

# MANAGING SHOCK REQUIREMENTS OF SHIPBOARD EQUIPMENT

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## ABSTRACT

Shock, in layman's term, is generally understood as a sudden and violent blow or impact. It is characterised as a dynamic disturbance with a short duration compared to the natural frequency of the affected equipment. Equipment subjected to shock beyond its fragility level can fail structurally and functionally. Generally, the extent of these undesirable effects increases with both the shock magnitude and duration. These effects can also be increased when the shock pulse frequency coincides with the affected equipment's natural frequency.

The management of shock requirement for equipment to be installed on board the Republic of Singapore Navy's ships is a constant challenge. Specifically, the equipment needs to be able to withstand the relatively infrequent, non-repetitive shocks experienced in handling, transportation and service environments. This challenge is made more acute considering the increasing use of commercial-off-the-shelf components as well as the installation of the same equipment across different classes of ships.

This article provides a brief introduction to shock specifications and requirements of shipboard equipment. The reader is then guided through aspects of shock management, such as shock isolation and qualification, followed by a short overview of some of the common international standards regarding shock specifications and qualifications.

*Keywords:* naval shock design, shipboard equipment, shock qualification, shock response spectrum, underwater explosion

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## INTRODUCTION

Naval vessels and the equipment on board such vessels are generally required to withstand and survive shocks. The most severe shocks that a naval vessel needs to withstand are usually those related to an underwater explosion (UNDEX), where explosives are detonated in the waters surrounding the vessel.

UNDEX generate shock waves that strike the hull of the naval vessel. The shock energy that is transmitted via the ship structure to the various locations on board the ship has the potential to damage equipment installed at these locations. Equipment damage usually occurs when the transmitted shock exceeds its design specifications. Forms of damage

include malfunction of electronic components within the equipment, mechanical deformation or collapse of the affected equipment and general interference between equipment due to misalignment or breakage from its mountings.

As such, the adequacy of the equipment design against shock is an important consideration during the acquisition of equipment to be installed and operated on board naval vessels. This is an aspect of equipment acquisition that is actively managed by DSTA engineers.

Through the numerous naval programmes managed by DSTA, the project teams have not only acquired an understanding of the international practices with respect to equipment design against UNDEX, but have also successfully tailored such practices to meet project needs.

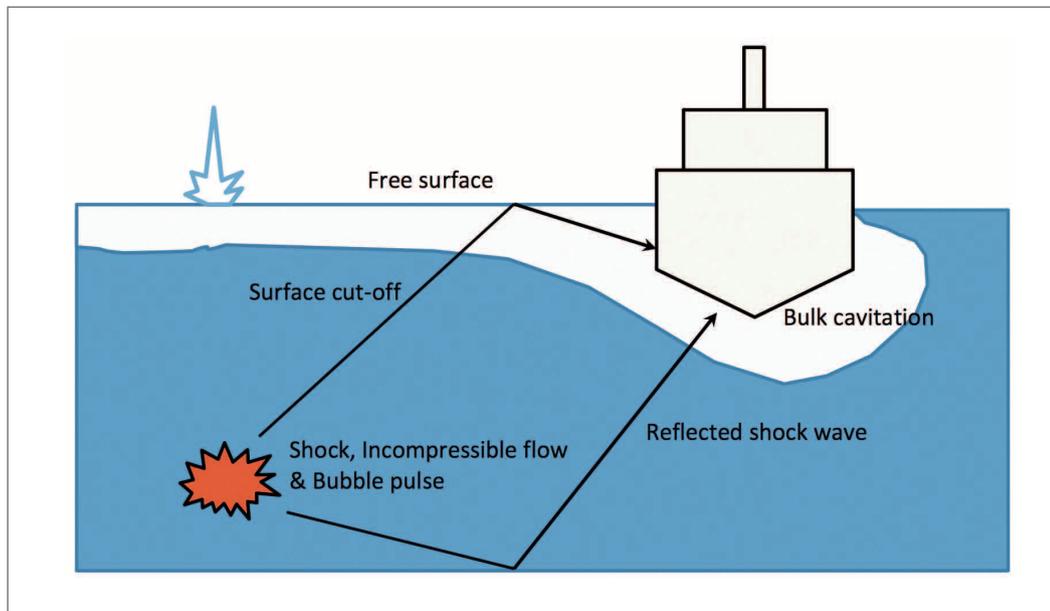


Figure 1. Probable shock loads on surface ship during UNDEX

## OVERVIEW OF UNDERWATER EXPLOSION

The phenomenon of UNDEX is well defined in numerous studies (Scavuzzo & Henry, 2000). In the initial phase of an UNDEX, a spherical shock wave propagates outwards from the detonation centre while a superheated gas bubble forms in the detonation centre. An instantaneous rise to peak pressure followed by an exponential decay to hydrostatic pressure is a characteristic of the shock wave pressure plot. Shock waves reflected off the seabed may contribute to the overall shock wave loading at the ship's hull should it be in phase with the spherical shock wave. This phenomenon is illustrated in Figure 1. Bulk cavitation is caused by the reflection of shock waves at the free surface (air/water interface) and the low capacity of water to withstand high tension levels. The cavitation region is observed as a circular, whitening region prior to a venting of the water column and it extends in a radial direction from the centre of the explosion. The closure of the cavitation region exerts additional shock loading on the ship's hull.

The gas bubble exerts high pressure loads on the ship's hull via incompressible flow as it migrates upwards and expands. The bubble then contracts due to hydrostatic pressure from the surrounding depths. Its internal pressure subsequently initiates a second cycle of expansion and contraction. This continues until the bubble energy<sup>1</sup> is dissipated or the bubble breaks through the water surface as a venting of water column and debris. The flow distribution of the expanding bubble is radial

and can lift the ship hull while the reverse flow of a contracting bubble can cause the hull to sag. The overall effect is amplified when the frequency coincides with the natural frequency of the hull girder. In the event where the bubble is within one bubble radius of the ship, collapse flow in the direction from the ship's hull towards the bubble centre is restricted. This will cause the bubble to collapse onto the hull and produce a water jet capable of breaching it. A general profile of bubble characteristics against time is illustrated in Figure 2.

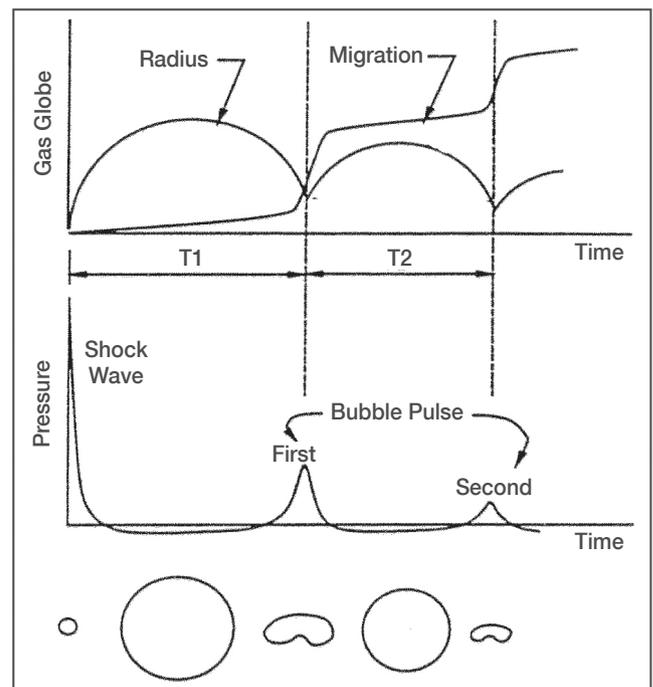


Figure 2. Bubble migration behaviour, pulse and shape with time (Reid, 1996)

# SPECIFICATION OF SHOCK REQUIREMENTS

## Shock Factor

While naval vessels are generally designed to survive and remain operational after exposure to UNDEX, the level or magnitude of UNDEX that a vessel is expected to be subjected to depends on ship type and its mission role. The magnitude of UNDEX that a naval vessel is designed to withstand may be estimated by an explosion energy parameter (shock factor) that relates the explosive quantity and position from the ship. Hull Shock Factor (HSF) is a representation of available energy that a shock wave contains which may damage the hull plating on the ship. Keel Shock Factor (KSF) is relevant when the relative position of the explosive charge and the angle of incidence of the shock wave with respect to the ship are taken into account. A vessel designed to a higher shock factor is able to withstand larger and hence more damaging UNDEX. The mathematical representations of both HSF and KSF are given below and illustrated in Figure 3.

$$HSF = \frac{\sqrt{W}}{R} \qquad KSF = \frac{\sqrt{W}}{R} \times \frac{(1 + \cos \theta)}{2}$$

- where W is the mass of explosive in trinitrotoluene (TNT) equivalence (kg)
- R is the stand-off distance between the charge and the target
- θ is the angle between a vertical line and diagonal drawn from charge to the ship's keel

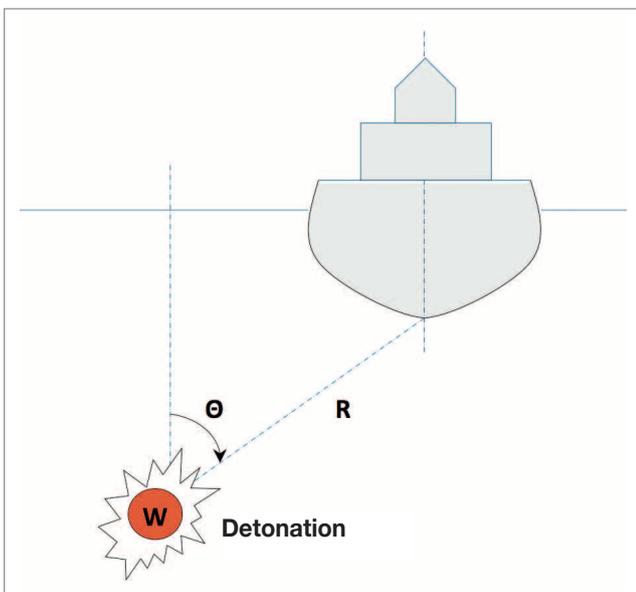


Figure 3. Relative position and distance of charge from ship in HSF and KSF calculations

## Shock Transmission in the Ship Structure

Except for equipment such as sonar arrays that are installed externally below the waterline, the majority of shipboard equipment are located within the vessel or on the superstructure above the waterline and are not directly exposed to the shock energy from UNDEX. Instead, the onboard equipment experience shock energy transmitted via the ship structure. And since shock energy dissipates as it travels through the ship structure, the shock experienced by equipment mounted on the higher decks or the superstructure would be lower than that experienced by those mounted inside the hull or on the lower decks.

As such, in larger ships where the shock energy is transmitted over relatively longer distances, shock levels can vary significantly between the lower decks and the upper decks. On such larger ships, the ship is frequently divided into zones and equipment installed within each zone will need to withstand a different level of shock. Equipment in the zone closest to the bottom of the ship is expected to experience the highest levels of shock. Shock level reduces from each zone to the next, moving up the ship structure. For a smaller ship where the attenuation by the ship structure is less pronounced, the entire ship may fall into a single zone for the purpose of managing equipment design against shock.

The concept of dividing the ship into zones is stated explicitly in both the German and British standards. An example of this is illustrated in Figure 4. Shock levels applicable to equipment are determined considering the equipment's installation location and orientation with respect to the ship.

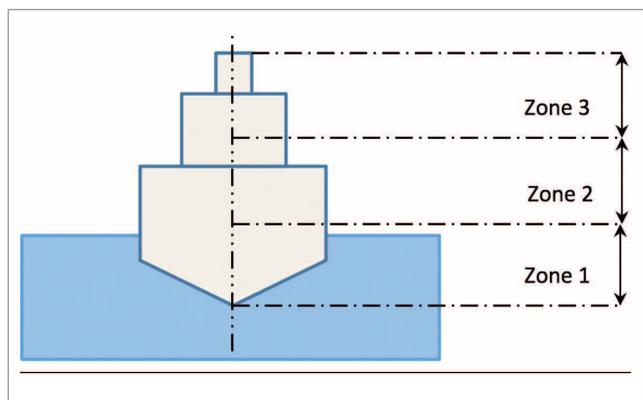


Figure 4. Example of ship shock zone variations across ship structure

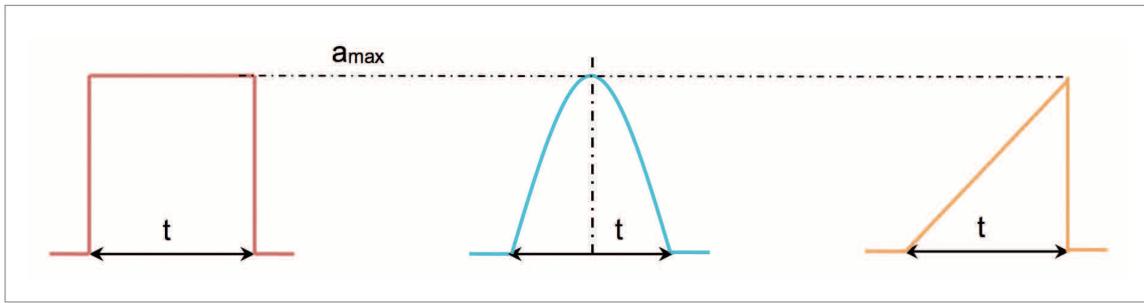


Figure 5. Examples of ideal shock pulse shapes (Left to right: Square, Half-sine and Terminal Peak Saw tooth)

For a given shock factor, the design of the ship is a significant determining factor of the shock levels seen by equipment at the various zones. The most appropriate way to derive the shock levels will be through analysis and whole ship shock test done by the ship builder. Over-reliance on generic shock specifications increases the risk of inadequate design.

### Representation of Shock Specifications

The shock requirement for shipboard equipment is most often specified as classical shock pulses or as a Shock Response Spectra (SRS). Some typical classical shock pulses are shown in Figure 5. The half-sine shock is most commonly used for the testing or qualification purposes of naval equipment.

Where the shock levels are derived through shock testing, the requirement will most likely be provided in the form of an SRS as described above. Shock Response Spectra can be viewed as a collection of the maximum absolute responses of a set of damped single-degree-of-freedom systems with negligible mass (as compared to the base input) to a time history base

input. Hence, it can be used as an indicator with regard to the damage potential due to a given shock input as the envelope of the spectrum establishes an upper bound of the shock load experienced by the item. One common form of presentation is in terms of peak acceleration response against natural frequency. The other medium of presentation is through the four-coordinate graph as illustrated in Figure 6. The displacement, velocity and acceleration response against natural frequency<sup>3</sup> are presented collectively in a single graph.

While classical shock pulse and SRS can be used to specify shock requirements, designers may have a preference to work with one or the other. The conversion of a classical shock pulse in time domain to its equivalent SRS in frequency domain can be mathematically tedious as it involves the solution of multiple second order differential equations. Clough and Penzien (1975) recognised that the SRS for each classical shock pulse has a characteristic shape, which is skewed by the magnitude and duration of the shock pulse. This observation allowed a simplified approach to determine the equivalent SRS of a classical shock pulse to be derived.

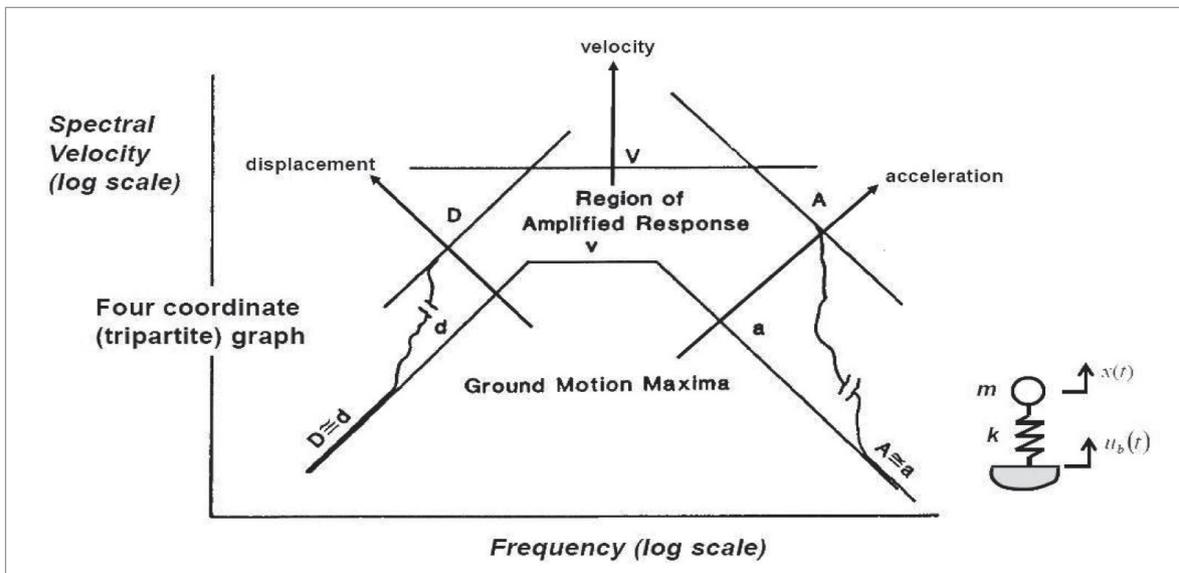


Figure 6. Generic representation of a SRS on 4-coordinate graph (USA Information Systems, Inc., 1989)

## Other Shock Requirements

While UNDEX is considered a rather stringent design requirement for shock and much engineering effort is often expanded to address it, there are other categories of shocks that an equipment may experience over its service life. During requirements definition, the various shock requirements may be addressed as individual shock requirements or as a single requirement that envelops all the individual requirements. In the former, the responsibility to determine the most constraining shock requirement or requirements falls on the equipment designer.

Viewed from another perspective, the UNDEX requirement is almost certain to be the most constraining shock design requirement for equipment that are permanently installed on a naval vessel. It would generally suffice that engineering teams conduct a simple review to confirm this prior to commencing shock design. For equipment that may be frequently disembarked from the naval vessel and deployed elsewhere over its service life, a thorough review of the applicable shock environment is usually carried out.

## DESIGN AGAINST SHOCK

For critical shipboard equipment, there are typically two approaches with regard to equipment protection against shock. One is to install resilient mounts between the equipment and its foundation to attenuate the shock entering the system where feasible. The other is to harden the equipment that needs to be rigidly mounted due to performance considerations. From experience, these are by far the most common approaches to protecting operational equipment against shock.

However the hardening of rigidly mounted equipment to withstand shock loads generally requires the equipment structure to be strengthened, leading to increased equipment weight. This is a concern in terms of naval platform design. Equipment with shock mounts need only be hardened to withstand the attenuated or residual shock loads. With less stringent equipment hardening requirements, the shock-mounted equipment will be lighter and there will be more opportunities to exploit the high performance of commercial-off-the-shelf (COTS) equipment in naval systems. An added advantage would be that equipment can be easily adapted to ship design to various shock factors by resizing the shock mounts.

For the sizing of shock mounts, several factors need to be considered. The dynamic deflections shall be less than the

maximum allowable deflection of the shock mount selected. Adequate clearance between the shock-mounted equipment and its surroundings must be ensured to prevent obstruction during dynamic deflections. The shock mount selected must also avoid resonance with the ship's excitation frequencies.

Finite Element Analysis (FEA) is often used during the detailed design phase to assist the designer in ensuring that the equipment design meets the shock requirements. FEA provides a modelling and simulation environment where the stress and the dynamic response of the equipment under shock can be determined and assessed even before any equipment is manufactured.

## SHOCK QUALIFICATION

Besides requirements definition, qualification is another important aspect of shock management. Shock qualification provides the technical evidence that the equipment design has fulfilled the requirements for design against shock.

The qualification can be achieved through testing, analysis or similarity. The decision hinges on the availability of qualification data, cost and, to a lesser extent, the project schedule. Analysis and testing can be synthesised; where testing cannot be carried out, analysis is used for inference. For developmental equipment, both approaches of qualification by testing and analysis have been applied.

Qualification is done to ensure that the equipment is able to withstand the effects of a predetermined shock input from handling, transportation and service environments while maintaining its functional performance as well as to ensure that the equipment remains attached to the shock isolator. An assessment of the overall equipment must also be made to ensure safety for the tested environments such as ensuring equipment structural integrity is retained and that it remains attached to its fixtures. For shock testing, tests may be carried out at equipment sub-assembly or component level if the equipment is too voluminous or heavy for the test machine. The input shock level must then be sized to the expected attenuated shock that the sub-assembly or component would experience to account for shock attenuation as the shock wave transverses through the whole equipment. A main drawback of testing is that it incurs higher costs in comparison to other qualification means. Hence, provisions are generally made to accept results of previous shock tests for the shipboard equipment provided these are assessed to be adequate.

This is particularly applicable for new equipment which is identical or similar to previously shock-tested and accepted equipment. In the event that differences exist between the new and previously tested equipment, the new equipment must be shown to possess equal or greater shock resistance for this means of qualification to be viable. In addition, the shipboard mounting location, orientation and dynamic characteristics for the new item must not be more severe in terms of shock loads than that of the original shock test.

## SHOCK QUALIFICATION STANDARDS

While the shock specifications are generally tailored to specific ship and specific threats, shock qualification is usually governed by standards to ensure consistency in the level of assurance. Table 1 presents a summary of the different international shock standards and standards for shock qualification testing.

There are several established shock standards in use by various countries for shock qualification of equipment pertaining to naval applications. The US military standards are most readily available and are available to the public at no cost. The European military standards and commercial standards are generally proprietary. The former are only available via government channels, while the latter need to be purchased from the issuing bodies.

With the exception of MIL-S-901, the shock qualification standards generally seek to subject the equipment to the required shock and to determine if the equipment can retain its

specified performance. When tested based on these standards, the equipment is subjected to the required shock generated by a shock table which in turn is driven by an electro-dynamic shaker or a hammer.

MIL-S-901 is unique in that depending on the weight of the equipment, it is tested on a specified shock machine or floating barge. As instrumentation of the test level is not mandatory, the test level and the level expected to be seen by the equipment in-service is not directly correlated. This is the US Navy de facto shock test standard for naval equipment. It can be speculated that the generic testing requirements ensures that a single qualification exercise can make certain that the equipment is adequate for installation on board most if not all classes of naval vessels in the US Navy fleet. Nevertheless, this article holds the view that instrumentation should be applied during MIL-S-901 qualification even though this is not a mandatory requirement.

Besides equipment designed specifically for the US military market, MIL-S-901 is rarely applied. Contractors generally fall back on the standards from their national bodies and where lacking, MIL-STD-810 may be applied.

For the test standards that require testing to the required shock levels, the key difference is in the level of rigour in terms of test repetition. For example, MIL-STD-810, where the default recommended test exposure is three blows per axis per direction, is one of the more rigorous standards.

Origin	Doc ID	Doc No.	Doc Name
International Electrotechnical Commission	EN IEC	60068-2	Environmental testing
Britain	BR Def Stan	3021 8470 00-35	Shock Manual (Metric) Volume 1 Shock and Vibration Manual Environmental Handbook for Defence Material
Germany	BV	043	Shock Resistance Specification for Bundeswehr <sup>4</sup> Ships
United States	MIL-S MIL-STD	901 810	Requirements for shock tests, high-impact shipboard machinery, equipment and systems Environmental Engineering Considerations and Laboratory Tests
France	GAM EG	13	General Environment Testing of Materials

Table 1. Environmental test standards reference table for shock test methods and procedures

## CONCLUSION

In conclusion, the general characteristics of shock and their effects on equipment are briefly discussed in this article, providing readers with a basic understanding on the nature of shock, its characteristics and principles in shock isolation. With an increasing trend in the insertion of COTS components and equipment in military systems, the emphasis is to ensure these COTS equipment are able to withstand the rigours of shock from the handling, transportation and service environments. An intimate understanding of the equipment's dynamic behaviour under these environments can uncover potential problems and verify that applied solutions work as intended in shock isolation work.

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## ENDNOTES

<sup>1</sup> 47% of the total energy released in an UNDEX goes into the pulsation of the gas bubble while the remaining 53% goes into the shock wave.

<sup>2</sup> Another format is via relative displacement. In this case, the acceleration values are derived by multiplying relative displacements by  $\omega_n^2$ , where  $\omega_n$  is the natural frequency in radians per second.

<sup>3</sup> Displacement is plotted at a 45 degree positive diagonal, velocity on the vertical axis, acceleration on the 45 degree negative diagonal and frequency on the horizontal axis.

<sup>4</sup> Bundeswehr is German for 'Federal Defense Force'.

## BIOGRAPHY



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