

additional heat to the SCR unit can be gained by placing the reactor upstream of the turbocharger; however, this temperature increase would not be large at low loads and the volume of the reactor would diminish turbocharger response when the engine changes load. The engine could be calibrated to have higher exhaust temperatures; however, this could affect durability if this calibration also increased temperatures at high loads (depending on the fuel used). For an engine operating on residual fuel, vanadium in the fuel can cause damage by reacting with the valves at higher temperatures. In addition, a catalyst that is formulated to be more reactive at lower temperatures is also more sensitive to sulfur poisoning. Any information that becomes available over the next few years would help us understand the potential for SCR systems to control emissions at low engine loads and ensure proper operation in port areas, where emission reductions are most important. This will help ensure that we adopt requirements with an appropriate expectation regarding the effectiveness of the anticipated emission-control technologies.

Sulfur in fuel is also a concern with an oxidation catalyst because, under the right conditions, sulfur can also be oxidized to form direct sulfate PM. At higher temperatures, up to 20 percent of the sulfur could be converted to direct sulfate PM in an oxidation catalyst compared to about a 2 percent conversion rate for a typical diesel engine without aftertreatment. Depending on the precious metals used in the SCR unit, it could be possible to convert some sulfur to direct sulfate PM in the reactor as well. Manufacturers would have to design their exhaust system (and engine calibration) such that temperatures would be high enough to have good conversion of NO, but low enough to minimize conversion of sulfur to direct sulfate PM. Direct sulfate PM emissions could be reduced by using lower sulfur fuel such as distillate.

SCR systems traditionally have required a significant amount of space on a vessel; in some cases the SCR unit is as large as the engine itself. However, at least one manufacturer is developing a compact system that uses an oxidation catalyst upstream of the reactor to convert some NO to NO<sub>2</sub>, thus reducing the reactor size necessary. The reactor size is reduced because the NO<sub>2</sub> can be reduced without slowing the reduction of NO. The catalytic reaction is faster by reducing NO<sub>x</sub> through two mechanisms. This compact SCR unit is designed to fit into the space already used by the

silencer in the exhaust system. If designed correctly, this could also be used to allow the SCR unit to operate effectively at somewhat lower exhaust temperatures. The oxidation catalyst and engine calibration would need to be optimized to convert NO to NO<sub>2</sub> without significant conversion of sulfur to direct sulfate PM. NO<sub>x</sub> reductions of 85 to 95 percent have been demonstrated with an extraordinary sound attenuation of 25 to 35 dB(A).<sup>30</sup>

A vessel using an SCR system would also require an additional tank to store ammonia (or urea to form ammonia). This storage tank would be sized based on the vessel use, but could be large for a vessel that travels long distances in U.S. waters between refueling, such as between California and Alaska. Urea consumption increases operating costs. If lower sulfur diesel fuel were required to ensure the durability of the SCR system or to minimize direct sulfate PM emissions, this lower sulfur fuel would also increase operating costs. The operational characteristics of ocean-going vessels may interfere with correct maintenance of the SCR system. Ferries that have incorporated this technology do not run continuously and therefore any maintenance necessary can be performed during regular down times. The availability of time for repair can be an issue for ocean-going vessels that operate continuously for long periods.

Because SCR units are so easily adjustable, if allowed, ship operators may choose to turn off the SCR unit when not operating near the U.S. coast. If they were to use this approach, they would need to construct a bypass in the exhaust to prevent deterioration of the SCR unit when it is not in use. To ensure that the SCR system is operating properly within 175 nautical miles of the U.S. coast, we would need to consider continuous monitoring of NO<sub>x</sub> emissions for engines using SCR. This is discussed in more detail below.

If the combustion is not carefully controlled, some of the ammonia can pass through the combustion process and be emitted as a pollutant. This is less of an issue for Category 3 marine engines, which generally operate under steady-state conditions, than for other mobile-source applications. In addition, in ships where banks of engines are used to drive power generators, such as cruise ships, the engines generally operate under steady-state conditions near full load. If ammonia slip still occurred, an oxidation catalyst could be

used downstream of the reactor to burn off the excess ammonia.

Slow-speed marine engines generally have even lower exhaust temperatures than medium-speed engines due to their two-stroke design. However, we are aware of four slow-speed Category 3 marine engines that have been successfully equipped with SCR units. Because of the low exhaust temperatures, the SCR unit is placed upstream of the turbocharger to expose the catalyst to the maximum exhaust heat. Also, the catalyst design required to operate at low temperatures is very sensitive to sulfur. Especially at the lower loads, the catalyst is easily poisoned by ammonium sulfate that forms due to the sulfur in the fuel. To minimize this poisoning on these four in-service engines, highway diesel fuel (0.05% sulfur) is required. In addition, these ships operate with the exhaust routed through the SCR unit only when they enter port in the United States, which is about 12 hours of operation every 2 months. Therefore, the sulfur loading on the catalyst is much lower than it would be for a vessel that continuously used the SCR system. To prevent damage to the catalyst due to water condensation, this system needs to be warmed up and cooled down gradually using an external system. Another issue associated with the larger slow-speed engines and lower exhaust temperatures is that a much larger SCR system would be necessary than for a vessel using a smaller medium-speed engine. Size is an issue because of the limited space on most ships.

*c. Fuel cells.* A third advanced technology that may allow for significant reduction of NO<sub>x</sub> emissions involves the use of fuel cells to power the vessel in place of an internal-combustion engine. A fuel cell is like a battery, except where batteries store electricity, a fuel cell generates electricity. The electro-chemical reaction taking place between two gases, hydrogen and oxygen, generate the electricity from the fuel cell. The key to the energy generated in a fuel cell is that the hydrogen-oxygen reaction can be intercepted to capture small amounts of electricity. The byproduct of this reaction is the formation of water. Current challenges include the storage or formation of hydrogen for use in the fuel cell and cost of the catalyst used within the fuel cell.

Recently, several efforts to apply fuel cells to marine applications have been conducted. These include grants from the Office of Naval Research and the U.S. Navy. The Office of Naval Research initiated a three-phase advanced development program to evaluate fuel

<sup>30</sup> Paro, D., "Effective, Evolving, and Envisaged Emission Control Technologies for Marine Propulsion Engines," presentation from Wartsila to EPA on September 6, 2001 (Docket A-2001-11; document II-A-72).