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Simulation Modeling for Testing of an Undersea Rescue System

CDR Nathan Luther—Master of Systems Analysis Program, Naval Postgraduate School, Monterey, CA

CDR Benjamin Pollock—Master of Systems Analysis Program, Naval Postgraduate School, Monterey, CA

Dashi Singham—PhD, Operations Research Department, Naval Postgraduate School [dsingham@nps.edu]

Abstract

Undersea Rescue Command (URC) can mobilize its people and equipment worldwide to conduct a rescue of personnel from a disabled submarine stranded on the sea floor up to depths of 2000 feet of seawater. In 2019, URC anticipates reaching Initial Operating Capability on a new system, Submarine Rescue System-Transfer Under Pressure, which allows survivors to remain under pressure throughout the process of being rescued. Modeling and simulation provides an opportunity to validate the procedures for the rescue before URC implements them in the real world. This study tested current URC procedures and offers recommendations for when to use different decompression policies, and analyzes the types of rescue delays to expect under the new system.

Introduction

Simulation modeling can be an effective way of testing the performance of potential systems before they are implemented. One main benefit is that the performance of many potential system configurations can be estimated using computer modeling, while it may be difficult or expensive to test such configurations on the actual system. Simulation has been used to provide analysis in numerous sectors, for example, healthcare, energy, defense, financial, and technology. Computing resources continue to become increasingly available, and simulation is becoming more popular as a tool for conducting analysis.

In particular, simulation is being increasingly used in test and evaluation for defense systems (Giadrosich, 1995; Marine Corps Operational Test & Evaluation Activity [MCOTEA], 2013). Simulation can be used in the prototyping stage to determine potential configurations with good performance. It can also be used in developmental test and evaluation to troubleshoot and determine whether the system will meet test requirements. Simulation can be used to determine the potential feasibility of a system without resorting to expensive physical testing. Even if operational tests are eventually required to ensure the system performs as expected, simulation can be used as a precursor to identify potential problems or improvements to be made.

This paper describes a research project that employs simulation to model the complex process of undersea rescue. In particular, the simulation model studies a new proposed system and compares different policies for operating the system. The research team worked directly with experts and operators of undersea rescue processes to build and evaluate the simulation model, and then used statistical analysis methods to evaluate different policies to answer research questions set out by the undersea rescue community.

Undersea rescue, like many other defense processes, can involve a high degree of uncertainty. The goal is to find the best policy that performs well given uncertainty in how specific model components may perform. Stochastic simulation programs are specifically designed to incorporate uncertainty, and we employ analysis methods here to compare different operational policies given this model uncertainty.

Undersea Rescue Process Simulation Model

Undersea Rescue Command (URC) can mobilize its people and equipment worldwide to conduct a rescue of personnel from a disabled submarine (DISSUB) stranded on the sea floor up to depths of 2000 feet. In 2019, URC plans to reach Initial Operating Capability on a new system, the Submarine Rescue System-Transfer Under Pressure (SRS-TUP) system. SRS-TUP will allow survivors from the submarine to remain under pressure throughout the process of being rescued from the time they exit their submarine into the rescue vehicle, up to the deck of the surface ship where URC's two submarine decompression chambers (SDCs) are located. They are transferred from the DISSUB to the rescue ship and into these chambers using a Pressurized Rescue Module (PRM). This pressurized transfer reduces the likelihood that survivors will suffer from decompression sickness or other decompression-related complications.

URC has initial procedures for its use, and cannot yet conduct real world testing on the system to validate that its procedures minimize expected rescue delay times and maximize overall rescue effectiveness. This study helps to verify these procedures by performing modeling and simulation of rescues at a wide variety of depths and DISSUB internal pressures.

During a rescue, there are two main policy options to consider. The PRM can bring 16 survivors up from a DISSUB per sortie, but the SDC can hold up to 35 people. URC decision makers must decide whether to start decompression after each rescue vehicle sortie or whether to wait until another sortie arrives before starting decompression. At higher internal pressures in the DISSUB, the decompression timeline becomes the limiting factor in the rescue, making it more critical to maximize the number of survivors in each decompression. Current procedures state that decision makers should expect decompression after each sortie method to result in no delays in the overall rescue unless internal pressure on the DISSUB exceeds 60 feet seawater (fsw).

The goal is to build a simulation to model the process of rescuing survivors from a pressurized disabled submarine. There are constraints on the number of survivors that can be transported at a given time. The URC will likely provide several rescuers on-board the DISSUB to assist with the rescue, known as a DISSUB Entry Team (DET). Additionally, the PRM requires two attendants for operations who breathe the same pressurized air and require decompression. Based on the length of the attendant's exposure, they may be able to conduct more than one sortie, but require a "clean time" between decompression and recompression, and there are limits on the number of sorties, or amount of pressure they can be exposed to more than once. There are also aspects of the model that are highly variable which are modeled in the simulation. One aspect is the time for different events to take place, like loading/unloading personnel from the modules, or the time to transport survivors from the DISSUB to the surface ship. Incorporating this uncertainty in a simulation model allows for different policies to be tested to see which ones perform best under unpredictable conditions.

Model Objectives

There are two possible decompression policies to consider when there are two available SRS-TUP chambers, and the analysis in this research guides when to use each of these policies:

- Alternate use of the two SDCs after each sortie. As each sortie arrives, it will unload its survivors in one of the SDCs, alternating between the two, and decompression will commence after each sortie.
- Alternate use of the two SDCs once each is full. As each sortie arrives, it will unload its survivors in one of the SDCs, with subsequent sorties unloading to the same SDC until it is near or at capacity, at which point decompression will commence.

The goal of the study was to determine what resources or policies are needed to execute a successful rescue as quickly as possible. The following were the two key research questions:

- When should each decompression policy (decompress immediately after each sortie, or only after the SDC is full) be used? How does that vary for different DISSUB internal pressures?
- How many PRM attendants are required to meet manning requirements to avoid creating any significant rescue delays?

These questions lend themselves to a simulation-based analysis because there are multiple options for employing the SDCs depending on expected sortie and decompression times. URC has procedures for SRS-TUP employment but lacks data demonstrating that those procedures are likely to produce the best rescue outcomes. As this specific system has yet to be fielded, there is no existing data set to analyze. Additionally, modeling and simulation provide a much larger data set over a range of DISSUB depths and internal pressures than could reasonably be achieved through real world testing.

Experimental Setup

The simulation model can vary two types of variables: decision variables and noise variables. Decision variables are those that must be chosen by the analyst in operating the system, and usually the analyst is trying to optimize the choice of decision variables. For example, the analyst may be using the simulation model to determine how many people to staff at a given station, or which routing pattern to use for aircraft or vehicles. Noise variables are uncertain variables that are uncontrollable by the analyst but must be modeled because they affect the performance of the model.

In this study, our decision variable is the decompression policy choice (alternate the use of SDCs after each sortie, or alternate after one if full). There are two major noise variables modified to test how the policies perform under different settings. The first is the depth of the DISSUB. Depths of 250, 1000, and 2000 fsw are considered. The second noise variable is the internal pressure of the DISSUB. This parameter was varied at values of 25, 30, 35, 40, 45, 50, 55, 60, 70, 80, 90, 100, 110, 120, and 132 fsw.

In order to assess the performance of the system, three measurers of effectiveness are considered. The first is the total time the rescue is paused while awaiting chamber availability. This compares the overall time to complete a rescue to a rescue with unlimited decompression capacity. The second metric is the average time for an individual survivor to complete rescue from start of the simulation, which correlates to the time survivors are waiting in the queue to be decompressed. The third metric is the number of required PRM attendants to complete rescue without delay.

Simulation Model Description

We used discrete event simulation to build a model for the rescue process from start to finish. Discrete event simulation is used to model stochastic and dynamic systems, and is an appropriate methodology for this problem to model the state of the rescue over time to keep track of operating personnel and survivors. Building simulation models can help answer questions about the system before it has been built, and can incorporate uncertainty in the model logic to help predict a range of possible outcomes. Because there is uncertainty in how long it will take the new SRS-TUP system to perform different functions, discrete event simulation can incorporate probability distributions for these times to ensure that the decision-maker does not overestimate the performance of the system by assuming deterministic values.

This project used Simio simulation software to model a rescue process and used aspects of the software to help answer the research questions. Simio is a state of the art discrete-event simulation modeling tool that is used in academia, industry, and government applications. Its strength is that it provides not only a clear framework for modeling discrete-event systems, but it also incorporates sophisticated analysis methods to allow the models results to be analyzed statistically.

The discrete-event framework in Simio can primarily be applied to queueing systems, which were adapted to model a submarine rescue. Survivors were modeled as entities which are transported through the different components of the rescue using vehicles which represent the PRM. The decompression process is modeled as a server with a processing time. A series of add-on processes are used to model custom logic unique to this problem that could not be modeled using standard objects. Add-on processes have options to implement coding logic such as if/then statements, update state variable values, and transfer entities or objects to new locations. Thus, Simio can be used to model complex systems without requiring specific coding knowledge by the user. For a detailed guide to Simio and simulation modeling, see Smith et al., (2017).

Additionally, Simio can implement state of the art simulation techniques, like ranking and selection (Kim & Nelson, 2001), to determine the best system configuration. Another advantage is that different policies can be directly compared using the same model as a baseline. For example, different decompression rules or clean time limits can be implemented by tweaking parameters in the model. Simio allows for simultaneous runs of the same model with different parameters which means manual changes do not need to be made. There is a tool called the Subset Selection Analyzer that can be used to statistically compare scenarios to choose the best policy. Finally, Simio makes it easy to run multiple replications quickly by taking automatic advantage of multiple cores on the same machine.

In order to obtain the best validation possible, the team compiled a document describing all the details of the rescue process that were modeled in the simulation program. This document was sent to the URC leadership for feedback on whether the parameters and system dynamics modeled were realistic. The simulation program itself could not be transferred due to licensing and computing restrictions, thus we made the effort to ensure that the model details were communicated without needing to train or explain the details of the simulation modeling program to others.

Then, the members of our team verified the simulation model was working as expected by comparing the details from the project description with the simulation model code. The simulation model was built with ongoing debugging to ensure all components were working.

Experimental Results

This study found that while URC’s procedures are generally correct, there are two potential issues to consider to achieve better results. Current policy suggests 60 fsw as the threshold for the internal pressure beyond which the decompression policy should switch from after every sortie, to waiting until the SDC is full. Simulation model results show that the crossover point at which decision makers should switch policies and fill a SDC with two sorties of survivors before starting decompression is lower, at 45 fsw.

This study also recommends that URC update their procedures for SRS-TUP to base the decision on the decompression rules based on the expected decompression time. When the expected decompression time is less than 12 hours (the approximate required time for two sorties), decompression should occur after each sortie because there is enough time to make the chamber available for the next sortie. When the expected decompression time is longer than 12 hours, decompression should occur only after the SDC is full.

Experimental designs and statistical methods are becoming increasingly important in assessing the performance of systems in test and evaluation (Ortiz & Harman, 2016; Hill, 2017). The simulation model was run under a variety of conditions, varying the number of survivors, rescue depth, and DISSUB internal pressure. In the end, most experiments involved 155 survivors to simulate a worst-case rescue with a large number of people to be transported. Initially, an experimental design was developed using a Nearly Orthogonal Latin Hypercube (NOLH) model (Cioppa & Lucas, 2007; Sanchez, 2011). This model chooses experimental design points to span the space of possible variables efficiently, rather than testing every possible combination of noise factors. A few key conclusions can be drawn from these results. In particular:

- With two chambers available, when the average decompression time is more than twice the average sortie time, delays in the rescue will be incurred for chamber availability. This is intuitive because there are two chambers and the sorties may arrive faster than the decompressions can occur. However, rescues involving fewer than two decompressions (due to a small number of survivors) will not incur delays.
- The average decompression time is largely a function of DISSUB internal pressure. This varies from just 2.7 hours to over 55 hours over the range of pressures evaluated and has the most significant impact on rescue delays.
- The average sortie time is largely a function of DISSUB Depth, but varies little over the range of data. With depth ranging from 264 to 2000 feet, the sortie time only changed from 5.07 to 5.81 hours. This effect was small compared to the decompression time.

To analyze the performance of the system, we consider three specific quantities that are measured in the simulation model.

- Average rescue delay per sortie (the total time the rescue is delayed due to SDC unavailability divided by the number of sorties)
- Time from first to last rescue (total time taken to complete the rescue)
- Average decompression time for survivors across the entire rescue

Two factors account for the rescue delays more than any other: the time required for decompression, and the decision variable of this decompression policy to use. We present each of our performance metrics according to these two factors. Figure 1 shows results with the average rescue delay per sortie displayed against the time required for decompression under each decompression policy. In each of the two policies, the decompression cycle time accounts for over 85% of the variability in the total delay in the rescue. Since decompression cycle time is driven by the DISSUB internal pressure, this pressure is the most significant factor in determining which decompression policy to use in a rescue.

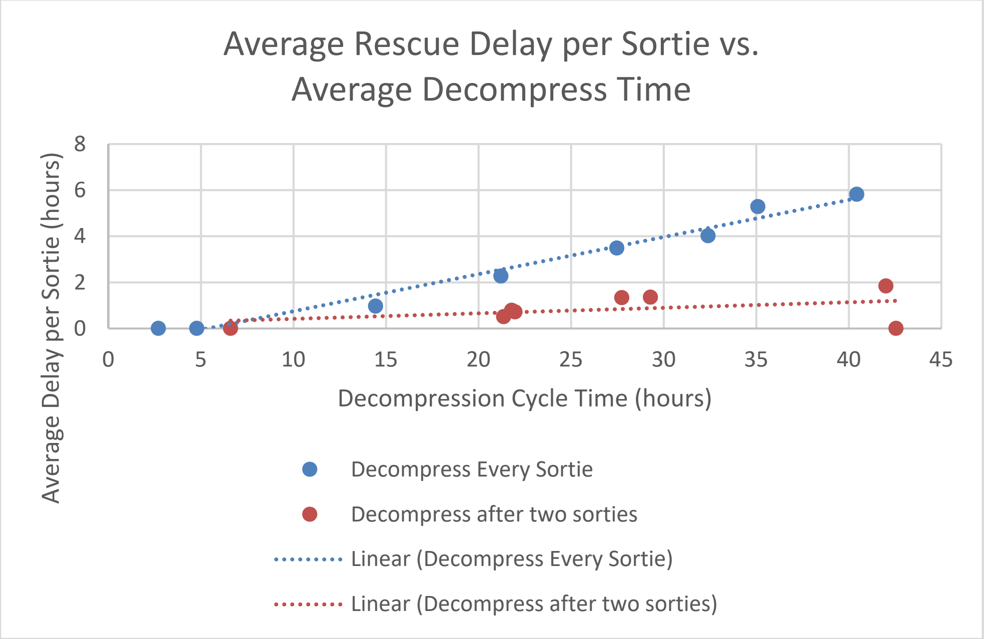

Figure 1. Average Rescue Delay per Sortie vs. Average Decompression Time

Next, rescues were simulated at DISSUB internal pressures from 25 to 132 feet of seawater. We measured the cumulative delay over the rescue (the total time for the rescue from start to finish) under each of these conditions for each of the two decompression policies. Plotting the cumulative delay against the DISSUB internal pressure (Figure 2), a clear distinction can be seen, with no delays in the rescue up to pressures of 40 ft sw. At pressures above 45 fsw, the expected decompression time became over twice than the sortie time, which warranted holding decompression until the chamber was full.

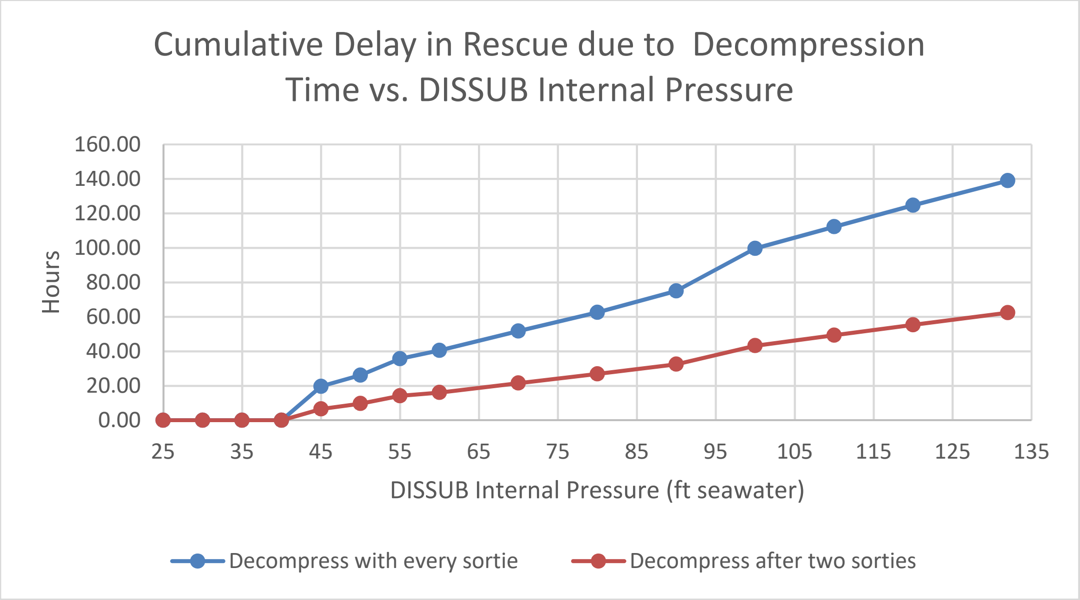

Figure 2. Cumulative Delay in Rescue due to Decompression Time vs. DISSUB Internal Pressure

However, just looking at the cumulative delay at the aggregate level fails to capture the effect on individuals. During rescues with short decompression times, survivors may be left waiting unnecessarily to decompress, increasing their risk of complications. We also looked at the average time for an individual survivor to complete decompression from the start of the rescue, which is graphed in Figure 3. For DISSUB internal pressures below 45 fsw, there is a slight efficiency advantage for decompressing after each sortie. Additionally, using only a single SDC to decompress survivors after every sortie for these lower pressures provides the flexibility of having the other SDC available for treatment of any survivors experiencing decompression complications. This is already captured in the URC's procedures.

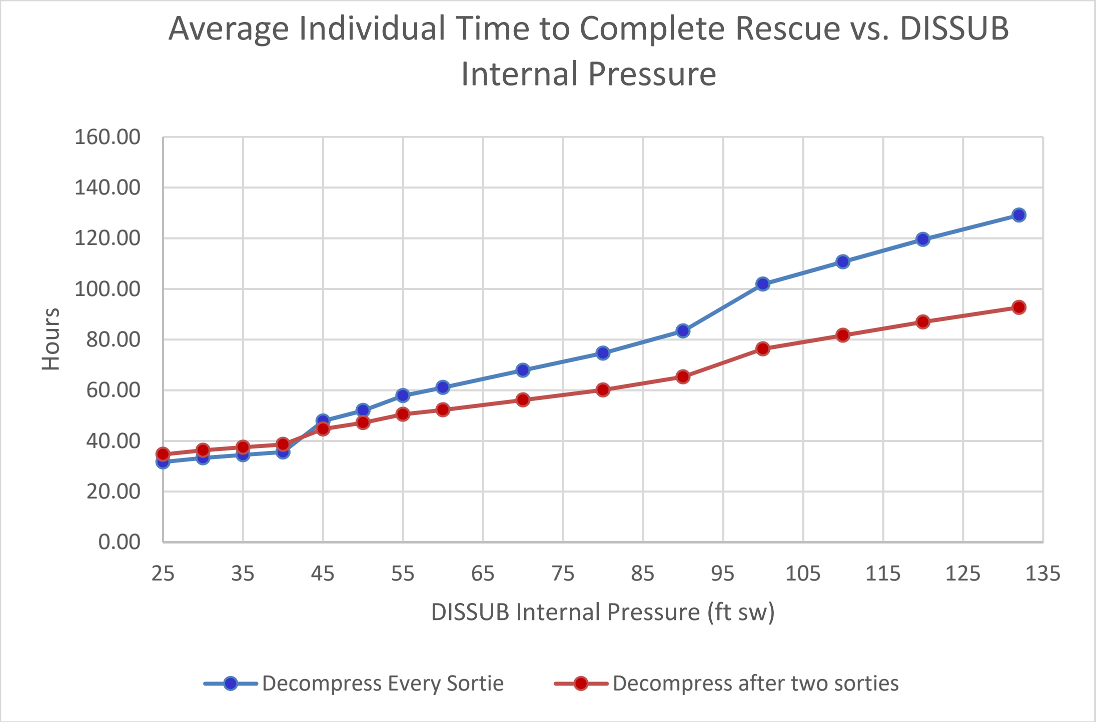

Figure 3. Average Individual Time to Complete Rescue vs. DISSUB Internal Pressure

Next, we study the number of attendants needed for the rescue to be performed successfully. URC must maintain enough qualified attendants on staff and ready to execute a rescue at all times. Conducting a rescue with fewer than the required number of attendants could result in pausing the rescue operation while waiting for attendants to complete decompression or their post-decompression clean time. Our model accounted for all attendants either on watch or otherwise unavailable and determined the maximum number of attendants needed for a given rescue.

With the first sortie, the PRM will bring two attendants that will stay on-board the DISSUB to assist the crew in the rescue. Based on the internal pressure in the DISSUB, these attendants will have a limited stay time, and need to be replaced by fresh attendants on a future sortie. Their return, however, takes away seats from the survivors, so this process effectively adds additional survivors that require rescue. For our simulations, we assumed that the URC will provide continuous coverage of two DISSUB attendants and swap them out as required. We use the model to determine how many total attendants will be needed.

The PRM attendants, who remain on the PRM through the rescue can either conduct watch turnover after every sortie or stay with the PRM for two cycles. After a single sortie, the PRM attendant will have been pressurized for less than four hours, so has not reached saturation. The attendant will be eligible for a reduced decompression timeline, and after waiting a “clean time” at atmospheric pressure will be available for a follow-on sortie. If any attendant were to stay on for a second sortie, they would remain exposed to the DISSUB pressure through that second cycle and require the same decompression cycle that the survivors entail. At this point, the attendant would not be available for additional sorties.

We ran our experiment varying the DISSUB pressure from 25 to 132 fsw using both options for attendants (a single sortie per attendants, and a dual sortie per attendants). Since we were trying to find the worst-case rescue situation, we used the design specifications of a 2000 fsw rescue depth and 155 survivors. The results are shown in Table 1 for the Time to Last Rescue (TTLR) under each option along with the number of attendants required not to delay the rescue.

Table1. Attendants Required for Rescues Under Various DISSUB Internal Pressures

				1 Sortie Per Attend.		2 Sorties Per Attend.	
DISSUB Attend	Total People (including 155 survivors)	DISSUB Internal Pressure		TTLR	Attendants Required (Average)	TTLR	Attendants Required (Average)
2	157	25		61.421	10	61.421	10
2	157	30		63.021	10	63.021	10
2	157	35		64.221	10	64.221	10
2	157	40		65.321	10	65.321	10
4	159	45		80.8515	10.08	80.8515	10
4	159	50		86.0462	11.2	86.0462	10
4	159	55		93.1536	11.12	93.1536	10
6	161	60		100.716	11.2	100.716	12
8	163	70		109.427	11.08	109.427	12
10	165	80		121.546	11.6	121.546	12
12	167	90		129.206	11.12	129.206	12
16	171	100		1732.97	20	145.775	12
20	175	110		1740.68	20	155.484	12
26	181	120		1754.23	20	171.711	12
30	185	132		1761.28	20	182.815	12

All rescues below the pressure of 55 fsw could be conducted without a delay for a sortie to enter the SDC with only 10 qualified attendants. The worst-case scenario, from a depth of 2000 ft, with 155 survivors pressed to 132 fsw, will require 12 qualified attendants. This number could increase if some sorties carry fewer than 16 survivors, which could happen if a stretcher needs to be used to carry an injured survivor, or if there are additional personnel on a sortie for medical or other reasons.

Conclusions

This study validated the URC's current policy for the SRS-TUP that the best policy is generally to decompress a chamber after two sorties when it is full, rather than decompressing immediately after each sortie. The current threshold policy for using this decompression policy when the internal pressure is higher than 60 fsw could instead be lowered to 45 fsw. Higher pressures result in longer decompression times, and thus decompressing after each sortie may result in delays for the next sortie that arrives. The current policy in use calls for decompressing after every sortie when the decompression time is less than the length of a sortie.

Our results show that decompressing after every sortie can lead to longer delays than waiting to fill an SDC before decompressing and that total delays in the rescue may range from 20 hours at 45 fsw internal DISSUB pressure to 140 hours at 132 fsw. The difference in URC's assumptions and the simulation results is most likely due to the simulation modeling 5% of survivors encountering some difficulty during decompression and requiring a longer decompression cycle. We selected the 5% value for the model after consulting with URC. It is also possible that there are numerous other causes for delay that are not predicted by the model, so we recommend URC allows a buffer time for unexpected problems.

Using a simulation model for the entire rescue process, we demonstrate the effects of two possible decompression policies on the time to complete a rescue. We incorporate uncertainty in the time to complete various aspects of the rescue, as well as vary the possible conditions (pressure, depth) associated with a scenario to find a robust policy that is preferred under extreme or poor conditions. In addition to determining which decompression policy to use, the study provides guidance on the number of attendants needed to complete the rescue, and the overall time to complete a rescue successfully. The results of the study were made available to URC for their planning purposes.

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