Next Generation Refrigerants:
Standards and Climate Policy Implications of Engineering Constraints

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ABSTRACT

There is no single perfect refrigerant for diverse air conditioning, refrigeration, and industrial applications. The predominant halocarbons (CFCs, HCFCs, and HFCs) combine excellent efficiency and safety with acceptable costs. However, they contribute to ozone depletion potential (ODP) and/or global warming potential (GWP). The Montreal Protocol has eliminated ODP by requiring replacement of CFCs and HCFCs with HFCs such as R-410A, R-407C, and R134a. The next focus is a worldwide technical and policy search for next-generation refrigerants with low global warming potential (LGWP). Potential options include "natural" refrigerants such as carbon dioxide (CO_2), hydrocarbons (HC), and ammonia (NH_3) as well as HFOs and HFO/HFC blends. All involve significant trade-offs among GWP, energy efficiency, safety, and cost. Environmental policy must consider the indirect effects of increased CO_2 emissions for less efficient refrigerants, not just the direct global warming (GWP) of the refrigerant. We must insist on using metrics such as *Total Equivalent Warming Impact* (TEWI) that balance refrigerant direct GWP, charge level, leakage emissions, and efficiency of the refrigerant in actual systems. This allows the best possible comparison of refrigerants for each application. In the right policy environment, we can achieve reduced environmental impact and increase efficiency. This will probably require increased differentiation of application-specific refrigerant choices that are associated with somewhat higher first costs but very attractive life cycle costs with acceptable safety and environmental impacts.

Background

One of the major transformations of the 20th Century is the widespread use of modern, effective, and safe space air conditioning, particularly for the hot climate in the South and Southwest of the U.S. Modern comfort air conditioning (and refrigeration) has been based on vapor compression cycles that rely on high-performance refrigerants that are safe, chemically stable, have good thermodynamic and thermophysical properties, and deliver cost-effective systems. Fluorocarbons have been the overwhelming choice for half a century, largely replacing the toxic sulfur dioxide and ammonia, the less cyclically efficient carbon dioxide, and the flammable hydrocarbons used earlier in the century.

Beginning the early 80's, CFC refrigerants containing chlorine (such as R-12) were found to diffuse up into the stratosphere. This chlorine was the principal cause of destruction of the ozone layer which protects life on earth from excess ultraviolet light. The hazard is represented by the refrigerant *ozone depletion potential* number (ODP). Subsequently, the Montreal Treaty banned CFCs for new equipment as of 2000. Further study implicated HCFCs used widely in unitary air conditioning, such as R-22, despite its low 0.05 ODP. Thus, HCFCs have been banned from new equipment as of January 1, 2010 in the U.S. except for aftermarket services.

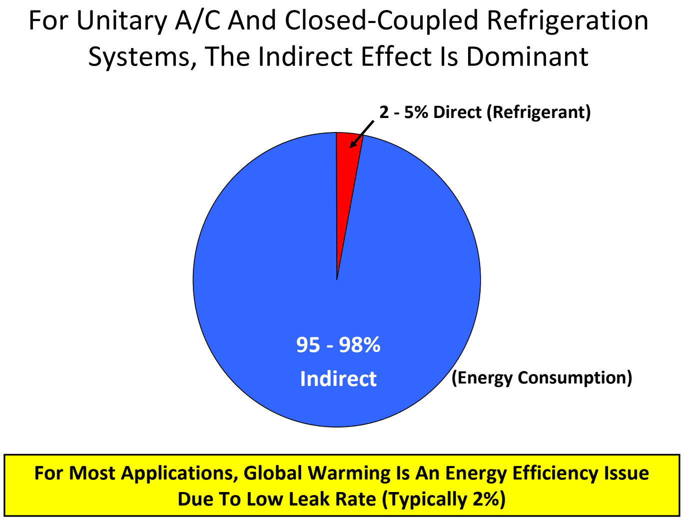
They have been replaced in most applications in the US with HFC-134a, and HFC blends such as R-410A and R-407C, compounds without chlorine, but only hydrogen, fluorine, and carbon.

But note that bad things happen *only when refrigerants are released into the atmosphere*. Mobile A/C and large supermarket refrigeration systems have been reported to leak up to 30% annually. [1] However, stationary air conditioning and refrigerator equipment shipped from the factory with sealed refrigeration systems has much lower leak rate about 2% annually and typically operate through their long life up to 20 years with little recharging service. Rather than banning HCFCs from air-conditioning equipment, an alternative approach might have been to contain/reduce leaks in equipment that is not sealed from the factory, and to require capture and reclamation of all refrigerant during servicing, instead of venting to the atmosphere. After all, there's no actual harm in use, only in release to the atmosphere. Although much progress was made in reducing refrigerant leakage from large centrifugal chillers, policy makers chose to ban the chemicals instead of regulating handling and use, setting an important regulatory precedent.

Indeed, climate preservation concerns broadened since the original CFC discoveries. In the upper atmosphere, the carbon-fluorine bond in fluorocarbons acts like carbon dioxide, reflecting longer-wave infrared radiated by the warm earth back to the earth, contributing to climate change through anthropogenic global warming. Thus, atmospheric chemists and policy-makers now consider the *Global Warming Potential* (GWP) of refrigerants, not just their ODP. The European Union has proposed to ban the use of refrigerants with GWP > 150 after 2011, effectively banning R134a in new mobile A/C. Recently, the U.S. Congress proposed to phase down the production of HFCs based solely on their GWP value with production cap beginning at 90% in 2012 and ultimately at 15% in 2033. [2]

This may be appropriate, but incomplete, because the refrigerant leak rate and/or the refrigerant's impact on energy use affect overall warming. The direct warming from high leak rate in Mobile A/C and Supermarket Refrigeration relative to energy use is much higher (*30-50% of the total)* than that in unitary Air Conditioning where the leakage contribution is much lower (< *5%)* as shown in Figure 1. From Figure 1, it is clear that even a modest difference in system efficiency can overwhelm the direct climate effect of a low GWP refrigerant.

Figure 1. The Small "Sliver of Direct GWP Effect" in Unitary A/C



The indirect impact of energy use on warming also depends on the mix of fuel sources used to produce electricity. Average electricity production in U.S. (the mix of coal- and natural-gas burning, plus hydropower and nuclear) emits about 0.65 kg CO_2/kWh [3]. Of course, CO_2 is a major greenhouse gas, so we have an uncomfortable situation: Depending on the mix of fuels that provide our electricity, a more efficient refrigeration system with a higher GWP may have *less* overall impact on climate than a less efficient refrigerant with lower GWP. This concept, which is named *Total Environmental Warming Impact* (TEWI), is one critical criterion in choosing the next generation of refrigerants. The direct *Global Warming Potential* (GWP) misses most of the impact of some refrigerant choices.

Depending on the mix of electricity sources that emit different amounts of CO_2/kWh, one system will be associated with more global warming than the other. That is, an air conditioner installed in Portland, Oregon will have a different TEWI than the same air conditioner in an identical house in Columbus, OH, even at the same indoor and outdoor temperatures. That's just because there's less CO_2 and thus lower TEWI and less effective global warming from the hydro-rich electricity sources in Portland than the coal-rich sources in Columbus. Thus, TEWI is a system construct at all scales: refrigerant, compressor, equipment, and electric grid. If requiring a low-GWP system leads to an inefficient system with much higher TEWI (and thus more climate impact), this would not be a good engineering trade-off. ***Lower refrigerant efficiency will require larger heat exchangers thus higher refrigerant charge***. This would be counter-productive for meeting warming reduction targets as efficiency standards increase. This may be an ***unintended consequence***.

Goals of this Paper

This paper is about trade-offs like those discussed above (*direct GWP vs. Efficiency*) for the next generation of refrigerants. There is no easy or obvious solution. As a metaphor, think about compressors as the prime movers, or engines, of almost all refrigeration systems. In this metaphor, their efficiency is limited by the "octane" of the "fuel". Its thermophysical properties also affect heat exchanger pressure drops and heat transfer. Refrigerants that have lower potential for efficient systems imply other factors have to be improved to maintain efficiency. This might be some combination of higher compressor cost, larger heat exchanger size, or accepting more flammability or toxicity in some applications. Widespread use of more flammable refrigerants will require very different equipment design as well as handling and use requirements which add costs.

In this context, a key goal of this paper is to encourage policy makers to apply good engineering and environmental judgments in selectively regulating refrigerant fluids based on specific applications and availability of better replacements. We also argue that *efficiency is much more important to overall global warming than direct GWP, and TEWI is a better criterion for selecting refrigerants.*

Another goal is to urge a dialogue among all stakeholders about the raging rapids ahead, to introduce an illustrative tool for the dialogue, and perhaps to speculate a bit about a future that may see more refrigerant differentiation by application. We focus on stationary air conditioning and refrigeration.

Discussion of Trade-Offs

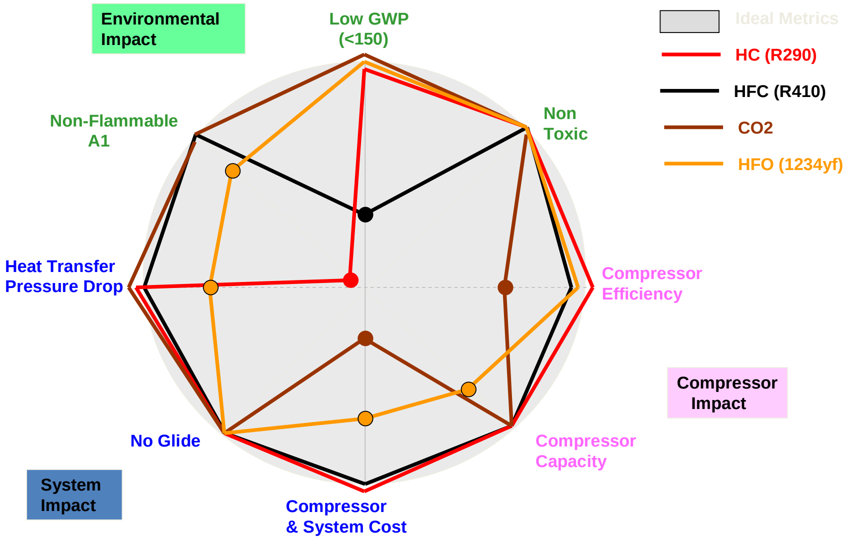
In response to the global climate issue, some refrigerant applications have migrated to "natural" refrigerants wherever acceptable. For example, Europe adopted hydrocarbons (HC) as a LGWP substitute for R134a in household refrigerators where the refrigerant charge is less than 150 grams and the system is hermetically sealed, so the safety risk is manageable. However, the high flammability of HCs has restricted adoption for higher-charge air conditioning applications. Japan developed CO_2 as LGWP solution for heat pump water heaters due to its attractive heating performance. However, CO_2 suffers from 10-15% lower system efficiency [4] than existing HFCs in air conditioning, particularly worse in hotter climates. Its efficiency could be improved by using two-stage cycle or adding expander or ejector but at significant additional cost. Its ultra high pressure requirements also raise equipment costs.

A new refrigerant named HFO-1234yf with a low GWP of 4 has been developed by chemical producers as a potential replacement for R134a. [5] This refrigerant is mildly flammable, but its safety risk has been deemed manageable by mobile A/C manufacturers, due to its relatively low charge (<1 kg). However, this risk would have to be re-assessed for the higher charge of unitary A/C applications like residential and light commercial air conditioners. These require about 1.0 kg of R410A per ton of capacity. Thus, a 5-ton A/C may take up to 5 kg of charge, equivalent to about half of the capacity of a propane grille tank. Moreover, HFO-1234yf has drawbacks as a replacement for R410A or R407C in unitary air conditioning: its low heat capacity, resembling R134a, requires larger heat exchange coils and cabinets.

So, the search for LGWP solutions continues for air conditioning. In a real sense, we've run the table for air conditioning. That is, some of the best chemists have been working on this issue, and we're about out of likely candidates on the Big Table, the Periodic Table of the Elements:

	Advantages	Disadvantages
Propane	Good Efficiency, low cost	Highly flammable
CO_2	Excellent GWP=1	Low Efficiency, System Cost
HFC-410A	Good Efficiency	High GWP
HFO1234yf	Excellent GWP=4	R134a-like capacity, mildly flammable

Figure 2. Tradeoffs in Replacing R410A



Note: As an example, propane (HC, R290) has low GWP and toxicity, and is good in all other properties *except* high flammability.

Figure 2 illustrates the tradeoffs in searching for a LGWP refrigerant solution with regard to the key desired attributes related to GWP, compressor and system performance/cost. In this "spider" diagram, the points on the outer radius for each property are preferred. For climate performance, it is preferable to have a refrigerant with GWP <150, and it should be non-toxic, non-flammable, and chemically-stable. For the compressor, it is important to have good thermodynamic properties for its capacity and isentropic efficiency. For the system/heat exchangers, good thermophysical properties and low temperature glide (preferably < 7°F) are needed for better heat transfer and pressure drop in practical, economical, air-cooled heat exchangers.

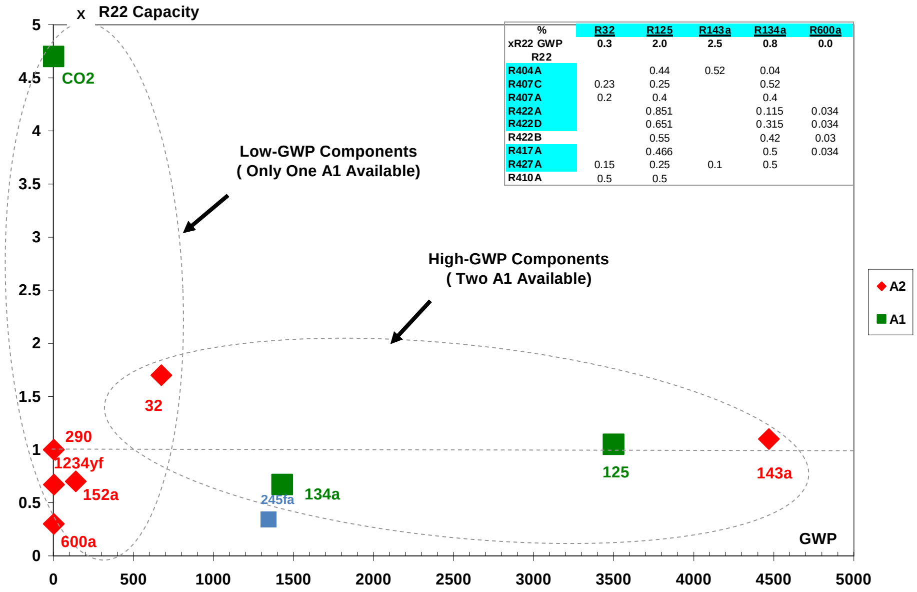
One potential solution is the concept of blending the new refrigerant HFO-1234yf with the existing HFCs to achieve higher capacity at slightly higher GWP. These mixtures are referred to as HFO blends. Thus let's review which existing HFCs are feasible and attractive for blending as well as what compositions would offer the best overall solution to balance the HFO-1234yf disadvantages.

Figure 3 shows several known single refrigerants by their GWP, safety and capacity relative to R22. Several blends are listed in the small table at top right of this figure including the widely used R410A. In unitary A/C applications, toxicity is generally not acceptable. Thus, refrigerants such as ammonia (NH_3), R1225 (fluorinated propene isomers) and CF3I (trifluoroiodomethane) are excluded because of their toxicity. Next, the refrigerants are differentiated by flammability class either as non-flammable (A1), highly flammable (A3) or mildly flammable (A2L) as recently adopted by ASHRAE 34 and ISO 817. In general, the HCs are in the A3 class and the HFOs are in A2L class.

The A2L class such as HFO-1234yf presents both a new LGWP opportunity and a new challenge in re-assessing the flammability risk level for the various applications. Except for CO2, most of the low-GWP refrigerants (<150 GWP) are flammable. Because of its ultra-high pressure, mixing CO2 with low-pressure HFO-1234yf would result in a zeotropic mixture with temperature glide too high to be acceptable for practical air-cooled heat exchanger. Mixing HC

R290 with HFO-1234yf could help balance the low-capacity of 1234yf but the blend flammability will likely still be A3 thus difficult for use in unitary A/C with higher charge.

Figure 3. TradeOffs Between GWP, Flammability & Capacity

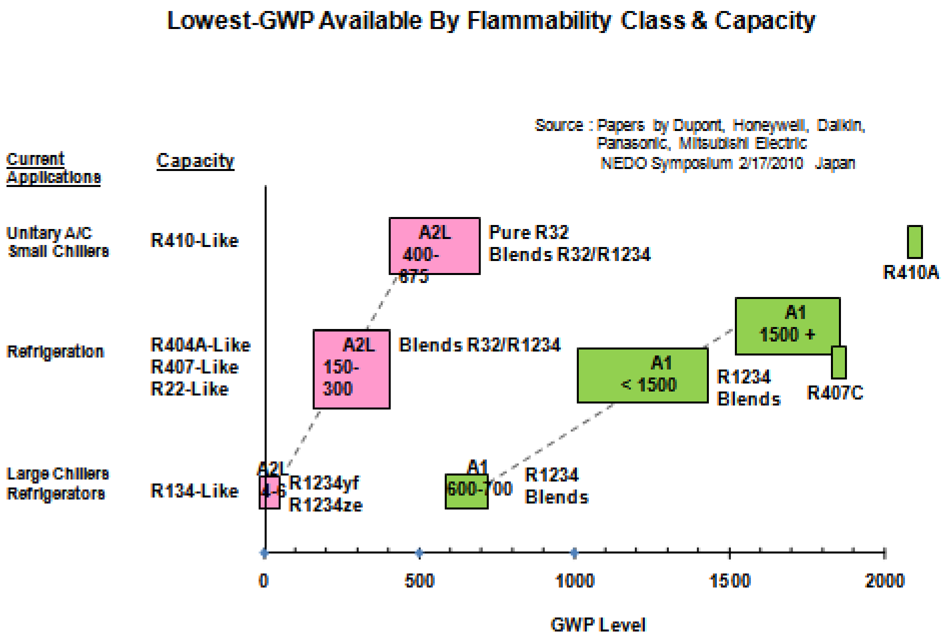


%	R32	R125	R143a	R134a	R600a
xR22 GWP	0.3	2.0	2.5	0.8	0.0
R22					
R404A		0.44	0.52	0.04	
R407C	0.23	0.25		0.52	
R407A	0.2	0.4		0.4	
R422A		0.851		0.115	0.034
R422D		0.651		0.315	0.034
R422B		0.55		0.42	0.03
R417A		0.466		0.5	0.034
R427A	0.15	0.25	0.1	0.5	
R410A	0.5	0.5			

Mixing with higher-GWP A1 refrigerants like R125 (Pentafluoroentane) may not achieve low-enough GWP due to its high 3500 GWP. Mixing R134a and HFO-1234yf does not solve the low-capacity issue. However, one notable refrigerant in this class is R32 (Difluoromethane) with an A2L rating and a moderate GWP of 675. During the 90's, the Air Conditioning, Heating, and Refrigeration Institute did evaluate R32 during its Alternative Refrigerants Evaluation Program (AREP). [6] R32 is 50% of the composition of the R410A blend, but 5-10% higher capacity, and has better system heat transfer/pressure drop properties. R32 stands out a potential good choice for blending with HFO-1234yf to achieve lower than its 675 GWP. The only tradeoff is that mixing R32 and HFO1234yf will still be an A2L flammable refrigerant, which would still present a new challenge for the industry. Another challenge with R32 is that it has higher compressor discharge temperature, thus more auxiliary cooling may be required at very hot ambient or low-temperature refrigeration conditions.

Figure 4 shows the possible GWP range for the various potential solutions classified by capacity/pressure that are R410A-like, R22/R407-like, and R134a-like, and also by flammability rating A1 or A2L. These refrigerants cover most of the current applications, R410A and R22 in unitary A/C, R407A/C for retrofits, R134a for large chillers and small commercial refrigerators. This chart is developed based on several papers from the NEDO conference in Japan. [7] The R32/HFO1234yf blends could offer equal or better efficiency than R410A in the GWP range of 400-675 based on several papers from the NEDO conference in Japan. This GWP range is because these HFO blends require at least 50% of R32 to achieve comparable capacity and efficiency to R410A. [7]

Figure 4. GWP vs. Flammability TradeOffs for R32/R1234 Solutions



Source : Papers by Dupont, Honeywell, Daikin, Panasonic, Mitsubishi Electric NEDO Symposium 2/17/2010 Japan

Figure 5 shows the tradeoff between direct GWP and indirect Efficiency relative to R410A for several solutions including the new HFO blends. For example, CO2 offers the lowest direct GWP but is the lowest on system efficiency (87% of R410A) resulting in higher TEWI. Highly flammable R290 (propane) is as efficient as R410A, but if a secondary loop (SL) has to be added for acceptable safety, then its system efficiency could drop to about 90% of R410A. In general, lower GWP is associated with lower efficiency or higher flammability or toxicity. R32 has been shown to be 2-3% higher system efficiency than R410A during the AHRI AREP 90's program. [6,12] Based on reports from the NEDO symposium on Feb.17, 2010 in Japan,[7] it is expected the R32/HFO1234yf blends would lie somewhere between R32 efficiency level (+2% better than R410A) and HFO1234yf level (-10% worse than R410A) depending on its composition as shown by the clouded area. In other words, the higher the HFO1234yf content in the blend to reduce GWP, the lower the efficiency.

Figure 5. TradeOffs Between GWP & Efficiency

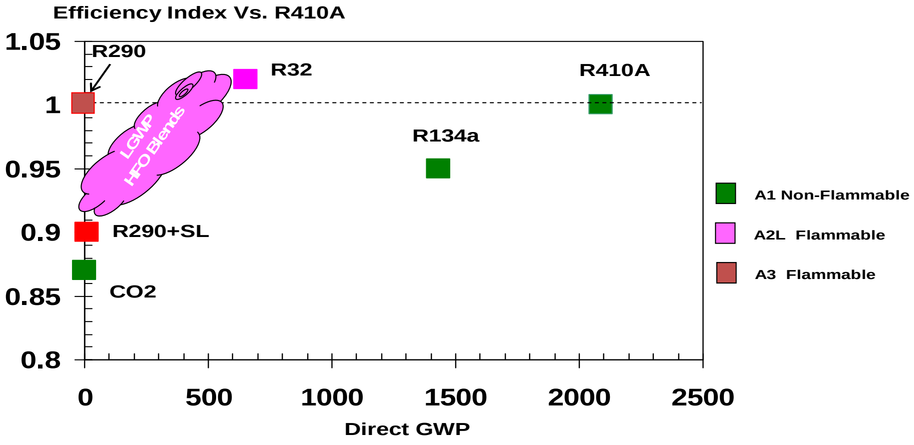


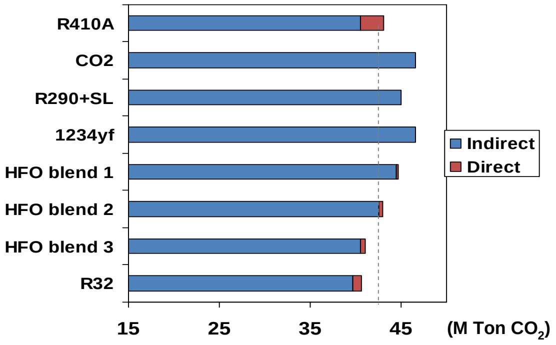
Figure 6 compares TEWI for several refrigerant options, with the stated assumptions. R32 and R32/HFO1234yf blends could potentially lower TEWI relative to R410A, with high enough R32 content. The blend could have worse TEWI if trying to get too low of a GWP such as 150 with too high HFO1234yf content. Several Japanese researchers reported at the NEDO Symposium that the blend needs at least 50-60% R32 (338-405 GWP) to get close to R410A efficiency.[7] But, remember that the direct GWP of pure R32 is 675, higher than the European goal of 150 for 2011.

Figure 6. TEWI as a Criterion for Selecting Refrigerant

Total Equivalent Warming Impact (TEWI)
Key Criteria For Selecting A/C Refrigerant

TEWI = **Indirect (Efficiency)** + **Direct (GWP)**

Source : Papers by Dupont, Honeywell, Daikin, Panasonic, Mitsubishi Electric
NEDO Symposium 2/17/2010 Japan



	Efficiency	GWP	TEWI
R410A	13.0 SEER	2088	43.1
CO2	- 13%	1	46.5
R290+SecLoop	- 10%	3	45.0
HFO-1234yf	- 13%	4	46.6
HFO Blend 1	- 9%	150	44.7
HFO Blend 2	- 5%	300	43.0
HFO Blend 3	+ 0%	400	41.1
R32	+ 2%	675	40.6

2% Annual Leak Rate
0.65 Kg CO_2/ kwh
15 Years Life Time

- **Energy Efficiency Is Key To Reducing Total Emissions**
- **Properly-Selected HFO Blends May Offer Lower TEWI Than R410A**

From the above analysis, the R32/HFO1234yf blends do not seem to offer lower TEWI over single R32 albeit offering lower GWP. Moreover, according to EPA Significant New Alternatives Program (SNAP) document, [8] HFO1234yf could cost up to $40-50 per pound initially, thus making this less attractive for such an incremental reduction in direct GWP compared to R32 which offers already a 68% reduction in GWP over R410A in addition to its 2-3% efficiency gain. In addition, R32 heat exchanger optimization may even increase efficiency further, due to R32's superior pressure drop and heat transfer characteristics. The only remaining challenge is its A2L flammability which is also same for any HFOs.

Implications by Applications

The above discussion implies that each equipment application with R410A, R404A, or R134a will likely require an optimized LGWP solution for best TEWI as illustrated in Figure 5. The most likely outcome is selecting different refrigerants for different kinds of equipment. The first of these transitions is underway today in Europe. For the long-lived, low-charge (<150g), low-leak sealed systems such as domestic refrigerators and beverage vendors, manufacturers and government officials have agreed that HCs such as isobutane, although highly flammable, are acceptable. Isobutane offers very low GWP, good performance at low cost and is compatible with inexpensive, easy-to-handle mineral oils. *The trade-off is manageable* in this application.

Carbon dioxide, (CO_2) is already the refrigerant of choice for some specialty applications. About two million "EcoCute" heat pump water heaters have already been installed in Japan, thanks in part to incentives to offset the high purchase price. CO_2 is also now being applied in low temperature refrigeration applications as a secondary fluid or in a cascade configuration where the pressure is lower. For thermodynamic reasons, CO_2 performs well in "high lift" applications. Ammonia (NH_3) is limited to industrial refrigeration applications where the large scale of the application justifies the specialized care required to deal with its toxicity and flammability. Neither CO_2 nor NH_3 have been acceptable for unitary A/C, due to efficiency or safety. All of these have been referred to casually as "natural refrigerants".

Today, in 2010, manufacturers are struggling with the question of next generation refrigerants for mainstream stationary equipment if the HFCs such as R410A, R407C, R404A are phased down. Due to their high leak rate (up to 25%/yr) and high charge (up to 3000 pounds per store), we expect that "applied built-up" systems like supermarket rack equipment will likely evolve toward secondary coolant loops, using CO2 or water-based brines to cool in-store equipment. Another alternative for supermarkets could be water-cooled or air-cooled self-contained equipment similar to those in fast-food stores. Using HCs may still pose challenging risks in these self-contained units since there could be up to 60 display cases per supermarket. Efficiency tradeoffs are raised in indirect systems since there is an additional heat transfer loss as well as pump energy required to circulate the cooling secondary loop fluid. Moreover, if we transition to secondary loop systems, the efficiency of the primary system will become a more important part of TEWI weighting: Since the direct GWP effect becomes significantly smaller, the TEWI would look similar to the unitary A/C. Thus, supermarket systems could share same LGWP solutions as A/C applications.

Regardless which supermarket system architecture is used in the next decades, an attractive immediate option is to switch the existing R404A (very high GWP of 3922) to lower-GWP near drop-in and more efficient alternatives such as R407C for medium-temperature (1774 GWP) and R407A (2107 GWP) for low-temperature applications, thereby realizing a 55% or

46% GWP reduction respectively. This interim transition would give the refrigeration industry more time to study the tradeoffs between A1 vs. A2L flammability, and capacity vs. efficiency for the low-GWP HFOs options shown in Figure 4. Moving from R404A to R134a (1430 GWP) is another interim possibility, but only for medium-temperature since R134a is less efficient than R404A at low temperatures. Past practice, standardizing on one refrigerant for both med-temp and low-temp, may not be possible in the supermarket of the future.

Large applied chillers (200+ tons) for large buildings using R134a could potentially replace it with HFO-1234yf without significant efficiency penalty if the chiller industry can tolerate A2L flammability with large amount of charge but very low leak. It is even conceivable that A2L flammability could be acceptable for outdoor air-cooled applications but not for indoor basements, an example of application differentiation. If not acceptable due to the very high charge, then we may have to accept a higher GWP in the range of 600-700 for an A1 solution. [7c] This tradeoff could well be acceptable due to low leak rate. The A1 option might have to be considered for supermarkets if the industry cannot deal with A2L refrigerant due to its high charge even with the use of secondary systems.

The situation for unitary residential and light commercial equipment is much less certain, and the subject of significant research effort by manufacturers now for a R410A successor. This segment is expected to become the largest refrigerant segment in the next couple of decades. One path is adoption of R32 or the R32/HFO1234yf blends refrigerants as successors to R410A. However, as shown in Figure 4, significant GWP reduction is only possible by accepting A2L flammability. This would require industry to develop new design, service, and handling guidelines. This task could take several years since no standards are available today for A2L refrigerants. ASHRAE 15 does not yet have provision for A2L refrigerants. Even accepting A2L, an HFO blend of about 500 GWP would likely be needed to match R410A efficiency. R410A is by default still the next best solution on the basis of TEWI if A2L turns out not acceptable.

The United States is likely to accept the small risks of HC refrigerants in refrigerators in kitchens (which also often have natural gas stoves and ovens), but will our legal system support A2L refrigerant for split systems with field-fabricated connections and refrigerant-to-air heat exchangers in the ducted air stream? Will we instead turn to secondary hydronic loops with outdoor chillers providing glycol to brine-to-air heat exchangers? Secondary loop systems require more energy due to added secondary heat exchanger loss and pump power, but this might be partially offset by less refrigerant line loss, no evaporator superheat, and potential for easier distributed zoning. It might develop that split systems that carry refrigerant into the building require very low flammability, while units that are completely outside the building or carry secondary refrigerant into the building can allow more flammable compounds.

Heat pumps portrayed as a more environmentally friendly than fossil-fuel boilers could end up with a different refrigerant choice than air conditioners. The recent growth of heat pump equipment requires also understanding heating efficiency (HSPF/COP) of LGWP solutions as opposed to the traditional focus on cooling efficiency (SEER/EER). This is currently the focus of research in Japan and China which are dominated by heat pumps. Clearly, more customization of refrigerants by applications is expected to optimize the tradeoffs between GWP, performance, flammability and cost.

Driven by efficiency and market differentiation, we should expect to see greater penetration of compressors with variable capacity, better controls, and wider use of other innovative low-charge technologies, such as microchannel heat exchangers which could reduce charge up to 30%. However, the refrigerant choice needs to be balanced with cost and affordability if we expect the industry and the economy to continue to grow.

The higher-performance technologies and new refrigerants are likely to suffer greater performance and safety degradation when improperly installed or serviced, particularly with flammable refrigerants. This is likely to have two consequences: even more emphasis on embedded controls with on-board leak detection diagnostic and mitigation capabilities, and the need for well trained installers.

Along this line, another very important consideration is servicing this decade's R410A systems after the HFC phase-down begins. By 2020, there will be a huge installed base of R410A A/C systems. Service for these units would likely require 40-50% of the total allowed refrigerant production, so there will be pressure to retrofit R410A with its LGWP successors. Unfortunately, there is currently no known non-flammable A1 solution available for retrofitting R410A (Figure 4). Thus, it will be very difficult to meet the proposed ultimate Waxman-Markey 15% GWP production cap by 2030, since the cap includes service requirements, not just new equipment. This retrofit issue is already a recognized issue for HFO1234yf in mobile A/C due to flammability.

Thus, to avoid the build-up of equipment that will continue to require R410A, we should transition new equipment from HFCs to LGWP refrigerant solutions as soon as possible. This will minimize the need for HFCs for aftermarket service in the future.

For new equipment, OEMs might be able to mitigate flammability risks from the factory albeit at added cost (leak detection devices, electrical sources isolation, ventilation, etc.). These measures may be beyond the capabilities of contractors who need to retrofit with (flammable) A2L refrigerants. This requires the industry to accelerate the development and introduction of LGWP solutions, or a change in the proposed production cap allowance to differentiate new equipment versus service.

Summary and Policy Implications

All options require trade-offs that need to be weighed in policy decisions now, Otherwise we could potentially face two more refrigerant phase-downs, which will cost the industry and customers additional $Billions. The refrigerant choices made in the near term will bound the limits of equipment efficiency in the future.As discussed above, natural refrigerants (CO_2, HC, NH_3) are not necessarily a panacea for A/C mainstream applications. The new HFOs family presents a new opportunity but considerable system efficiency testing will be needed for the industry to sort out the proper tradeoffs for each application.

Until 2020, HFCs like 410A are still expected to dominate in HVAC applications since it will take years for the industry to develop and migrate to new LGWP refrigerants. Coupled with this, the HVAC industry is also facing the upcoming 2015 proposed federal regional efficiency standards.[9] These two issues will challenge the industry. ***Refrigerants with lower efficiency will require larger charge mass, which would be counterproductive for meeting both increased efficiency standards and global warming reduction.***

There will be enormous industry effort as manufacturers race to find and validate new solutions that offer lower environmental risk for mainstream stationary air conditioning. In such an environment, all parties must help policy decision-makers understand that there are trade-offs and work together to evaluate these trade-offs on the path to efficiency and sustainability. We hope the “*spider*” diagram is one tool to illustrate these tasks.

***TEWI should be the comparison metric to avoid** "**unintended consequences**" of regulation based solely on GWP which may lead to less efficient refrigerants and unintended higher TEWI. This is particularly for applications where direct GWP is small compared to TEWI, such as unitary A/C and Chillers.* A refrigerant with 150 GWP (HFO) is much less efficient than a refrigerant with 675 GWP (R32) in actual systems. If an upper limit has to be placed on GWP because TEWI is a complicated concept to regulate, then the GWP level should be set by applications (for example <700 GWP for unitary A/C) taking into account current knowledge about tested system efficiency data.

It is ***prudent to "not rush" with a GWP-weighted consumption phase down schedule until the industry has pooled collective resources to conduct evaluation programs where all LGWP solutions are identified by new and service applications, tested and compared for system efficiency and TEWI**. The sooner this gets done the sooner the supporting data will be available for better decision. This will require open participation from the chemical suppliers to provide the LGWP refrigerants for evaluation. This collaborative process is similar to that occurred in the US in the 90's through the AHRI AREP program, and has recently occurred within the Japanese (NEDO and JRAIA)[10] and Chinese industry consortia focusing on quantifying the efficiency picture.*

We would also urge the industry's organizations responsible for standards and building codes such as AHRI, ASHRAE to *accelerate assessing the design safety and handling requirements for the use of A2L flammable refrigerants* since it is inevitably needed for lower GWP. ***Until flammability risk is better understood, it is recommended the phase-down schedule have provisions for higher GWP cap for the retrofit service versus new equipment segments.***

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