smaller than 10 μm (PM_{10}), sulfur oxides (SO_x), methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). The three greenhouse gases (GHGs) (CH_4, N_2O, and CO_2) were weighted by their global warming potentials to estimate CO_2-equivalent GHG emissions. Emissions of the five urban air pollutants were further separated into total emissions and urban emissions to provide a better indication of human exposure to air pollution that would result from a given combination of 3X fuel and propulsion system technologies.

The IMPACTT model was used to estimate annual energy consumption and emissions production by conventional and 3X vehicles by considering vehicle stock and usage and emission rates from GREET runs. In IMPACTT, age-based tailpipe emissions rates were obtained from EPA's MOBILE5b and PART5 models for conventional SI and CI engines operating on gasoline and diesel fuel, respectively. Average operational emissions rates for nonconventional engines and fuels were estimated on the basis of the assumptions presented below. Although MOBILE5a and PART5 are under criticism for not predicting emissions accurately, they are still the most widely used models in the United States.

Emissions standards are an important reason for considering alternative propulsion systems in the PNGV program. In the United States, new vehicles must meet the federal Tier 1 emissions standards. Tier 2 standards, requiring a further 50% reduction (beyond Tier 1 standards) in vehicle emissions for model-year 2004 and beyond, may be adopted in 1999 (vehicles in California must now meet stricter low-emission vehicle standards). It is generally believed that 3X vehicles will be subject to Tier 2 standards for VOC, CO, and NO_X and the ultra-low-emission vehicle standard for PM. For this study, we assumed that RFG-fueled SIDI engines would meet Tier 2 standards. All other SIDI engines (fueled with methanol, ethanol, CNG, LNG, and LPG) were assumed to meet Tier 2 standards. If an alternative fuel offers inherently lower emissions than RFG, emissions reductions were assumed for that fuel. We further assumed that 3X CIDI engines fueled with RFD would at least meet Tier 2 standards for NO_x, CO, and VOC and the ultra-low-emission vehicle standard (i.e., 0.04 g/mi) for PM. As with SIDI alternative fuels, CIDI fuels that offer inherently lower emissions were assumed to achieve greater reductions than RFD.

Fuel-Cycle Energy and Emissions Estimates

Figures 2–4 display percent changes in urban emissions of VOC, SO_x and PM_{10} for each of the propulsion system/fuel combinations examined. Each figure depicts results for a single pollutant as a series of curves showing annual percentage increases or decreases from the reference scenario forecast. Curves that are all but indistinguishable are combined to aid interpretation. Note that each propulsion system/fuel alternative was examined in the context of a scenario that contained a significant portion of conventional vehicles. Thus, emissions were computed for a combination of conventional and 3X technologies, so results are less striking than would be the case for 3X technologies alone.

Nitrogen Oxides (NO_x). Urban NO_x emissions are not shown because of relatively small differences among the alternatives. The four CIDI fuels (RFD, DME, FT50, and B20) were assumed to meet equivalent Tier 2 emission standards and thus were essentially equivalent to results for RFG, methanol, ethanol, LPG, and the gaseous fuel alternatives. Methanol and gasoline fuel cells offer the largest reduction in urban NO_x emissions — 35% in 2030. H_2 fuel cells achieve a somewhat lower NO_x reduction because of their relatively higher upstream emissions.

CO. Reductions in urban CO emissions range from essentially zero to about 35% in 2030; fuel cells achieve the greatest reductions, and SIDI engines on any of six fuels achieve the lowest. Given the CI engine's proven record of relatively low CO emissions, it is not surprising that diesel-like fuels (RFD, DME, FT50, and B20) achieve the second-best CO reduction, approximately 28% in 2030.

VOCs. Urban VOC emissions reductions range up to approximately 37% (Figure 2). H_2 fuel cells are the clear leader in reducing VOC emissions, methanol fuel cells are a close second and gasoline fuel cells are third. CIDI engines fueled by RFD, DME, FT50, or B20 and SIDI engines fueled by LPG, CNG, or LNG achieve almost half the reduction of H_2 fuel cells.

SO_x. Urban SO_x emissions are closely related to the volume of fuel used. Thus, all propulsion system/fuel alternatives reduce urban SO_x emissions because of their tripled fuel efficiency (Figure 3). H_2 fuel cells, LPG, CNG, ethanol, and DME achieve the greatest reductions, but urban SO_x represents a very small share (on the order of 13%) of the total SO_x attributable to light-duty vehicles. Most SO_x emissions come from upstream fuel processing, which tends to occur outside urban areas.

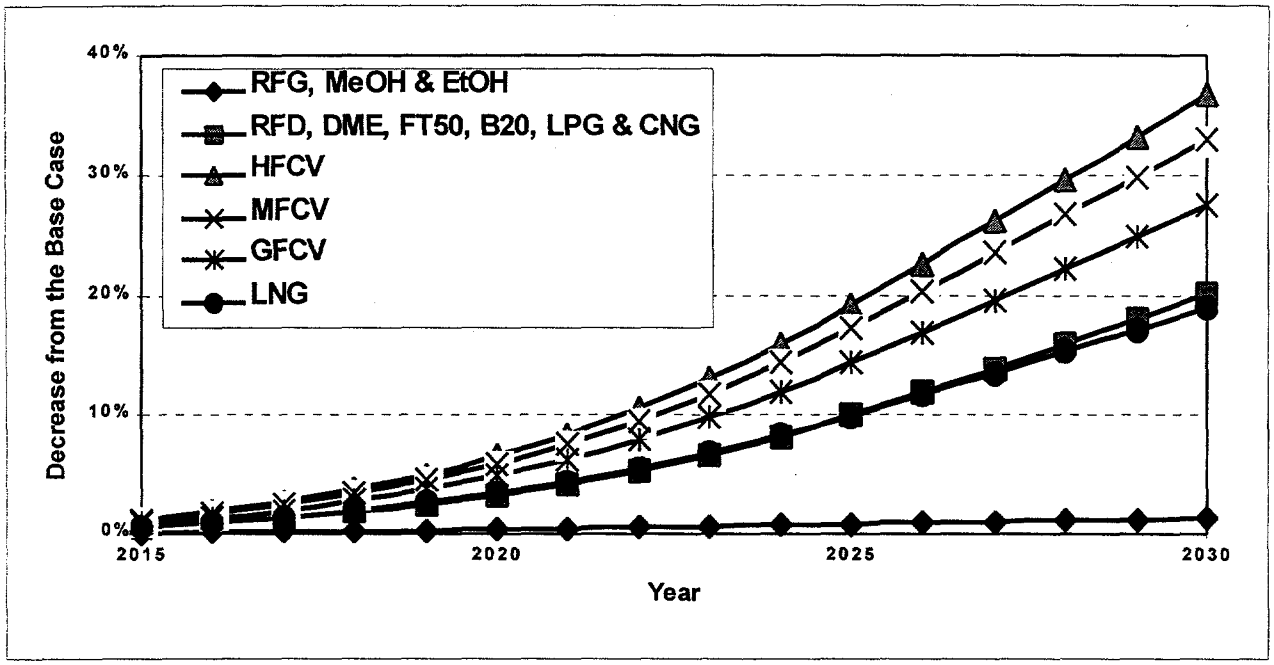

Figure 2 Changes in Fuel-Cycle Urban VOC Emissions by 3X Technology/Fuel Alternative

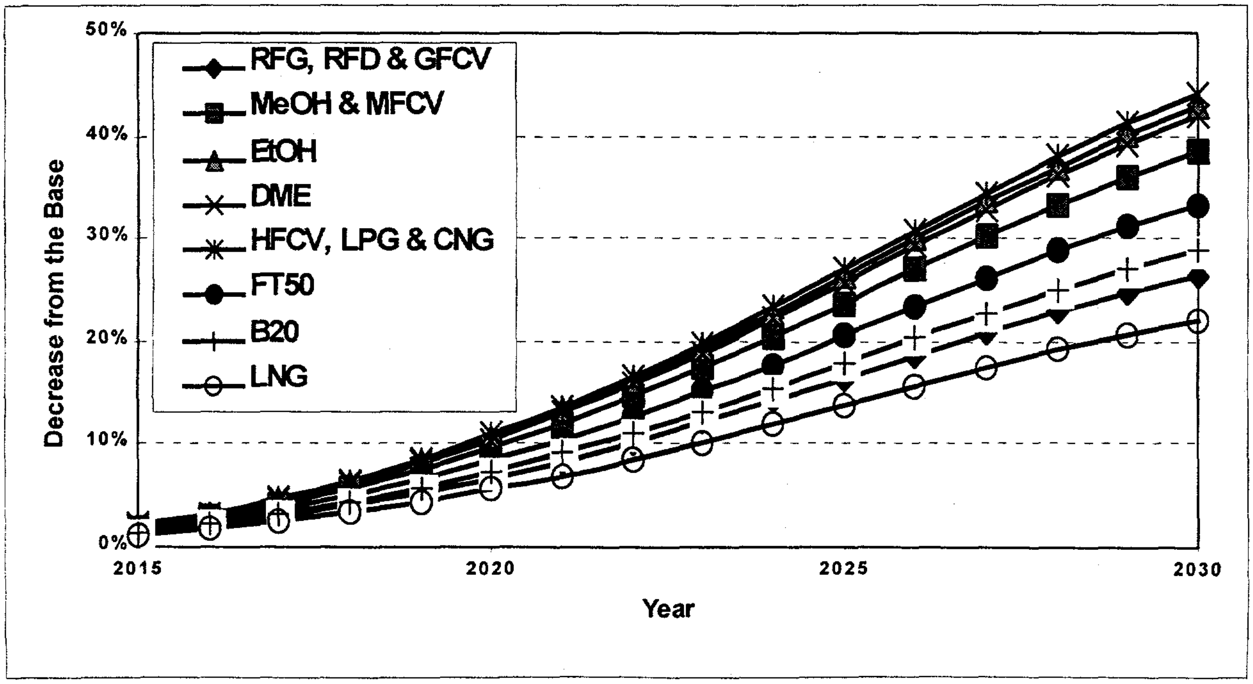

Figure 3 Changes in Fuel-Cycle Urban SO_X Emissions by 3X Technology/Fuel Alternative

PM_{10}. With the exception of DME, diesel-like fuels increase PM_{10} emissions (Figure 4). Excluding RFG, DME, and LNG, which have little effect on PM_{10}, all the other alternatives decrease PM_{10} emissions by approximately 15%. Note that the increase for diesel-like fuels occurs despite the assumption of a "Tier 2 equivalent" exhaust emission standard of 0.04 g/mi.

GHGs. Figure 5 shows that changes in total GHG emissions. Note that because CO_2 accounts for the bulk of GHG emissions and all propulsion system/fuel alternatives share the same fuel efficiency, emission reductions from non-renewable fuels are clustered. Chief among the low-GHG alternatives is ethanol-fueled SIDI engines and H_2 fuel cells, both of which generate no CO_2 from vehicle operations (the carbon in ethanol comes from carbon in the atmosphere via photosynthesis). When combined with the conventional vehicles (and their GHG emissions), these low-GHG alternatives achieve overall reductions (from all light-duty vehicles, both 3X and conventional) of 46% (for ethanol) and 33% (for H_2).

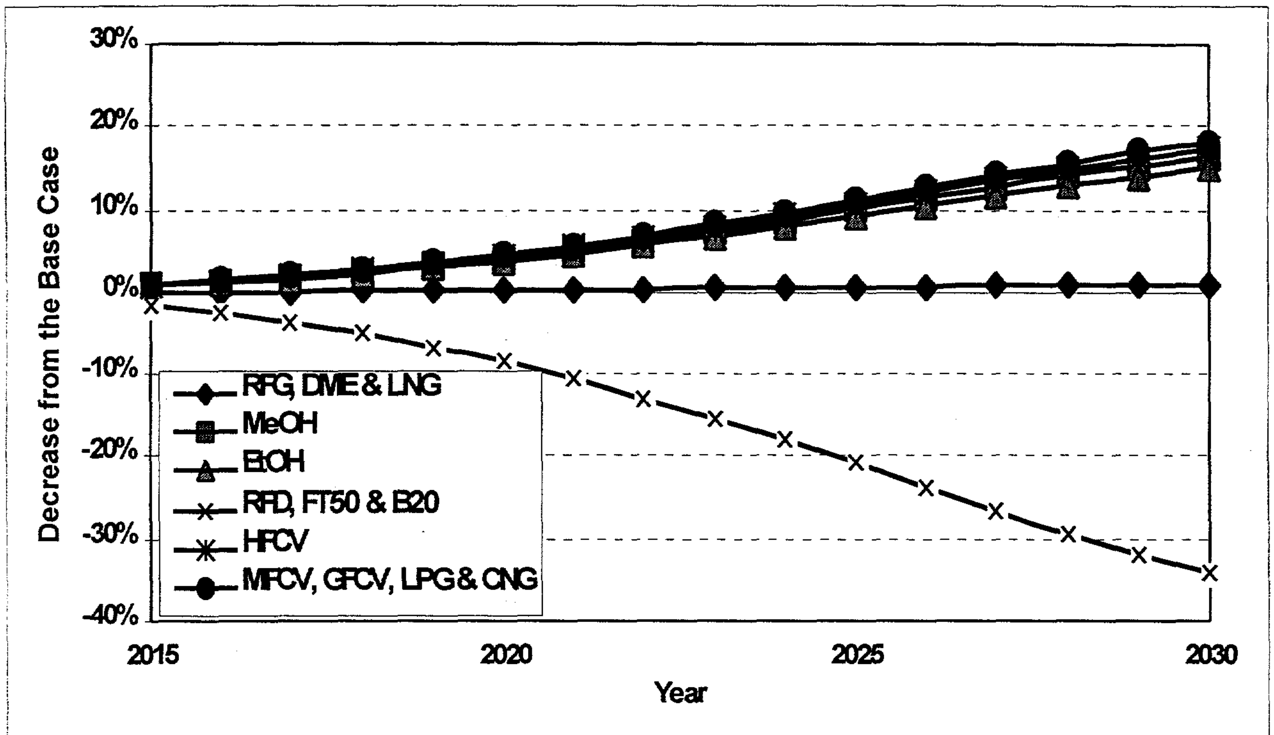

Figure 4 Changes in Fuel-Cycle Urban PM_{10} Emissions by 3X Technology/Fuel Alternative

Petroleum. Several of the technology/fuel alternatives consume nonpetroleum fuels (Figure 6). Clearly, the alternatives cluster into three groups: largely petroleum fuels (i.e., RFG, RFD, and B20), part petroleum fuels (i.e., FT50 and LPG), and largely nonpetroleum fuels (i.e., H_2, methanol, ethanol, DME, CNG, and LNG). By 2030, the nonpetroleum alternatives achieve an approximately 45% reduction in total petroleum use. The part petroleum alternatives (i.e., FT50 and LPG) achieve the next-best reduction — approximately 35% under that scenario.

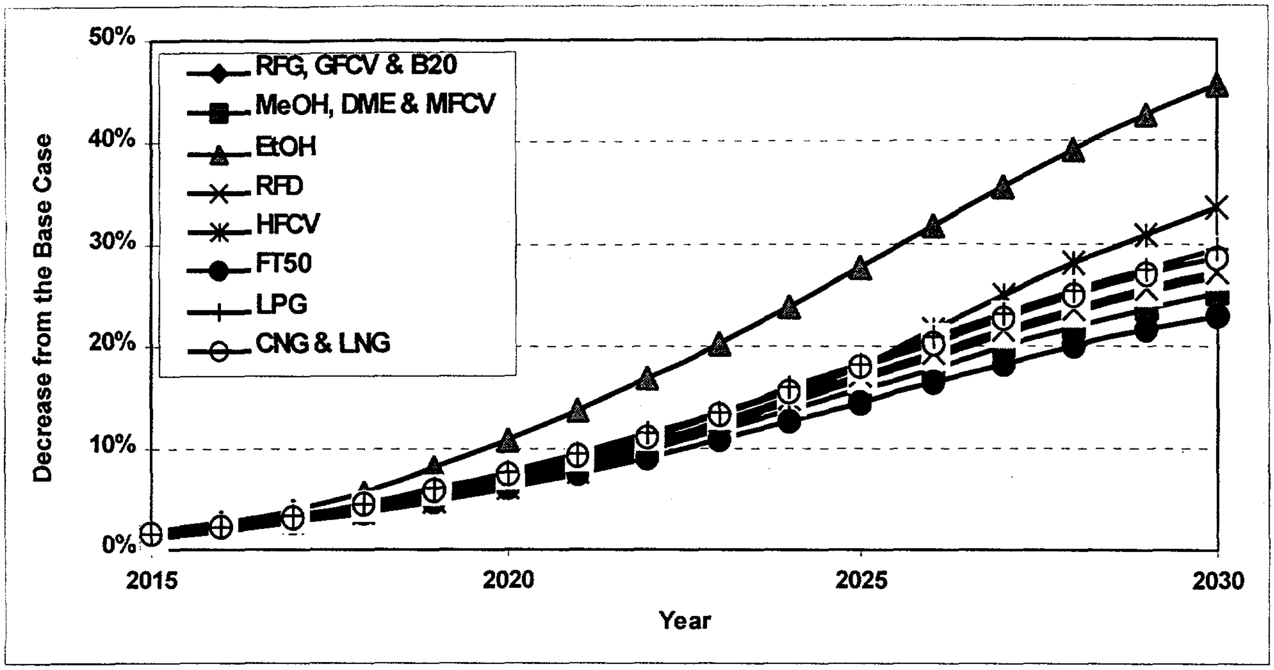

Figure 5 Changes in Fuel-Cycle GHG Emissions by 3X Technology/Fuel Alternative

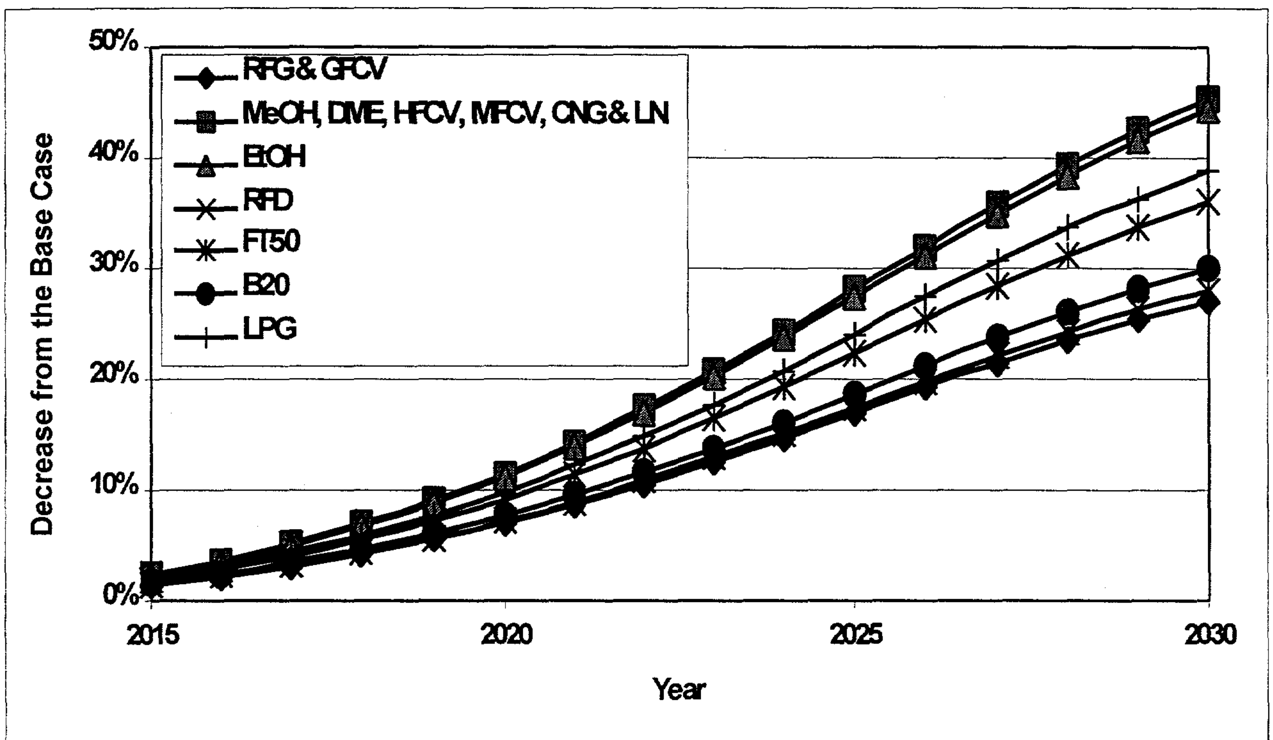

Figure 6 Changes in Fuel-Cycle Petroleum Use by 3X Technology/Fuel Alternative

CONCLUSIONS

Our study reveals that supplying gasoline-equivalent demand for the low-market-share scenario requires a capital investment of less than \$40 billion for all fuels except H_2, which will require a total cumulative investment of \$150 billion. By contrast, cumulative capital investments under the high-market-share scenario are \$50 billion for LNG, \$90 billion for ethanol, \$100 billion for methanol, \$160 billion for CNG and DME, and \$560 billion for H_2. Although these substantial capital requirements are spread over many years, their magnitude could pose a challenge to the widespread introduction of 3X vehicles.

Fossil fuel use by U.S. light-duty vehicles declines significantly with introduction of 3X vehicles because of fuel-efficiency improvements for 3X vehicles and because of fuel substitution (which applies to the nonpetroleum-fueled alternatives). Petroleum use for light-duty vehicles in 2030 is reduced by as much as 45% relative to the reference scenario. GHG emissions follow a similar pattern. Total GHG emissions decline by 25–30% with most of the propulsion system/fuel alternatives. For those using renewable fuels (i.e., ethanol and H_2 from solar energy), GHG emissions drop by 33% (H_2) and 45% (ethanol).

Among urban air pollutants, urban NO_x emissions decline slightly for 3X vehicles using CIDI and SIDI engines and drop substantially for fuel-cell vehicles. Urban CO emissions decline for CIDI and FCV alternatives, while VOC emissions drop significantly for all alternatives except RFG-, methanol-, and ethanol-fueled SIDI engines. With the exception of CIDI engines fueled by RFD, FT50, or B20 (which increase urban PM_{10} emissions by over 30%), all propulsion system/fuel alternatives reduce urban PM_{10} emissions. Reductions are approximately 15–20% for fuel cells and for methanol-, ethanol-, CNG-, or LPG-fueled SIDI engines.

Table 3 qualitatively summarizes impacts of the 13 alternatives on capital requirements and on energy use and emissions relative to the reference scenario. The table clearly shows the trade-off between costs and benefits. For example, while H_2 FCVs have the greatest incremental capital needs, they offer the largest energy and emissions benefits. On the basis of the cost and benefit changes shown, methanol and gasoline FCVs appear to have particularly promising benefits-to-costs ratios.

Table 3 Impacts of Propulsion System/Fuel Alternatives for 3X Vehicles Relative to the Reference Scenario

Parameter	RFG	MeOH	EtOH	LPG	CNG	LNG	RFD	DME	FT50	B20	GFCV	MFCV	HFCV
Cost of fuel production	0[a]	--	--	-	-	-	0	---	-	0	0	--	---
Cost of fuel distribution	0	-	-	-	---	-	0	-	0	0	0	-	---
Total energy use	+++	++	+	+++	+++	+++	+++	++	++	+++	+++	++	+
Fossil energy use	++	++	+++	++	++	++	++	++	++	++	++	++	+++
Petroleum use	+	+++	+++	++	+++	+++	+	+++	++	+	+	+++	+++
GHG emissions	++	++	+++	++	++	++	++	++	++	++	++	++	+++
VOC emissions[b]	0	0	0	++	++	++	++	++	++	++	+++	+++	+++
CO emissions[b]	0	0	0	0	0	0	++	++	++	++	+++	+++	+++
NO_x emissions[b]	0	0	0	0	0	0	0	0	0	0	+++	+++	+++
PM_{10} emissions[b]	0	++	++	++	++	0	---	0	---	---	++	++	++
SO_x emissions[b]	+	+++	+++	+++	+++	+	+	+++	++	+	+	+++	+++

[a] 0: no change; +: a little better; -: a little worse; ++: better; --: worse; +++: best; ---: worst

[b] Urban emissions

ACKNOWLEDGMENTS

This work was sponsored by the U.S. Department of Energy's Office of Advanced Automotive Technologies. In particular, the authors thank Dr. Pandit Patil and Ed Wall for their technical suggestions, guidance, and review on the project that this paper summarizes. The submitted manuscript has been prepared by the University of Chicago as Operator of Argonne National Laboratory ("Argonne") under Contract No. W-31-109-ENG-38 with the U.S. Department of Energy. The U.S. Government retains for itself, and others acting on its behalf, a paid-up, nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.

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