Aviation erosion of the rudder has been a serious problem in the high-speed container ship industry. It is well known that the lifetime of a conventional coating system is about six months against cavitation bubble collapse. Although STS 316L stainless steel has been applied to prevent the problem, there are several drawbacks with that method such as high repair cost and poor workability, which necessitated the development of a cavitation-resistant, low-cost coating system with workability.

Metal substrate erosion by cavitation occurs at the ship’s rudder because of high-speed sailing and supersizing and has affected large container carriers operating at speeds over 20-knots. Cavitation can cause erosion and corrosion on the edge of the propeller and damage the coated surfaces of the rudder. When damaged by cavitation erosion, the rudder vibrates badly during sailing and the direction of the ship becomes difficult to control. In the worst cases, a ship will become non-operational and thus, cavitation erosion is one of the major factors in determining the rudder’s lifetime.

The cavitation erosion problem hasn’t been solved yet, although numerous studies have been performed on this issue. In this study, a series of cavitation-resistance tests were conducted with laboratory-scale test apparatus to simulate the actual cavitation and erosion phenomena. Selected test methods that could
properly simulate the cavitation behavior and reasonably classify cavitation and erosion resistance grade of the candidate materials were identified.

Cavitation Mechanism
There are two theories that explain cavitation: the micro jet and the shock wave theory. The micro jet theory suggests that a liquid jet is generated very fast by the asymmetrical collapse of cavitation bubbles. The jet crushes the surface of a metal substrate and creates damage such as a crack or erosion. This theory has been documented by using high-speed photography and various studies about the cavity collapse. It is the dominant damage mechanism on the initial collapse of a cavity.

Secondly, the shock wave theory proposes that the shock wave is created by the rapid movement of the interface between a cavity and liquid. In his book, Cavitation and Bubble Dynamics, Christopher Earls Brennen maintains that it causes fatigue and plastic deformation on the surface of a material. A cavity’s explosive power can measure about 10,000 atmosphere of pressure (atm) and this power can causes a noise, vibration and plastic deformation, and a ship’s rudder will suffer from repetitive pressure wave impact. That collapse pressure causes damage to protective coatings on rudders and as a result, the corrosion of a rudder’s surface can be accelerated by exposure to seawater.

Specimen Preparation and Test Methods
Specimen Preparation
Two types of conventional coating systems and three types of cavitation-resistant coating systems were prepared as shown in Table 1 (p. 40). In the case of coating system A, a self-polishing copolymer (SPC) anti-fouling paint was applied to an epoxy primer and tie coat. Coating B was an anticorrosion epoxy paint. Coatings C and D were commercial products for cavitation-resistant coatings consisting of an unsaturated polyester resin with glass flake. Coating E was an unsaturated polyester resin type with four layers of carbon sheets. The film thickness of the coatings tested was based on the recommendation of each manufacturer.

Test Methods
Cavitation erosion-resistance tests were performed according to ASTM G32, “Standard Test Method for Cavitation Erosion Using Vibratory Apparatus,” and ASTM G134, “Standard Test Method for Erosion of Solid Materials by Cavitating Liquid Jet.” Figure 1 (p. 40) shows the test apparatus configurations. The mass losses of the test specimens were evaluated using a precision balance with an accuracy of 0.0001 grams. Prior to the measurements, the test specimens were dried in an oven at 80 C. The test was run until the coating was eroded to the metal surface; measurements were performed at

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10-minute intervals. The mean depth of erosion (MDE) in microns, for each sample after each 10-minute exposure was calculated as follows:

\[ \text{MDE} = \frac{\Delta W}{10 \rho A} \]

Where \( \Delta W \) is weight loss in mg/\( \Delta t \), \( \rho \) is specific gravity of dry film, \( A \) is surface area of specimen (cm²).

The cumulative mean depth of erosion (CMDE) was calculated from the slope of MDE-time curve.

The time to come to CDME 50 (the time taken to reduce the coating to 50 μm) was calculated from the slope of CMDE-time curve and the time to erode to the metal surface was also calculated to evaluate the erosion resistance. Optical microscopy was used to help determine the mechanism of the erosion and interpret the results of the cavitation tests.

### Results and Discussion

#### Vibratory Apparatus Test (ASTM G32)

The antifouling coating of system A was eroded in 10 minutes by cavity collapse due to its low abrasion resistance and the hydrolysis reaction in water. System A was eroded to the metal surface in 40 minutes and coating B was eroded to the metal surface in 50 minutes. Coating C was eroded to the metal surface after 220 minutes and had the best performance compared to the other test specimens.

Cavitation-resistant coatings C and D had a high erosion rate in the initial stage because the resin was mainly being eroded, but the erosion rate decreased as the glass flake, having high durability, became gradually exposed on the surface. Coatings C and D are the same generically, but performed differently most likely due to differentiation in the manufacturers’ selection of resin monomers and pigments such as glass flake, extender or filler.

The carbon fiber sheet was less effective than the glass flake because coating E was eroded up to the metal surface after 130 minutes, but coating E showed the best performance as far as time to CDME 50 (t50). Although t50 is an important index showing the erosion resistance, it is considered in this study to be more important for excellent performance to measure the time to erode to the metal surface. As a result of the vibratory apparatus test method, coating C, consisting of unsaturated polyester with glass flake, had the best cavitation erosion resistance compared to other candidate coatings.

#### Cavitating Liquid Jet Test (ASTM G134)

The result of the erosion test by cavitating liquid jet showed similarity to the test results from the vibratory apparatus test. Coating A was eroded to the metal surface after 70 minutes but the anti-fouling coating was completely eroded after only 10 minutes.

In the case of coatings C and D, erosion time to the metal surface was 150 and 40 minutes, respectively. Coating E was eroded after 170 minutes and time to CDME 50 (t50) was 59 minutes. This means that coating E showed the best performance against high-speed water flow, including the cavity. From these results it was concluded that coating E, containing four layered-carbon sheets, had the best cavitation erosion resistance compared to the other coatings tested.
Conclusion
A comparison of the vibratory test (ASTM G32) and the cavitating liquid jet test (ASTM G134) is shown in Table 2. The vibratory apparatus test method proved to be more suitable in evaluating the erosion resistance of organic coatings compared to the cavitating liquid jet test method because it had better reproducibility and sensitivity, as well as uniform surface erosion characteristics by cavity contact.

It was therefore concluded that the best coating for cavitation erosion resistance was an unsaturated polyester with glass flake pigmentation.

About the Authors
Hee-Baek Lee is a researcher in the protective coatings research department of Hyundai Heavy Industries Co., Ltd. He earned his Master of Science degree in polymer synthesis from the University of Ulsan in Korea. Lee's specific focus is the optimization of painting processes related to ships and construction equipment.

Chung-Seo Park is a head researcher and team leader in the protective coatings research department of Hyundai Heavy Industries Co., Ltd. He has almost 15 years of experience in the research and development of protective coating materials used in the marine and oil and gas industries. Park received his Master of Science degree in industrial chemical engineering from Pukyung National University in Korea. He is a NACE-certified Coating Inspector, Level 2.

Seong-Mo Son is a senior researcher in the protective coatings research department of Hyundai Heavy Industries Co., Ltd. He has been involved in coating analysis and feasibility testing since 2006. Son earned a Master's degree in chemistry from Dong-A University. He is currently responsible for anti-fouling coating performance of ship hulls and passive fire protection for offshore projects.

Kyung-Jin Park is a material researcher at Hyundai Heavy Industries Co., Ltd. She earned her doctoral degree in materials science and engineering from Korea Advance Institute of Science and Technology. Park's research field is corrosion engineering and material selection for oil and gas plants.

Sang-Sik Park is a block painting manager for the shipbuilding division of Hyundai Heavy Industries Co., Ltd. He has been involved in block painting production of commercial vessels, drillships and offshore projects for 10 years. Park earned a Bachelor's degree in chemistry from Kyungpook National University. He is currently responsible for block painting production of semi-submersible drilling rig projects.