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The Next Generation of Automobile Emissions Reduction: Innovative Control of Off-Cycle Emissions

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ABSTRACT

Innovative heat management technologies can reduce emissions from cars by an order of magnitude. Substantial reductions would be realized during cold starts and in evaporative emissions. Such improvements result from a new class of variable-conductance steel vacuum insulations that insulate during one time period and take advantage of beneficial thermal conditions during another. Around a catalytic converter, for example, such control allows heat from one driving cycle to catalyze engine-out emissions occurring at the beginning of the next cycle. As with other more efficient uses of heat in automobiles, reduced complexity and cost are likely compared to supplemental catalyst heating systems. In a similar way, thermal cycling of fuel and the resulting vapor release can be reduced or avoided.

Urban air quality could be greatly improved by the wide availability of vehicles using these technologies early in the next century. This paper presents analyses and prototype data supporting the design, operation, and rapid market penetration of internal combustion engine vehicles with significantly lower emissions based on such improved thermal management. Potential implications for fleet emissions are discussed.

AMBIENT AIR POLLUTION

Air pollution caused by motor vehicles is a big problem. Numbers published by the U.S. Environmental Protection Agency (EPA) show that one-quarter to one-half of air pollution comes from motor vehicles.[1] In the case of carbon monoxide (CO), the overwhelming majority of motor vehicle emissions come from light-duty internal combustion vehicles.[2] More than 90 cities and airsheds are on EPA's list as failing to attain ambient air quality standards for one or more of six criteria pollutants.[3]

The criteria pollutants that are tied to automobile emissions are ozone and carbon monoxide (CO). Nitrogen oxides (NO_x) are also produced by all fossil fuel engines, as well as by every other fossil fuel combustion source. Lead used to be a direct tracer for automobile emissions, but the fraction of lead in the air from gasoline combustion is shrinking rapidly. Particulate matter is, like NO_x, pollution produced by motor vehicles and stationary sources. This paper will focus on ozone and CO, and on ozone's precursors, volatile organic compounds (VOCs) and NO_x.

CO emissions and ambient CO air pollution have been greatly reduced—despite an increase in vehicle miles travelled (VMT)—because of the emission control technology that developed in the late 1960s.[2] Unfortunately, this trend is reversing: by the year 2000, the increase in VMT is predicted to overshadow current technology improvements.[1]

Ozone is one of the most persistent and intractable ambient air pollution problems. Its atmospheric chemistry is complicated, with precursors of VOC + NO_x + sunlight. The VOC contribution itself is difficult to pin down because of widely varying reactivities and sources (anthropogenic and biogenic). NO_x is extremely difficult to control. While EPA predicts some further progress in mobile VOC emissions control before a levelling off, the outlook for mobile NO_x contributions is poor.

CONTROL OF AUTOMOBILE EMISSIONS

Emissions standards over the past few decades describe the major reductions that have taken place (Figure 1). To attain challenging goals, a wide variety of technology and transportation control strategies are being developed. These include a family of mandated low-emission vehicles (Figure 2) with near future dates for implementation, especially in California. Exhaust emission standards for *new* cars were first set in 1968 (1965 in California). Following the 1970 federal Clean Air Act, catalytic converter technology and electronic fuel control mechanisms were implemented to meet stricter federal emission standards. These emission standards today stand as a very small fraction of the level a few decades ago. The left bars in Figure 2 are the smallest set on the right end of Figure 1. The future mandate for further emissions points to a ideal state of zero emissions for new cars. California has some theoretical ideas for achieving these lower emissions standards that may not be supported by mass production technology but which would appeal to car customers.

This paper discusses new technological approaches that may support the attainment of these goals. These approaches are not production ready, but can be expected in the 5- to 10-year time frame.

In particular, we present a new technology that in laboratory and initial vehicle testing has demonstrated the potential for greatly reducing or eliminating cold start emissions. It may have further application in the reduction or elimination of evaporative emissions.[4,5,6,7] Both are emission sources that have often been thought to be intractable. Just as important, this new technology may achieve the reductions at a low net cost, with low or no maintenance, and with few balance-of-system effects.

COMPONENTS OF AUTOMOBILE EMISSIONS

In a hypothetical future vehicle that qualifies as an Ultra Low Emission Vehicle (ULEV), one estimate of the total emissions shows 25% coming from evaporative emissions, 30% from cold starts, and 45% from the steady-state operation of the engine (Figure 3).[8]

Steady-State

The engine-out emissions of today's automobiles are chiefly CO, NO_x, and a wide variety of other chemical compounds associated with combustion and generally categorized as hydrocarbons or VOCs. Their gross output is determined by a number of variables, the most important of which are the engine type, size, fuel, and operating characteristics. For light vehicles, the engine is typically a gasoline-powered piston type of four, six, or eight cylinders, with displacement from 1.5 liters to about 4 liters.

Post-treatment of automobile exhaust emissions with three-way catalytic converters is effective in converting most harmful engine-out pollutants to less noxious gases. Hydrocarbon conversion rates during steady-state or hot-stabilized operation, when neither the engine nor the catalytic converter are cold, are often higher than 90% for most pollutants (Figure 4).[9] Even with such high conversion efficiencies, the amount of time spent in the steady-state mode results in significant total emissions. Advanced engine designs will reduce engine-out emissions by better controlling air/fuel ratios and internal temperature extremes.

With generally smaller propulsion engines running cleaner and improved steady-state exhaust gas post-treatment, advanced emission mandates can be met. A mid-term goal for reduction in steady-state emissions of a factor of three from today's levels may be achievable, and is reflected in Figure 3.

Cold Start

Before the engine or catalytic converter in a typical car can be warmed by combustion, pollutants pass through the exhaust system and out the tailpipe untreated. This cold-start emission problem accounts for a majority of the tailpipe emissions from light-duty vehicles. Large reductions in cold-start emissions appear to be possible with a number of hardware solutions that ensure adequate light-off temperatures in the catalytic converter at or near the beginning of an operating cycle. For example, supplemental heating systems that use electric resistance elements or small gasoline burners can heat the catalytic converter in four to 20 seconds, depending on the system. The amount of energy used does not have a big effect on gas mileage, and amounts to a reduction of only about 1/10 mile per gallon over a typical driving cycle.

Catalyst heater technology can make dramatic reductions in cold-start emissions (Figure 5). With adequate thermal management of the catalytic converter, a tenfold mid-term emissions reduction goal may be achievable. This also is reflected in Figure 3.

Evaporative

The final component of today's automobile emissions is another thermally induced problem related to fuel storage and delivery (Figure 6). As shown in the graphic, stored fuel is now influenced both by heat from outside and by the constant circulating of fuel into and out of the hot engine compartment.

Evaporative emissions are all VOCs. They come from the fuel being stored in the fuel tank or other parts of the engine, and are caused by high temperatures during and between driving cycles. Outside heat sources, including the car's exhaust system, the sun, the road, and the circulation of fuel through the hot engine compartment, cause thermal cycling of fuel in the tank.

With nonrecirculating fuel delivery recently making its appearance in some automobiles, renewed attention is being paid to reducing the thermal cycling of the stored fuel itself. Simple insulation could be one way to reduce evaporative emissions significantly.

Without insulation the temperature of the fuel and the resulting evaporative emissions ramps up predictably when exposed to standard test conditions, as shown in Figure 7. With proper thermal protection of fuel storage, a mid-term goal may be achievable in which evaporative emissions are reduced by a factor of six below the emissions shown in Figure 3.

Meeting the emission reduction goals in all three of the above categories will result in total emissions lower than those otherwise projected for many low-emission vehicles.

TECHNICAL EMISSION CONTROL POTENTIAL

Steel thermos technology has been in use for more than 20 years, and NREL researchers have worked for several years on modifying and improving the technology. As can be seen in Figure 8, very thin steel panels containing a vacuum space can result in very high insulating performance. Such panels may need internal glass or ceramic spacers to prevent atmospheric collapse.

NREL researchers demonstrated a variable conductance feature that uses hydrogen as a heat transfer medium (Figure 9). While a maximum turn-down ratio of 200 (between insulating and conducting performance) appears possible, we have accomplished only about 100 to this point, with an insulating values of about R-20 at one time and R-0.2 at another.

Innovative heat management technologies can reduce emissions from today's cars by keeping the catalytic converter hot enough and the fuel storage cool enough to prevent pollutant discharge from untreated exhaust gas and evaporating fuel. In a catalytic converter with the variable conductance feature, dispensation of sufficient hydrogen into the vacuum space can make the catalytic converter wall a thermal conductor, shedding heat that might otherwise melt it. If the converter overheats consistently it could lose its potential for catalytic reaction. Overheated catalysts are common. This variable insulating technology can thermally regulate the catalytic converter to keep it below its high temperature failure point and, ideally, above its fully functioning light-off temperature.

By drawing the hydrogen back into the hydride, the catalytic converter wall once again becomes an insulator, and the catalytic converter retains the heat generated during the previous driving cycle. With this disabling mechanism shaped into a cylinder around an automotive catalytic converter, we've successfully held the temperature above 350°C for 17 hours (Figure 10). According to EPA measurements, more than 95% of all car starts occur within 17 hours after the car is turned off. Such performance may allow cold-start emissions that are one-tenth the ULEV levels (Figure 11).

Evaporative emissions are, again, a thermal management issue. By simply reducing or eliminating the thermal cycling of the fuel and fuel vapor, the resulting vapor release can be reduced or avoided. With smaller fuel tanks engineered into more efficient cars, vacuum insulation treatment could be considered for the thermal management of fuel temperatures. Evaporative emissions may be reduced below the ULEV levels by a factor of six (Figure 12).

Hybrid electric vehicles provide a special case where thermal management can greatly improve overall emissions. These electric propulsion cars typically use smaller, non-propulsion engines to generate electricity for battery recharge or to assist with passing power. Since those engines may be operated at a single point or within a limited range of speeds, engine-out emissions are greatly reduced. Battery propulsion also takes up part of the load, resulting in zero on-road emissions. Finally, post-treatment of the reduced engine-out emissions may be more effective. This encourages us to project a total steady-state emissions reduction from a hybrid electric vehicle of as much as a factor of eight.

These emission reductions are independent and cumulative. When we add them together we find a potential for sub-ULEVs that is encouraging for the cause of clean air (Figure 13). These reductions could be achieved in either gasoline or alternative-liquid-fueled vehicles, built by the millions on standard assembly lines.

CONCLUSIONS

With a large number of vehicles using these technologies, urban air quality could be greatly improved early in the next century. An early prototype variable conductance insulator was tested on an assembly line vehicle at a major U.S. manufacturer in 1994. In the first test of a prototype on a real car, total driving cycle tailpipe emissions of CO were reduced by more than 50%, and hydrocarbons were reduced by 30%. Sufficient laboratory prototype test data have been collected to determine that this technology has the potential to reduce gasoline engine automobile emissions to the same order of magnitude as ultra-low-emission vehicles and to potentially compete with zero-emission vehicles when total life-cycle emissions are included.

The technological potential for thermal management of emissions described here will work synergistically with improved efficiencies to greatly reduce future automobile emissions. The U.S. Office of Technology Assessment recently reported: "It is worth noting that the development of many of the efficiency technologies that apply to all powertrains (lightweight materials, low-friction tires, advanced aerodynamic designs, etc.) will yield a *gasoline*-fueled auto of considerable attractiveness, with a built infrastructure and built-in public acceptance, probably capable of attaining emission reductions that might reduce some of the critical environmental arguments against it."[10]

While our focus was on this new technology's potential to reduce mobile source emissions, it should be made clear that the best initial fit for these new techniques may be with that hybrid electric vehicles. Hybrids appear to offer the best compromise between emission reduction requirements and market demand for reliable, low-cost vehicles.

Such emission reduction strategies will require close cooperation with regulatory agencies if they are to be commercialized. Regulators are not interested in quick fixes based on calibrations that cannot be maintained over the life of a car. Solutions must demonstrate structural and operational durability. If the challenge for new technologies is to prove durability, a costly and necessary exercise to obtain user acceptance, then a serious question for air quality analysis is whether better, cheaper, and more efficient technologies can realistically make it to market.

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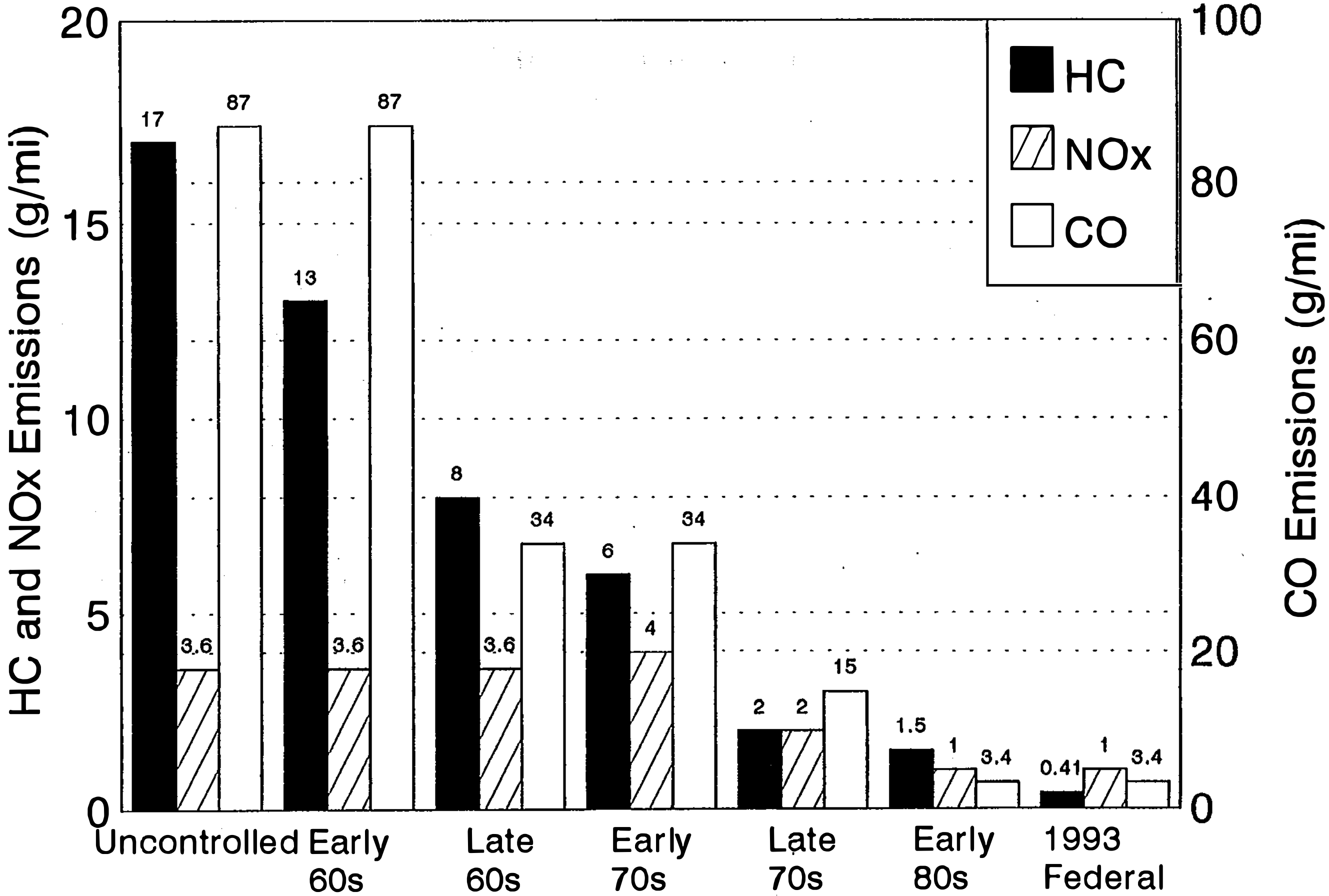

Figure 1. Historical progress in passenger car emissions control.

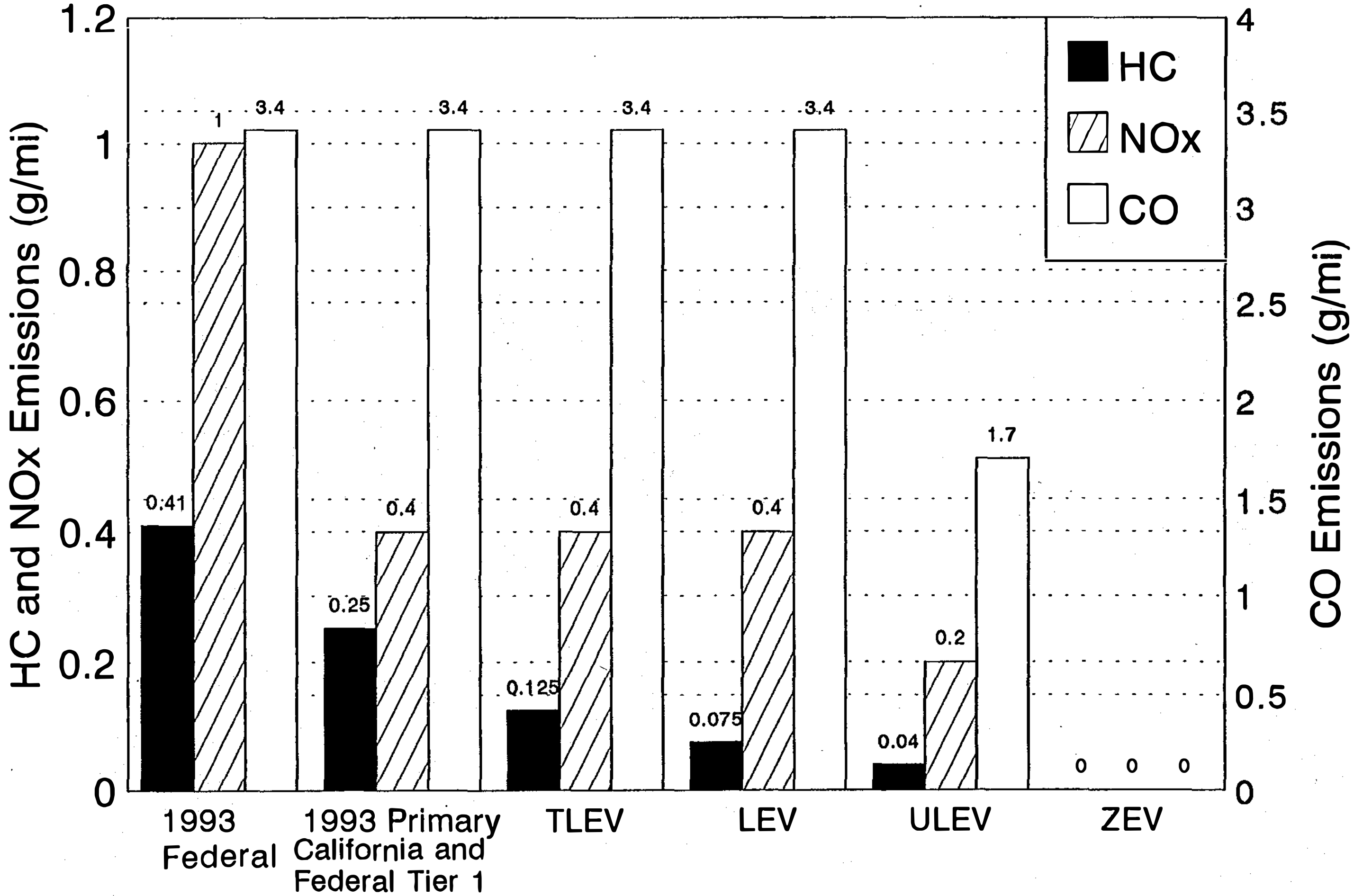

Figure 2. Recent evolution of passenger car exhaust emissions standards.

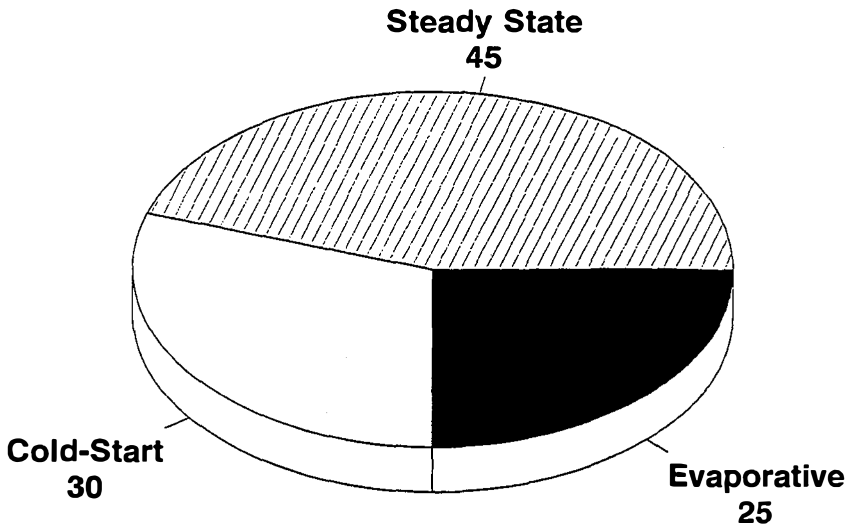

Figure 3. Projected ULEV emissions (%)

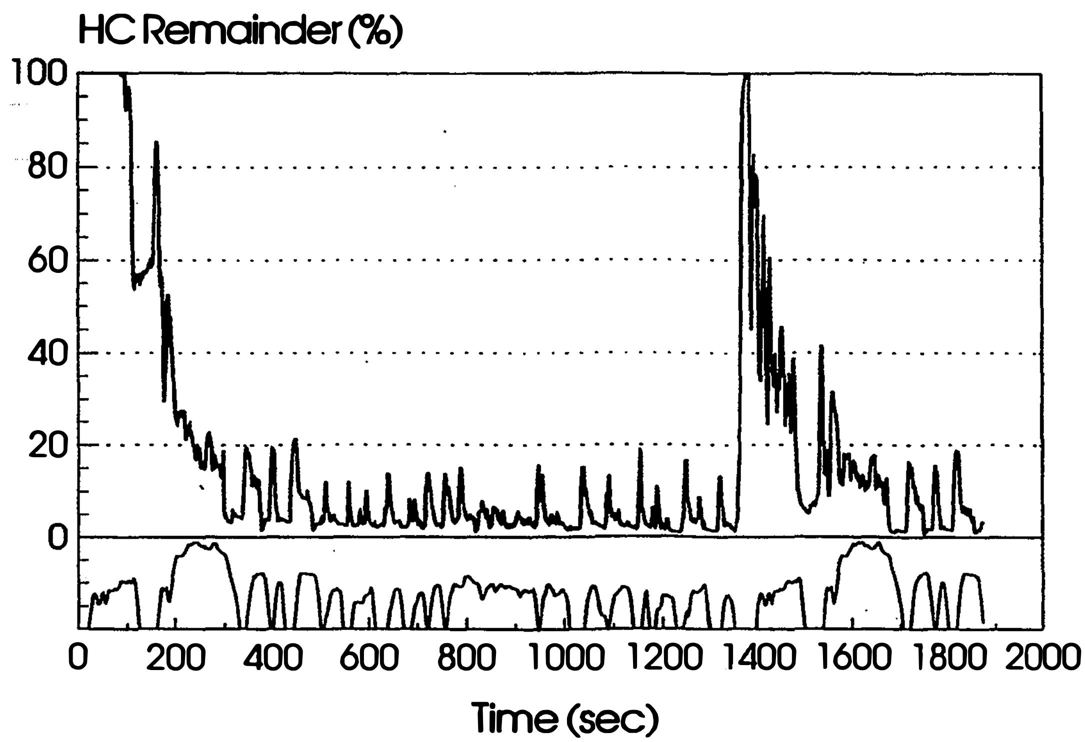

Figure 4. Cold-start hydrocarbon emission breakthrough shown by Bag 1 and Bag 3 spikes.[9]

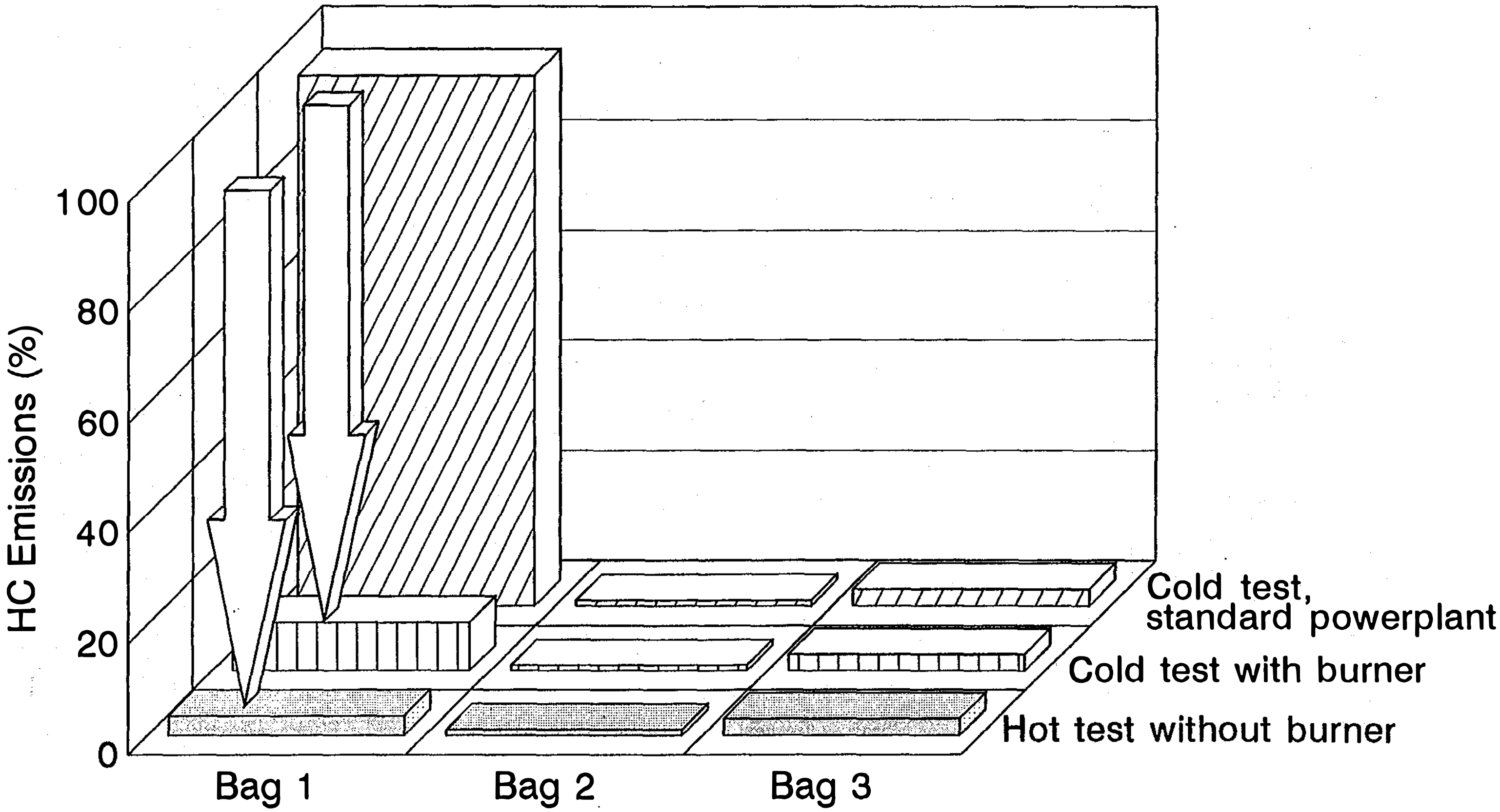

Figure 5. Potential for reduction of exhaust emissions.

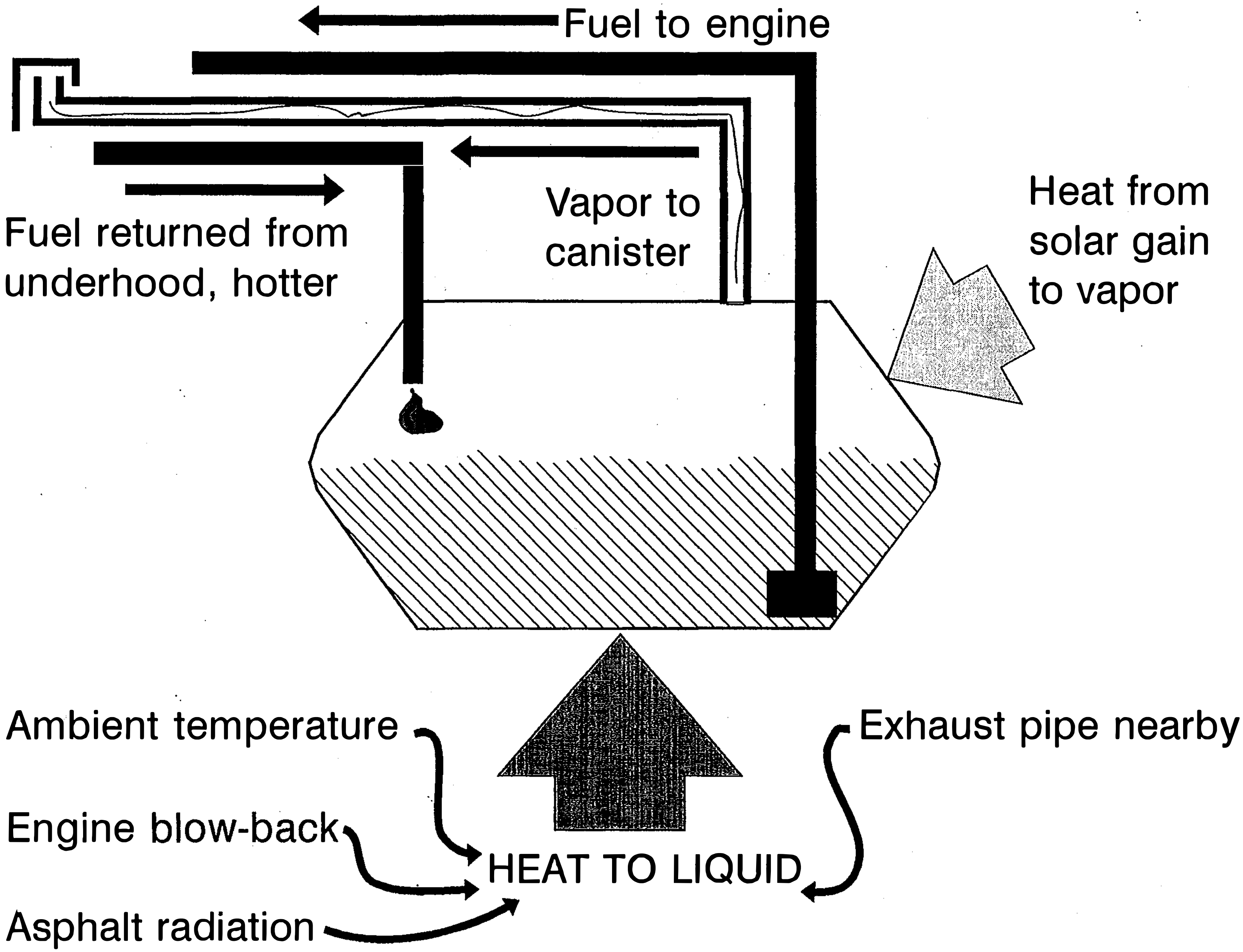

Figure 6. Thermal drivers of fuel evaporation.

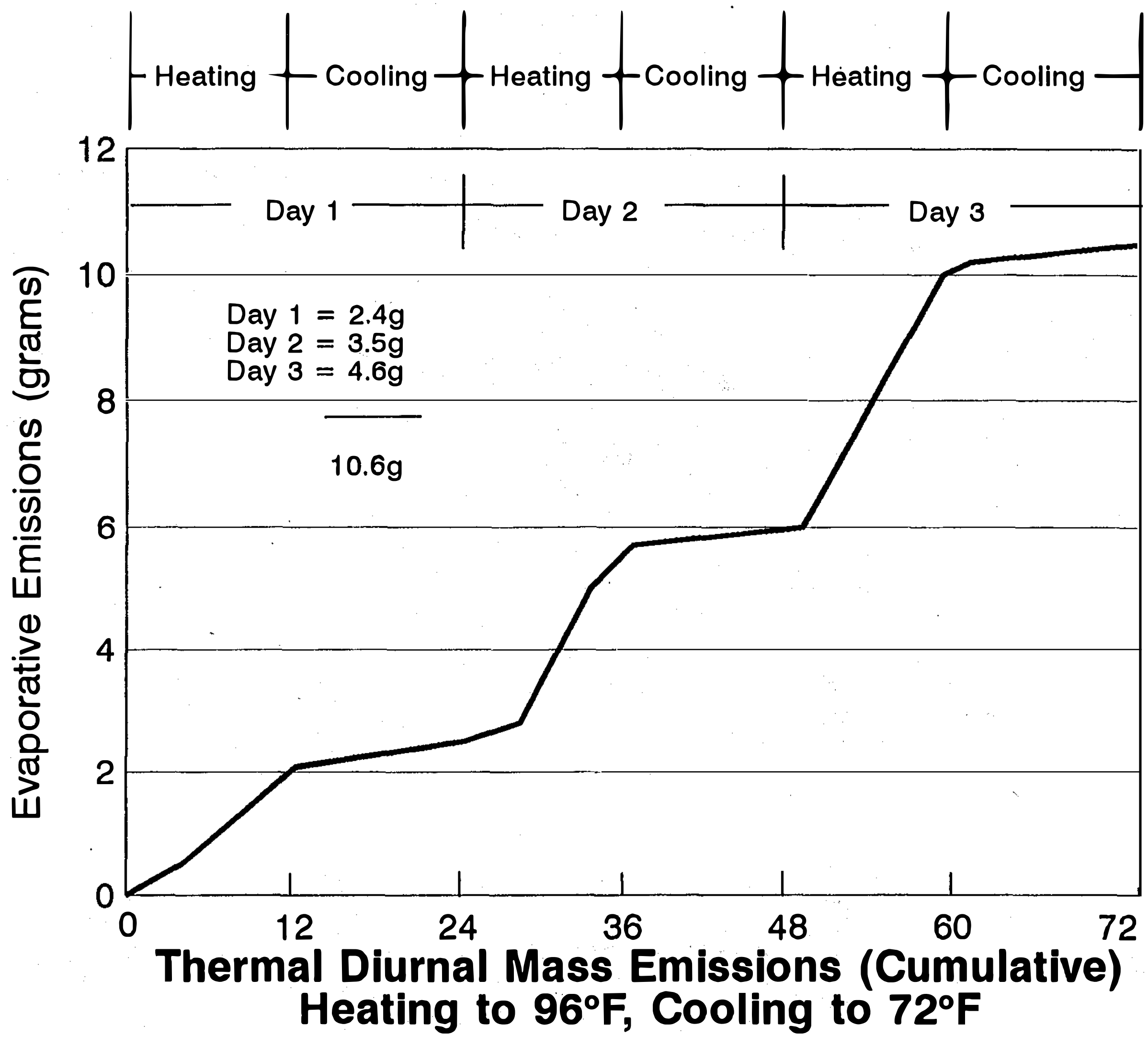

Figure 7. Ramping of evaporative emissions with extended hot soaks.[11]

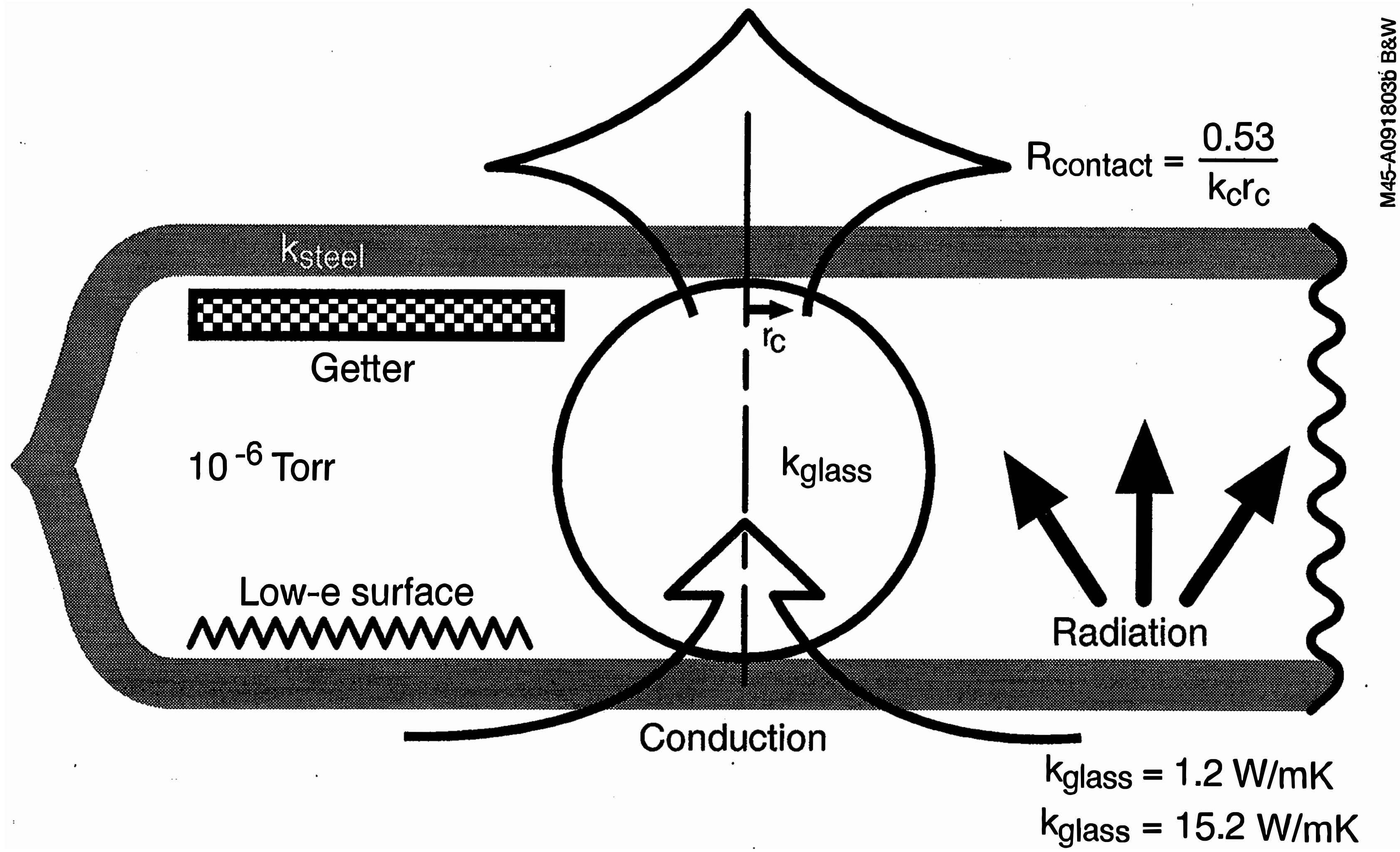

Figure 8. Steel vacuum insulations have a potential of R100 per inch versus R5 for foam, and they are durable and structural.

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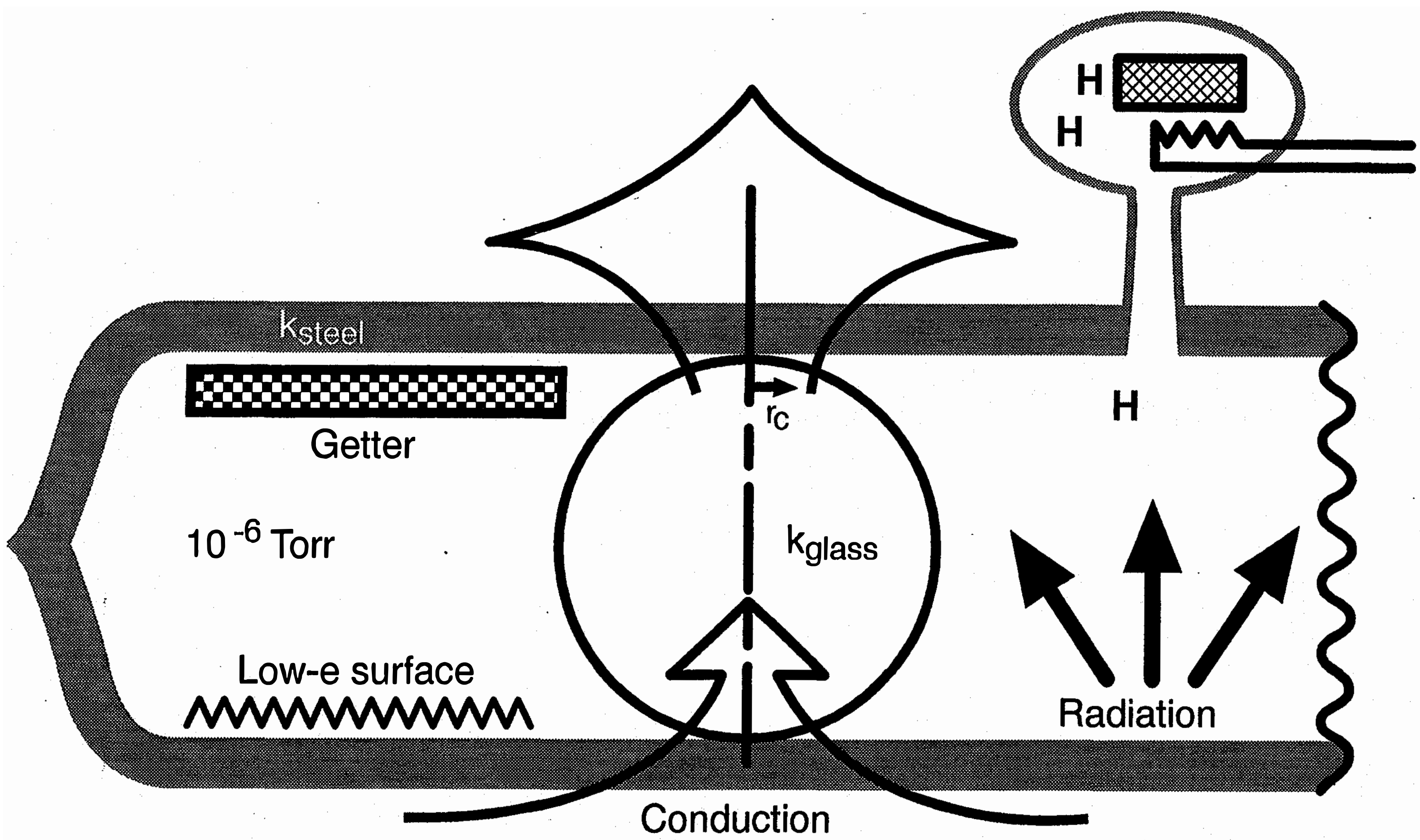

Figure 9. Variable conductance insulations have a reversible disable feature; the gas mechanism is shown.

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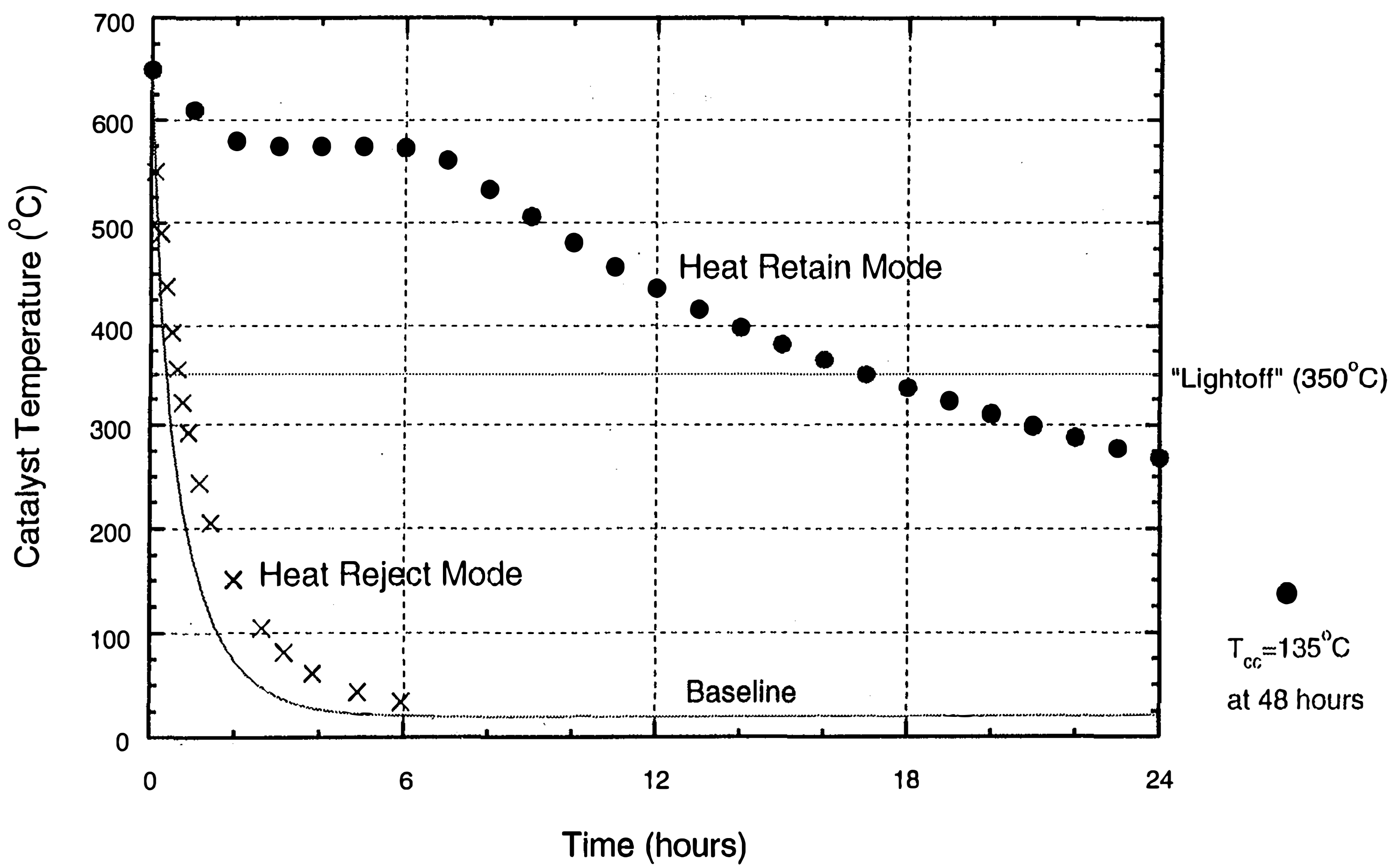

Figure 10. Thermal data from experimental catalytic converters in which temperatures were held above light-off for 17 hours.

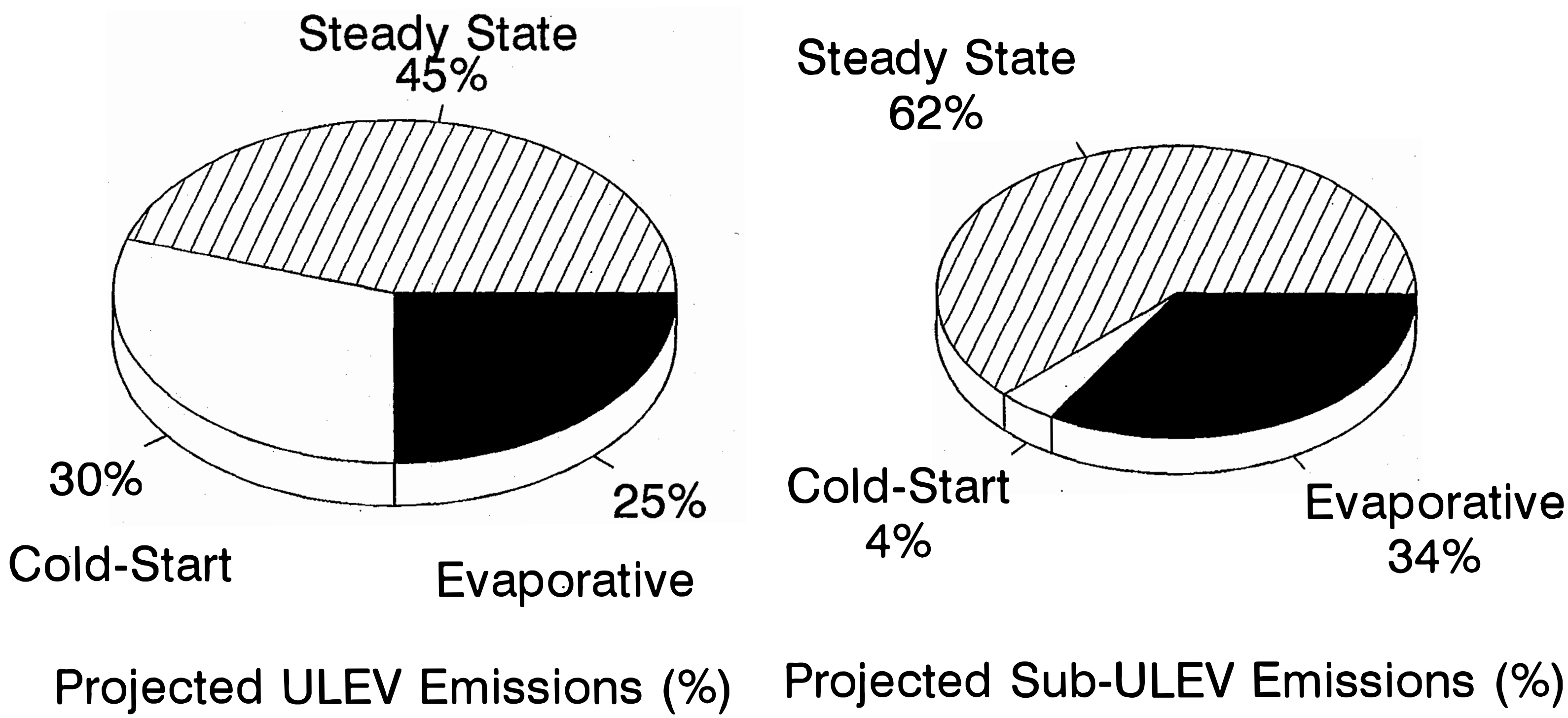

Figure 11. Potential cold-start emission reductions, assuming that thermal-hold feature can reduce cold-start emissions to one-tenth of the base case.

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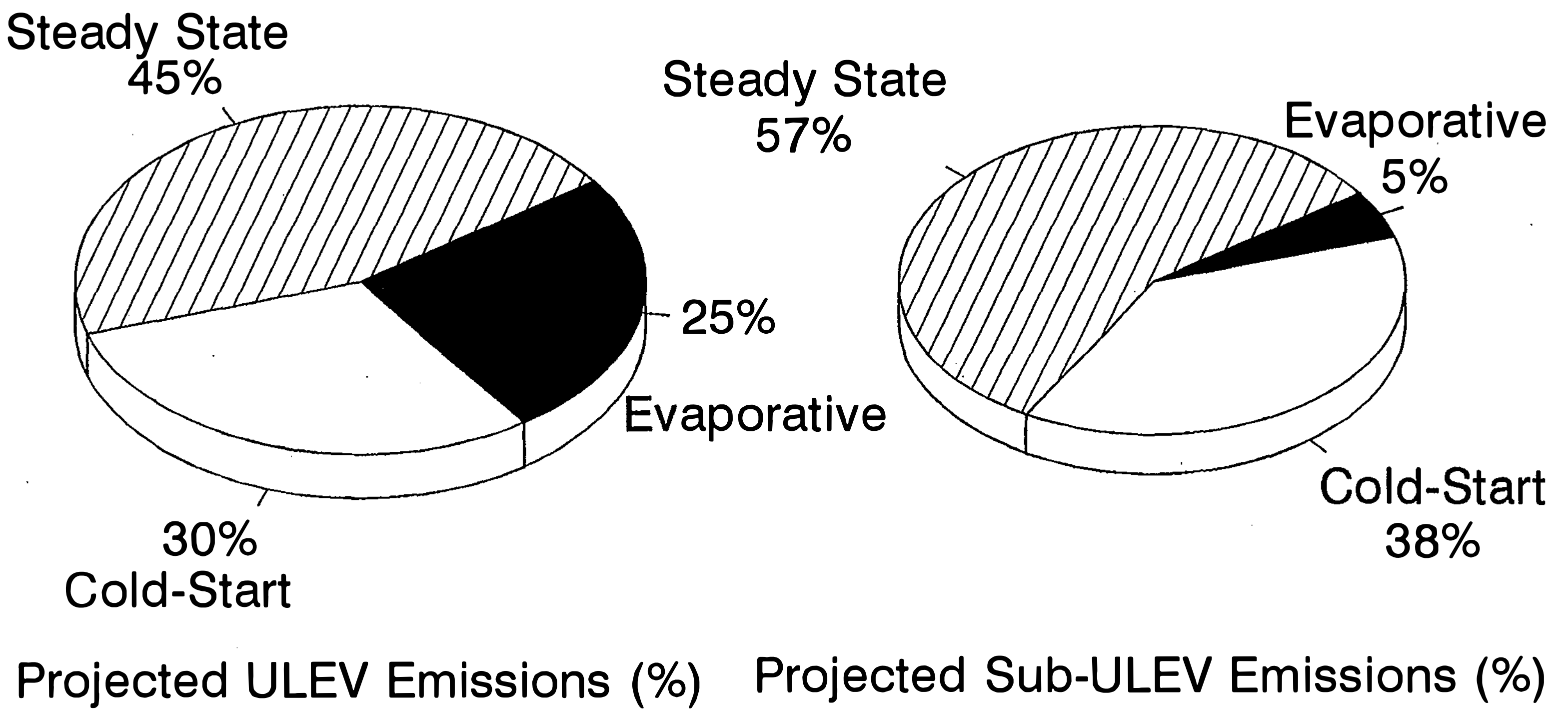

Figure 12. Potential evaporative emission reductions, assuming that the thermal control feature can reduce tank evaporation to one-sixth of the base case.

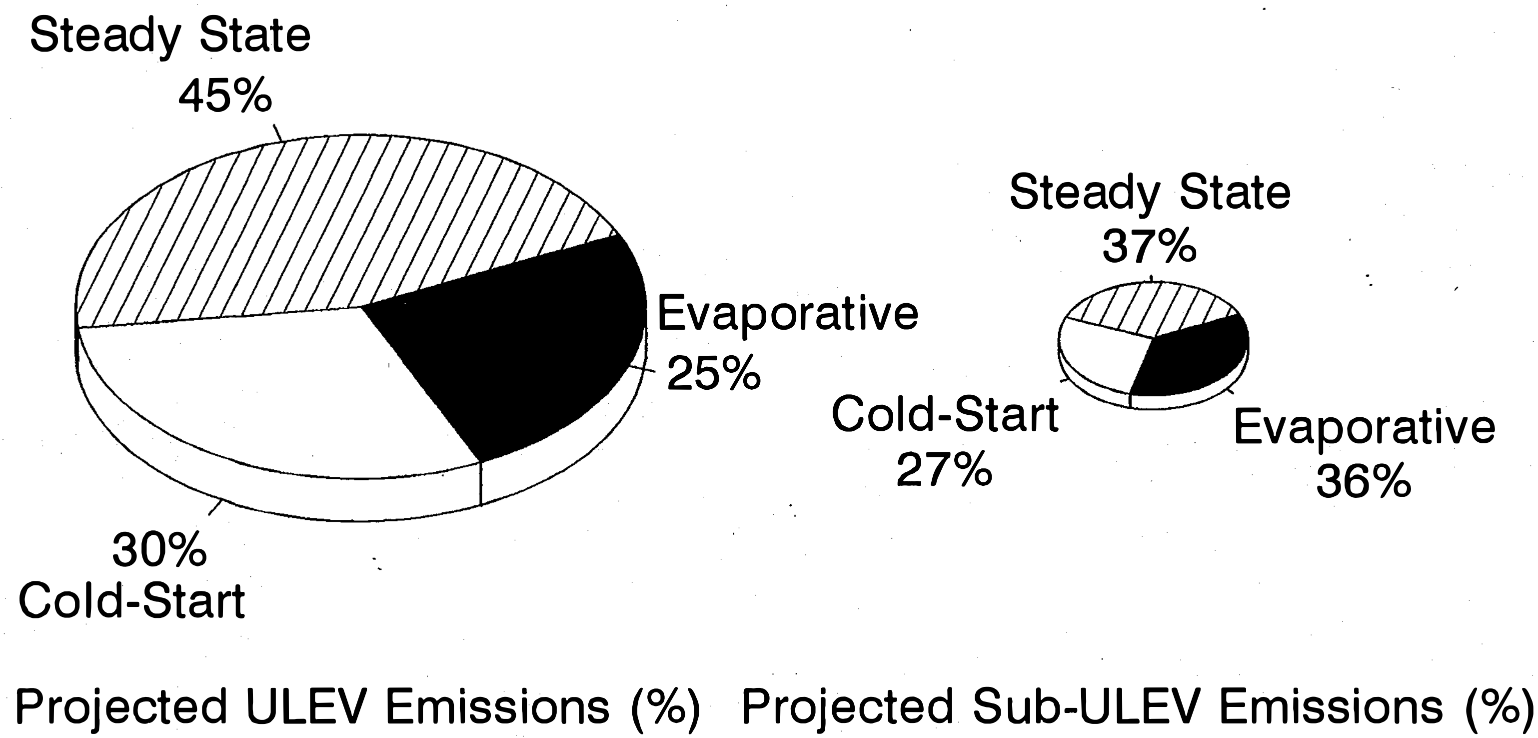

Figure 13. Potential of additive emission reductions.