REBUTTAL TO TROMP *ET AL.*'S RESPONSE, *SCIENCE* 302:226–229, 10 OCT. 2003

Tromp *et al.*'s 13 June 2003 article assumed that a global hydrogen industry would leak 10 to 20% of its throughput, and cited this figure to two references neither of which said anything of the sort. Such extreme leakage in a commercial H_2 production and delivery system would trigger immediate shutdown to prevent serious safety and economic problems. Knowing of no evidence for H_2 leakage rates within at least an order of magnitude of the claimed range, I wrote to the authors' contact, Y.L. Yung, on 13 June asking if they had any, but have received no reply.

Now these authors, with J.M. Eiler as senior respondent, seek to defend their key assumption by shifting the supposed leakage source (at least very largely) from the hydrogen supply and transportation system to boiloff from the cryogenic storage tanks of LH_2-fueled cars—an "important part…of current plans for a hydrogen economy and…prone to H_2 losses."
But their 12 new citations for this claim (*1*)—five of them nontechnical news stories—don't support it either, for two reasons: cryogenic automotive engineering and H_2 system economics.

First, LH_2 boiloff from an automotive cryogenic storage tank does not equate to gaseous (G) H_2 emissions. Boiloff begins after a "dormancy" interval that the authors' ref. 11 states for the Linde/GM tank is 3 days from filling (their ref. 7 says 0 to 3 days) and their ref. 4 states is ~4 to 5 days in "a completely filled state-of-the-art design." (Most cars are run daily.) Boiloff then ranges from ~4% per parking day for the Linde/GM tank design to only 1%/day as stated in their ref. 4 (*2*). That source also explains that in properly designed automotive tanks, boiloff creates cold pressurized GH_2 that is held above the LH_2 and used as the first fuel when the vehicle restarts (*3*). In parking so prolonged as to exceed most tanks' ~0.5–0.6 MPa headgas capacity (after a dormancy period that increases to the extent the LH_2 tank is only partly filled), the excess GH_2 would in practice be not vented but catalytically oxidized to meet safety regulations, using commonplace (not just imaginable) technology, as Lehman's letter and the authors' ref. 12 suggest. It is thus implausible that any material fraction of boiloff from automotive LH_2 tanks would enter the atmosphere. Yet Tromp *et al.* assume that all boiloff will do so, from every car, at worst-case rates (30□ DOE's 2015 goal), after zero dormancy.

Second and more importantly, as my 10 October letter explained, LH_2 is "so costly to produce and distribute that it is only 10^{-3} of current H_2 production…and is unlikely to compete in any significant future markets except cryoplanes, which should have low H_2 losses." (*4*) Yet from the goals of diversified R&D portfolios, the existence of a few LH_2 concept cars, an emerging European technical standard for LH_2 refueling equipment, and BMW's unique interest in LH_2 (albeit not for traction fuel cells) the authors conjure up a broad industry trend toward LH_2 storage for fuel-cell vehicles. This is the opposite of the truth. LH_2 technology works, remains an option, and retains a dwindling band of enthusiasts, but most vehicle designers now favor compressed GH_2 because it is cheaper, lighter, and easier, and because the range limitations formerly imposed by its greater bulk (*5*) have been overcome. No designer proposes "low-pressure" H_2 tanks, which would indeed have "poor range," but high-pressure GH_2 tanks don't, are commercially available, are cheap to mass-produce, and are the modern industry norm. More exotic storage methods may well emerge but, like LH_2, are not necessary.

For example, an uncompromised, cost-competitive, quintupled-efficiency, midsize fuel-cell concept SUV designed in 2000 (*6*), using then-standard 35-MPa GH_2 tanks, has a simulated driving range (*7*) of 531 km (exceeding Tromp *et al.*'s ~400-km or DOE's 484-km benchmark).

That range should rise to ≥850 km with today's 70-MPa tanks. The key is not a novel H_2 storage technology such as DOE seeks, but rather a highly integrated vehicle design that cuts tractive load 3× through an ultralight advanced-composite body (*8*) and low drag. The SUV could carry five adults in comfort, and 1.96 m^3 of cargo with the rear seats folded flat, in a vehicle the size of a Lexus *RX-300*, haul a half-ton up a 44% grade, and accelerate 0 to 100 km/h in 8.3 s. Other designers have addressed GH_2's packaging challenges in other ways.

Lossless high-pressure tanks' acceptance by nearly all automakers is due not just to their adequate range and excellent safety, but also to superior whole-system economics. Tromp *et al.* claim LH_2's greater *compactness* "suggests [it]…could outcompete the alternatives on the open market, despite less effective fuel efficiency" (*9*). But *cost* matters too. Their only evidence that LH_2 can beat GH_2 in $ per dispensed kg, their ref. 5 (apparently based on data from competing central-plant providers), assumes that decentralized methane reformers at filling stations will deliver ~1.8–2.4× costlier H_2 than its leading vendor, or almost any other expert, believes (*10*).

The authors' claim of competitive LH_2 prospects, like their original leakage-rate claim, appears to rest on a deficient understanding of hydrogen and automotive technology and of their own citations of 10 October. Indeed, their refs. 2 and 4 describe LH_2's unpromising economics, their refs. 2 and 3 emphasize other storage technologies, and their ref. 7 shows that LH_2 receives less of GM's R&D funding than any other technological storage option.

Tromp *et al.* still don't acknowledge that H_2's atmospheric impacts would depend not on gross H_2 emissions, as they claimed, but on *net* effects, including how switching to H_2 would reduce or eliminate current anthropogenic H_2 and other (notably CO_2) emissions, depending on the H_2 production methods adopted. But first let's recognize that their claimed 10 to 20% gross leakage rate remains as absurd as when they first published it—too high by one or two orders of magnitude. Properly counting offsetting decreases in H_2 and other emissions would thus almost certainly decrease, not increase, net anthropogenic H_2 emissions to the atmosphere. Discussing when those emissions might occur and what they might do can wait until we get their sign right.

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1. All 12 are posted. Missing URLs are: ref. 2 at www.hut.fi/Units/AES/staff/hottinen.htm, ref. 3 www.jlab.org/hydrogen/talks/Milliken.pdf, ref. 6 http://media.gm.com/about_gm/vehicle_tech/fuel_cell/stationary/operation.pdf, ref. 9 http://216.239.53.104/search?q=cache:HqNOlgzXgc0J:www.h2cars.biz/artman/publish/printer_7.shtml+Hydrogen+goes+a+long+way&hl=en&ie=UTF-8, and ref. 12 www.clean-and-safe.org/task_forces/auto_safety/project.php?page=showcomments&id=89.
2. The authors' response ascribes a 2 to 4%/day range to their refs. 6 (3 to 4%/day), 7 (4%/day), 11 (4%/day) and 12 (1 to 3%/day), ignoring their ref. 4's 1%/day. Their ref. 2 cites a recent range from 0.06%/day for large to 3%/day for small tanks, and states that the losses "can be reduced through proper insulation." Their ref. 1 sets DOE loss targets of 2.4%/day in 2005 but only 0.12%/day in 2015, 15 to 30× less than they assume.
3. When parked, excess H_2 can be trickled into the fuel cell (an already-installed way to oxidize it safely and usefully) to top up the load-leveling device, to maintain minimum fuel-cell or car temperature in very cold weather, or to perform other standby functions.
4. The losses are low because cryoplanes' tanks would be kept cold continuously, their fuel used soon after filling, their boiloff used for fuel, and their time spent mostly in the cold

of high altitude, while major airports would use very large (hence low-boiloff) tanks fed by cryogenic pipelines, not by small truck- or railborne tanks, and could reuse boiloff to fuel stationary generators, such as those that power parked airplanes.

5. LH_2 has a greater volumetric density than high-pressure GH_2, but if compressed-GH_2 tankage is small enough to package, then what matters is system mass, which favors GH_2. The 35-MPa GH_2 SUV mentioned in the following paragraph stores 3.4 kg (137 L at 35 MPa) of GH_2 in three tanks totaling 26.2 kg plus 7 kg of filler, lines, regulators, etc. The H_2 mass is thus 11.5% of the filled tank mass or 9.9% of the filled system mass—exceeding the 9% DOE system-mass-fraction goal for 2015 cited in Eiler *et al.*'s reply's ref. 1, and comparing well with the 5.3–10.9% LH_2 range cited in their ref. 7. The Linde/GM cryogenic tank described in their refs. 10–11 weighs 90 kg and holds 4.6 kg of LH_2—a filled tank H_2 mass fraction of only 4.9%, or 57% worse than 35-MPa GH_2 tanks.
6. www.hypercar.com/pages/casestudies.php; A.B. Lovins & D.R. Cramer, "Hypercars®, hydrogen, and the automotive transition," *Intl. J. Vehicle Design*, in press, 2004.
7. The simulation yielded USEPA combined urban/highway driving performance equivalent to 2.38 L/100 km, 42 km/L, or 99 miles per US gallon, after multiplying all vectors in the USEPA driving cycles by 1.3 to emulate realistic on-road fuel economy. (The average MY2000 US small light truck was EPA-rated at 11.47 L/100 km or 20.5 mpg, but actually did 18.7% worse than that; the 1.3□ speed multiplier should at least compensate.) The simulation was independently performed by Forschungsgesellschaft Kraftfahrwesen mbH Aachen using an industry-standard second-by-second physics simulation tool and empirical component maps. Each driving cycle was run three times in succession to minimize any artifacts of the initial state of charge of the 35-kW load-leveling batteries. The platform's detailed virtual design was developed by Hypercar, Inc. and prime contractor TWR Engineering (UK).
8. Manufacturable at competitive cost at midvolume using Hypercar, Inc.'s patented Fiberforge™ process: D.R. Cramer & D.F. Taggart, "Design and manufacture of an affordable advanced-composite automotive body structure," *Procs. 19th Intl. Battery, Hybrid and Fuel Cell El. Veh. Sympos. & Exhibition*, EVS-19 (Seoul), www.hypercar.com/pdf/Hypercar_EVS19.pdf.
9. Apparently an odd reference to the energy required for liquefaction, currently ~40% of the H_2's Higher Heating Value, hence 47% of its Lower Heating Value (the energy content relevant to fuel cells), according to Eiler *et al.*'s references. This seems somewhat high: very large (>40 T/day) 2001 state-of-the-art liquefaction plants can reduce the 35% to 28%, and with more advanced techniques, to ~21%, or 7 kWh/kg. The theoretical minimum energy for converting 0.1-MPa (ambient-pressure) n-GH_2 to p-LH_2 is ~3.92 kWh/kg: W. Weindorf, U. Bünger, & J. Schindler, "Comments on the Paper by Baldur Eliasson and Ulf Bossel, 'The Future of the Hydrogen Economy: Bright or Bleak?'," including Addendum, July 2003, L-B-Systemtechnik, Ottobrunn, Germany, http://www.hyweb.de/News/LBST_Comments-on-Eliasson-Bossel-Papers_July2003_protected.pdf.
10. *E.g.*, C.E. Thomas, "Hydrogen and Fuel Cells: Pathway to a Sustainable Energy Future," http://66.160.67.66/PDF_Documents/whitepaper.pdf, which uses comparable or slightly more pessimistic assumptions (including a 9% higher gas price).
11. The writer holds options or shares, currently worth a total of less than $10,000, in three firms related to fuel cells, and chairs one of them (Hypercar, Inc.).