the results derived in the pursuit of compliance with performance-based standards [8] as the common platform for a rational comparative assessment of the vessel's level of safety derived by what are considered to be equivalent routes. In this respect, the following are noteworthy:

(a) The KG limiting curve derived on the basis of SOLAS '90 two-compartment standards is taken as the basis for KG values to be used in all calculations. In this respect, the worst SOLAS damage is considered as the reference case.

(b) The limiting survival sea state (Hs) is taken from model experiments corrected as necessary (linear interpolation) to account for differences between actual and limiting KG values.

2.1 Test Matrix

A sample of 16 Ro-Ro vessels is considered all complying marginally with SOLAS '90 two-compartment standards. These vessels were selected to form a representative sample of the EU passenger/Ro-Ro fleet considering size, type and compartmentation thus allowing for meaningful comparison and a critical evaluation of emerging trends concerning the level of safety provided by the current damaged survivability assessment methods.

2.2 Wave Environment

The wave environment used in the numerical simulations and physical model tests is representative of the North Sea and is modelled by using JONSWAP spectra as shown in the table below.

Table 1: Sea States (JONSWAP Spectrum with $\gamma = 3.3$)

Significant Wave Height H_s [m]	Peak Period T_p [sec]	Zero-crossing Period T_0 [sec]
1.0	4.00	3.13
2.0	5.66	4.42
2.5	6.33	4.95
3.0	6.93	5.42
4.0	8.00	6.25
5.0	8.95	7.00

$H_s/L_P = 0.04$ ($L_P= 0.25H_s$); $T_P = (2\pi\ L_P/g)^{1/2}$ ($T_P = 4H_s^{1/2}$); $T_0 = T_P/1.279$

2.3 Deterministic Regulations

SOLAS '90 REGULATIONS

According to SOLAS '90 the following criteria must be met at the final equilibrium condition after damage:

- ❖ A minimum range of 15 degrees beyond the angle of equilibrium, which should not exceed 12 degrees for two-compartment flooding and 7 degrees for one compartment flooding.
- ❖ A minimum area of 0.015m.rad under the residual GZ curve.
- ❖ A minimum residual GM of 0.05m with a maximum GZ of at least 0.10m, increased as necessary to meet certain stipulated heeling moments due to wind heeling, passenger crowding and lifeboat launching.

As indicated in the foregoing, the worst SOLAS damage is chosen by considering minimum stability entities, namely minimum GZmax.

STOCKHOLM AGREEMENT

The Stockholm Agreement requirements demand that a vessel satisfies SOLAS '90 criteria (allowing only for minor relaxation) with, in addition water on deck by considering a constant height, calculated according to Figure 1, depending on the vessel's residual freeboard ad the operational sea state (H_s). In this study the limiting sea state is calculated by increasing the significant wave height until marginal compliance is achieved.

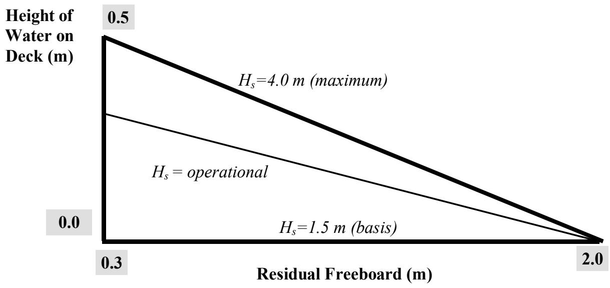

Figure 1: Stockholm Agreement

2.4 Performance-Based Standards

The standards considered under this heading pertain to assessing a given ship in a given damage scenario and operational environment on the basis of her performance (floatability, stability, capsizal resistance, dynamic behaviour) by means of physical or numerical testing. In this respect, considering the uncertainties associated with the problem in question, this route requires invariably the definition of critical damage scenarios to be tested in representative (critical) operational environments as a means of achieving a quantitative representation of a level of safety to be used for comparison purposes. Following this line of thinking, the Model Test Method of SOLAS '95 Resolution 14, [4], was recommended by the IMO Panel of Experts as the "Equivalent" route for compliance with the Stockholm Agreement requirements. Figure 2 below depicts the experimental set-up.

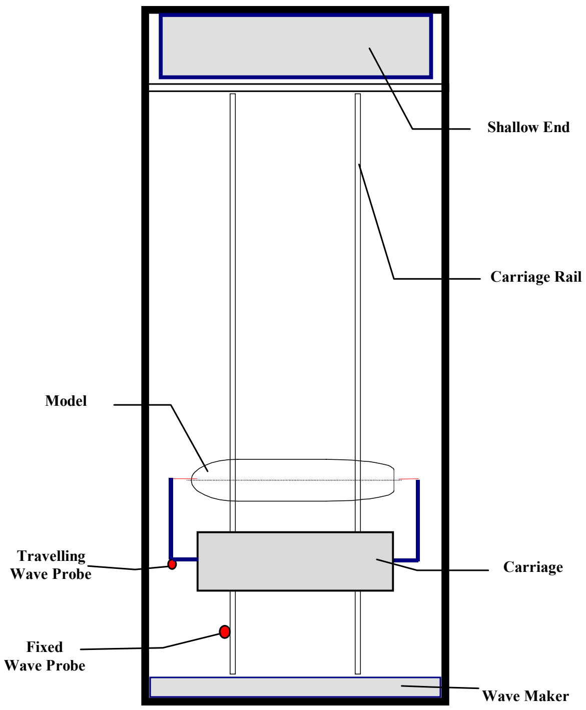

Figure 2: The Model Test method – Experimental Set-up

The Model Test Method comprises testing a ship model in two (typically worst SOLAS and midship) damages and in two sea states of JONSWAP spectral formulation of $4(H_s)^{1/2}$ and $6(H_s)^{1/2}$ peak periods, each test repeated 5 times, thus resulting in 20 tests, survival of which implies compliance with the Stockholm Agreement requirements. The same procedure could be used by either physical or numerical experiments (following exactly the same set-up and procedure) to identify the limiting H_s a vessel could survive and use this as a measure of her safety (damage survivability) or performance-based standard. Following this route, SSRC has completed some 65 physical model test approvals for passenger Ro-Ro vessels operating in northern Europe and some 80 vessels by numerical simulations, thus having available a unique database of performance-related measures of Ro-Ro vessels, including damage survivability boundaries (these are normally given in the form of a band denoting the upper – 100% capsize – and lower – 0% capsize – limits of capsizal resistance) that could be used for comparative assessment as well as in support of derivation of performance-base survival criteria.

2.5 Probabilistic Procedures

The first probabilistic damage stability rules for passenger vessels, deriving from the work of Kurt Wendel on "Subdivision of Ships", [9] were introduced in the late sixties as an alternative to the deterministic requirements of SOLAS '60. Subsequently and at about the same time as the 1974 SOLAS Convention was introduced, the International Maritime Organisation (IMO), published Resolution A.265 (VIII). These regulations used a probabilistic approach to assessing damage location and extent drawing upon statistical data to derive estimates for the likelihood of particular damage cases. The method consists of the calculation of an *Attained Index of Subdivision*, A ($A = \Sigma p_i s_i$, where p_i= probability that this compartment or combination of compartments are being flooded and s_i= probability that the vessel will survive flooding of that (or those) compartments), for the ship which must be greater than or equal to a *Required Subdivision Index*, R, which is a function of ship length, passenger/crew numbers and lifeboat capacity. Index R sets the required safety level, whilst Index A provides a measure of the safety level.

The next major step in the development of stability standards came in 1992 with the introduction of SOLAS part B-1 (Chapter II-1), containing a probabilistic standard for cargo vessels, using the same principles embodied in the aforementioned regulations. The same principle is also the basis for the current IMO regulatory development of "Harmonisation of Damage Stability Provisions in SOLAS based on the Probabilistic Concept of Survival".

An important addition to the probabilistic procedures, particularly for Ro-Ro vessels, was developed during the Nordic Project [7], culminating to a proposal of a framework for new probabilistic damage stability standards, similar to IMO Resolution A.265 and SOLAS Part B-1.

IMO RESOLUTION A.265 (VIII)

The original method of calculating factor *s* was developed by adopting an experimental approach aiming to establish a simplified relationship between environmental and stability-related parameters for a damaged ship and hence determine capsizal resistance in a given sea. On the basis of limited model tests carried out separately in the United Kingdom, [10] and the USA, [11] such a relationship was established, expressed in the form:

$$(H_s)_{critical} = f(GM_f*F_e/B)$$

where, $(H_s)_{critical}$ ⇒ critical significant wave height (characterising a limiting sea state)
GM_f ⇒ flooded metacentric height
F_e ⇒ effective freeboard
B ⇒ beam of the vessel

Deriving from the above, the probability that a ship with a given value of the stability parameter (GM_f*F_e/B) will survive damage in a given sea state will be equal to the probability of not exceeding $(H_s)_{critical}$. The formulation given in A.265 (VIII) is:

$$s = k * \sqrt{\frac{Fe * GM_f}{B}}$$

DRAFT HARMONISED REGULATIONS

The approach adopted by the Draft Harmonised Regulations of SLF 42 for calculating factor *s* is to use residual GZ curve parameters similar to cargo ship regulations of SOLAS part B-1 (in Chapter II-1). However, water accumulation on deck is not taken directly into account, which is a major deficiency, particularly for Ro-Ro vessels following large scale flooding.

$$s_i = c \cdot \sqrt[4]{\left(\frac{GZ_{max}}{TGZ_{max}}\right)\left(\frac{Range}{TRange}\right)\left(\frac{Area}{TArea}\right)}$$

C Static heeling coefficient,
GZ_{max} Maximum GZ at final equilibrium,
TGZ_{max} Target value of GZ_{max},
Range Positive stability range,
Trange Target value of positve stability range,
Area Area under positive stability,
Tarea Target value of positive area

NORDIC PROJECT PROBABILISTIC FRAMEWORK

In addition to the effects considered in the above regulations, effects like water on deck and cargo shift have been included. The framework also addresses damage stability modelling, in particular standards for intermediate stages of flooding and cross flooding. The proposed method of calculating the subdivision index follows the basic methodology and principles of the harmonisation work in IMO with two major changes:

- Vertical extent of damage (v-factor) based on results from collision simulations
- Probability of survival (factor *s*), in order to include effect of water on deck, cargo shift and progressive flooding.

The latter, in particular is expressed as a combination of two factors, as explained next:

$s_i = s_{a*} s_w$, where

s_a = probability to survive pure loss of stability, heeling moments, cargo shift, angle of heel and progressive flooding. As per IMO recommendations $s_a = C \cdot F \cdot K \cdot (GZ_{max*} \cdot range_* area)^{1/4}$

s_w = probability to survive water on deck as result of wave action. This can be calculated directly from the wave height distribution, again based upon the critical wave height.

3. SAFETY EQUIVALENCE

Deriving from the foregoing considerations and using the sample of 16 marginal SOLAS '90 two-compartment standard vessels from the SSRC database for which the survival H_s limits have been established experimentally, limiting H_s values were also determined according to Stockholm Agreement and through numerical simulations. In addition the Attained Index of Subdivision has been calculated for all 16 vessels using the three methods of calculation outlined in the foregoing. The results are summarised in Table 2 and Figures 3 and 4 for ease of comparison and discussion purposes.

Table 2: Relative Measures of Safety

Limiting Hs [m]				Attained Index A		
Model Test	Operational Limits	Numerical Simulation	Stockholm Agreement	A.265 (VIII)	SLF 42	NORDIC PROJECT
3.23	1.90	3.08	2.00	0.824	0.830	0.776
4.40	4.00	4.38		0.650	0.839	0.832
3.02	2.60	3.14		0.645	0.685	0.658
3.80	3.40	3.42		0.647	0.742	0.627
3.89	3.40	3.52	2.43	0.612	0.857	

3.47	3.40	3.59	4.06	0.512	0.656	
3.07	3.40	3.14	2.17	0.554	0.738	
2.82	2.50			0.763	0.757	0.756
2.91	2.80	2.82	1.60	0.674	0.816	
3.86	3.40	3.83	2.90	0.695	0.868	0.745
3.45	3.00	3.08	2.27	0.737	0.785	0.785
3.49	2.50	3.32	1.60	0.721	0.832	
3.97	3.00	3.30	1.79	0.577	0.837	
4.00	3.40	3.63		0.621	0.795	0.792
4.25	3.00	3.61	1.92	0.613	0.814	
3.03	2.50	2.86	1.77	0.696	0.891	0.852

Based on the derived results, the following points are noteworthy:

- The agreement between the numerical and experimental results, particularly in the range of relevant sea states is very good. This suggests that, numerical tools have reached a stage where survivability boundaries can be successfully predicted and hence performance-based assessment of safety levels be confidently undertaken.
- Ships satisfying SOLAS '90 two-compartment standards (even marginally) appear to survive sea states with H_s over approximately 3m. This result is rather encouraging considering that SOLAS '90 is the global standard for passenger/Ro-Ro ferries.
- The safety level inherent in the Stockholm Agreement calculation method is considerably higher than the level determined through performance-based methods, typically, by 1.25m on average.
- Lack of consideration of water on deck renders A.265 unsuitable for application to passenger/Ro-Ro vessels, as demonstrated by the results (magnitude and trend) presented in Figure 4.
- Both the Draft Harmonised Regulations and Nordic Project framework lead to comparable results, mainly because they both allow directly (Nordic Project) or indirectly (SLF 42) the effect of water on deck. Interestingly, the results show that the level of safety, as represented by Index A, would be higher when water on deck is taken into account explicitly.
- Finally, the 27 year old question could now be answered: for a SOLAS '90 two-compartment standard vessel to survive on the average 3.5m, the average value of Index A (Nordic Project) ought to be 0.75.

4. CONLUDING REMARKS

In the wake of resent marine disasters, number of new instruments for assessing damage survivability have been proposed/adopted, whilst efforts are still ongoing to establish acceptable harmonised damage stability calculations based on probabilistic approaches and on performance-based assessments. It would appear that the latter are here to stay, thus providing added motivation for development in this direction as well as efforts to understand the relative measure of safety provided by each method. This will, in turn promote better understanding of the emerging principle "Equivalent Level of Safety" and facilitate its adoption in the immediate and long term, as a more efficient route to achieving higher safety standards by utilising state-of-the-art knowledge to the full.

5. REFERENCES

[1] IMO Resolution MSC.12 (56) (Annex), "Amendments to the International Convention for the Safety of Life at Sea, 1974: Chapter II-1 – Regulation 8", adopted on 28 October 1988.

[2] IMO Resolution 14, "Regional Agreements on Specific Stability Requirements for Ro-Ro Passenger Ships" – (Annex: Stability Requirements Pertaining to the Agreement), adopted on 29 November 1995.

[3] Vassalos, D, Pawlowski, M and Turan, O, "A Theoretical Investigation on the Capsizal Resistance of Passenger/Ro-Ro Vessels and Proposal of Survival Criteria", Final Report, The Joint North West European Project, University of Strathclyde, Department of Ship and Marine Technology, March 1996.

[4] IMO Resolution 14, "Regional Agreements on Specific Stability Requirements for Ro-Ro Passenger Ships" – (Appendix: Model test method), adopted on 29 November 1995.

[5] IMO Resolution A.265 (VIII), A.266 (VIII), and explanatory notes, 'Regulation on Subdivision and Stability of Passenger Ships (an Equivalent to part B of Chapter II of the 1974 SOLAS Convention)', IMO, London, 1974.

[6] IMO, SDS Working Group,' Development of Revised SOLAS Chapter II-1 Parts A, B and B-1', SLF 42/3,London, 1998.

[7] RUSAAS, S., JOST, A.E.E. AND FRANCOIS, C.: "*Framework for a New Stability Standard*", Final Report, Task 6, The Joint North West European R&D Project, 1996.

[8] Vassalos, D: "Comparative Levels of Safety Achieved by the Stockholm Agreement and SOLAS '95 Regulations", 4th NORDCOMPASS Seminar on 'Ferries and Passenger Ships', Copenhagen, Denmark, February 1998.

[9] Wendel, K, "Subdivision of Ships", Diamond Jubilee International Meeting, New York, June 1968, pp 12-1 to 12-21.

[10] Bird, H. and Browne, R P: "*Damage Stability Model Experiments*", Trans. RINA, Vol. 116, 1974, pp. 69-91; also in: The N. Architect, October 1974, ibid.

[11] Middleton, E H. and Numata, E: "*Tests of a Damaged Stability Model in Waves*", SNAME Spring Meeting, April 1970, Washington DC, paper No. 7.

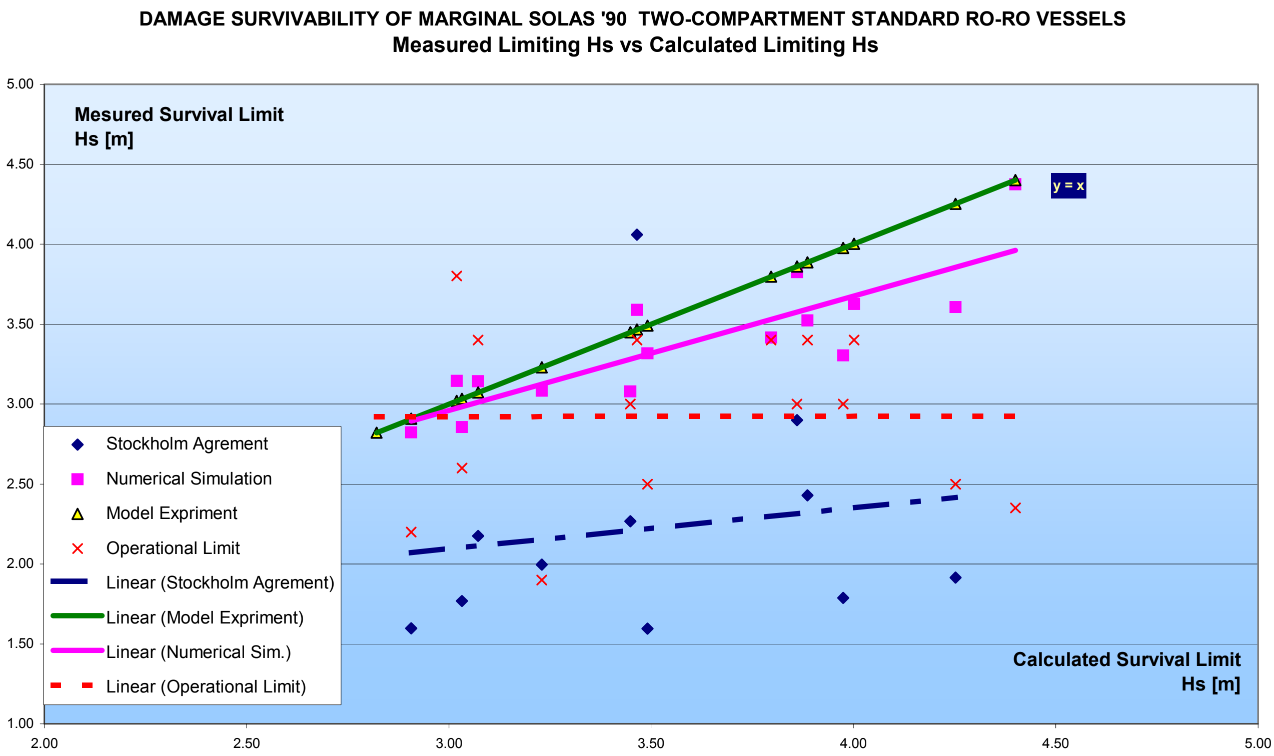

Figure 2: Performance based comparison.

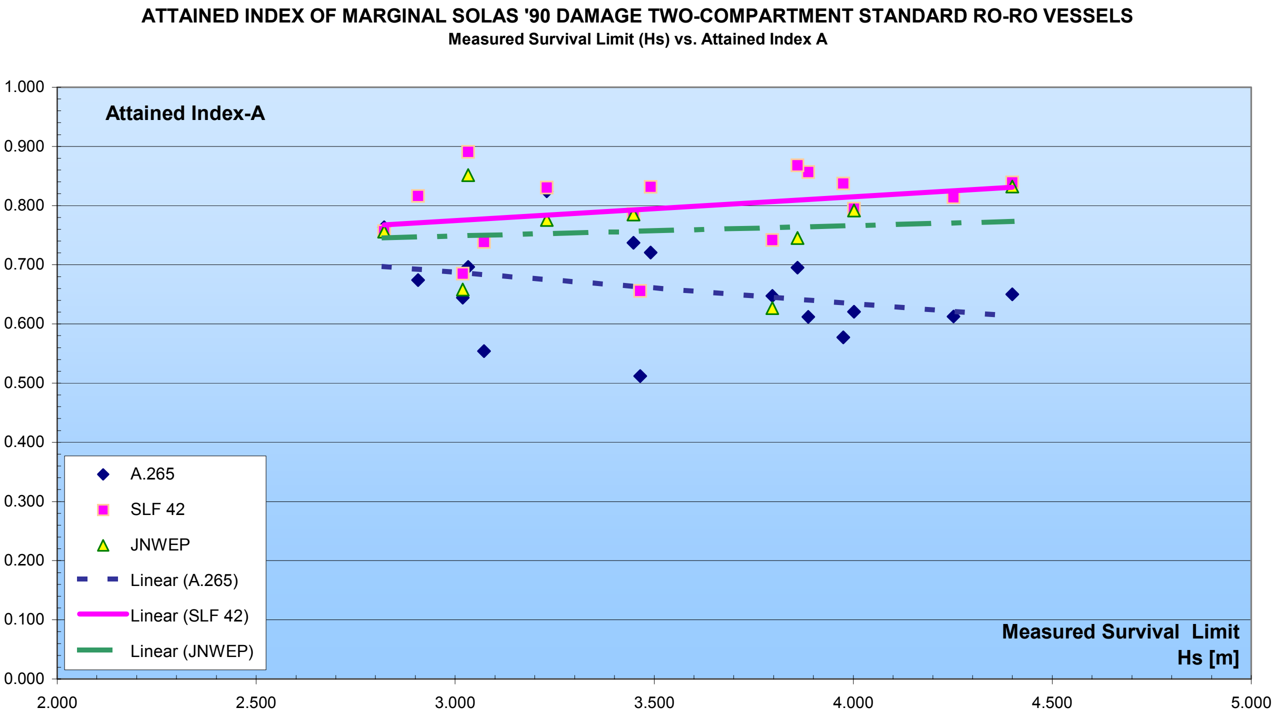

Figure 3: Comparison of Attained Index A for Current Probabilistic Instruments