

REFRIGERANTS FOR DEEP MINE REFRIGERATION

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ABSTRACT

The operating conditions for deep mine refrigeration differ from conventional comfort conditioning and typically are more extreme. The thermal loads are less dependent on ambient air temperatures, cooling requirements are nearly continuous, and system reliability is critical for miner survival, health, and productivity. Refrigerant selections must address looming environmental phase-outs of some common choices as well as new considerations. First, electricity prices are increasing in many mine locations. Second and particularly in some developing countries, inadequate power supplies are forcing demand limits or even curtailments to make capacity available for other uses. Third, mines are going deeper to reach previously untapped or previously less economic minerals. The greater depths both increase thermal loads and heighten flammability concerns with more limited egress. Additionally, mining firms are under pressure to be socially responsible, to avoid mandates and attract investment. This paper reviews refrigerant options for deep mine systems.

1. INTRODUCTION

As mine depths increase to 4-5 km (2.5-3.1 mi), virgin (undisturbed) rock temperatures in locations with high geological thermal gradients approach 60-70 °C (140-158 °F) (del Castillo, 1988; MVS, 2006; Ramsden *et al.*, 2001; and Rostoll, 2008). A second load component results from auto-compression of ventilation air (AIRAH, 2007) primarily by adiabatic compression from increasing pressure due to depth, similar to water pressure increases with depth in oceans. Auto-compression raises the ventilation air temperature approximately 16 K (29 °F) at 4 km (2.5 mi) (Ramsden *et al.*, 2001). Additional cooling loads result from supply air heat during warm weather, excavation and extraction machinery, fissure water, oxidation, use of explosives, lighting, personnel, service water, and miscellaneous sources (Biffi and Bluhm, 2001; Brake and Fulker, 2000; Brake, 2001a; Pickering and Tuck, 1997). The collective result is a high, nearly continuous, and critical requirement for heat removal. Surface cooling of ventilation air and chilled water supplies is effective to depths of 1500 to 2000 m (5000 to 6500 ft) depending on local conditions, but auto-compressive heat from air and chilled water forces use of underground refrigeration as mine depths increase. Use of ice slurries or hard ice extends the depths serviceable with surface systems, but auto-compression again limits the serviceable depths with partial or full melting of the ice.

High capacities and flexible distribution (reticulation) requirements limit practical chiller options for surface installations to water-cooled systems employing centrifugal (radial turbo) or large screw compressors. Limited flammability is manageable and ammonia (R-717) is widely used as the sole refrigerant or in the low-stage of cascaded systems. Underground installations primarily employ centrifugal chillers, but operation in confined spaces, limited egress, and potential presence of combustible mine gases effectively preclude consideration of flammable or even moderately flammable refrigerants. Access to underground systems is limited, and both the equipment movement and operational disruption costs mandate high durability. The high load-profiles and required reliability for both surface and underground chillers force use of systems with multiple chillers, typically with excess aggregate capacity to enable maintenance and accommodate individual unit failures. Bailey-McEwan (2001), Bluhm *et al.* (1998), Brake (2001a and 2001b), Marks (2007), McPherson (1993), and Ramsden *et al.* (2007) provide further background information on and identify additional design considerations for mine refrigeration systems.

The majority of recent installations use R-134a (a hydrofluorocarbon, HFC) and/or R-717 (ammonia) in surface chillers and R-134a in underground chillers. Although less common, some new installations use R-123 (a hydrochlorofluorocarbon, HCFC). Older equipment also employs chlorofluorocarbons (CFCs) including R-11, R-12 and R-114; HCFCs such as R-22, and blends such as R-500 (a blend containing a CFC).

2. CHANGING CRITERIA

Several factors, beyond refrigerant phaseouts, are forcing further examination of refrigerant selections:

- Electricity prices are increasing, significantly so in many deep mine locations.
- Particularly in some developing countries, inadequate power supplies necessitate demand limits or even curtailments to make electricity more available for urban and manufacturing uses.
- As mines go deeper to reach previously untapped or previously less economic minerals, cooling loads increase from geothermal heat, auto-compression, and machine loads. These increases force improved efficiency, to offset higher cooling loads, as well as system innovation such as lowered chilled water supply and raised return temperatures and use of both ice slurry and hard ice systems.
- Mining firms are under intense pressure to be perceived as socially responsible to avoid mandates and to attract investment, hence they are seeking to be and to be seen as environmentally responsible and pioneering.

All four factors dictate improved efficiency and, in some cases, replacement or at least conversion of older, less efficient equipment.

3. REFRIGERANT OPTIONS

The following discussion addresses current and new refrigerant options for deep mine refrigeration.

R-22 is no longer widely used in deep mines except for small, ancillary equipment to air condition support buildings, break areas, and control rooms. As an HCFC, R-22 is subject to *consumption* phaseout under the Montreal Protocol (1987) as revised:

- For non-Article 5 countries, excluding earlier steps: 75% reduction from defined *base level* by 2010, 90% by 2015, 99.5% by 2020 then limited to service existing equipment, and 100% by 2030.
- For Article 5 countries: freeze at defined *base level* by 2013, 10% reduction from the defined *base level* by 2015, reduced by 35% by 2020, 67.5% by 2025, 97.5% by 2030 and then limited to service existing equipment, and 100% by 2040.

Some countries, notably those in Europe and for R-22 also Canada and the USA, have accelerated schedules that already preclude R-22 use in new equipment. While not regulated by the Kyoto Protocol (1997) predicated on control by the Montreal Protocol (1987), R-22 emission is still a high concern as a greenhouse gas. Manufacturers have discontinued R-22 in new chillers using centrifugal compressors.

R-123 (also an HCFC) is in use in both surface and underground chillers with centrifugal compressors; it also is used as a retrofit service fluid for older R-11 (a CFC) chillers. R-123 is subject to the same consumption reduction and phaseout schedules under the Montreal Protocol indicated above for R-22, but – except in Europe – most countries have not accelerated its phaseout owing to its much lower ODP and significantly lower emission rates. R-123 has very low GWP (one of the lowest among fluorochemicals) and a short atmospheric lifetime; it is not regulated by the Kyoto Protocol (1997). Environmental assessments indicate indiscernible impact on the ozone layer attributable to its very low ODP and the minimal emission rates inherent to its low pressure (Calm *et al.*, 1999, 2006, and 2008; Molina MJ *et al.*, 2004; Wuebbles *et al.*, 1997 and 2009). Consistent with Calm *et al.* (1999) and Wuebbles and Patten (2009), Seager and Theis (2003) concluded that “policies that favor marginal reductions in ozone depletion without regard for other environmental effects (e.g., climate change) may have unintended and detrimental consequences.” Wuebbles and Patten (2009) also note that unlike alternatives with even shorter lifetime, R-123 “is not a volatile organic compound and should not have an effect on local and regional air quality.” Several candidates to replace R-123 are under evaluation and testing, but such examination is proprietary and neither the leading options nor resulting performance impacts have been published as yet.

R-134a is the most common refrigerant in recent installations for both surface and underground deep mine chillers; it also is used as a retrofit service fluid for older R-12 and R-500 chillers. As a hydrofluorocarbon (HFC), R-134a is not addressed by the Montreal Protocol (1987), but its emissions are controlled by the Kyoto Protocol (1997). Its use and emissions in chillers and other stationary applications are regulated

and/or taxed in some national regulations, notably in some European countries. Near-term R-134a phaseout for mobile air conditioning (MAC), by 2011 in new designs in Europe (EU, 2006), is likely to yield one or more alternatives as discussed by Calm (2008) and Calm and Hourahan (2011). As with R-22 and R-123, recovered refrigerants from retired systems and expected service fluids are likely to suffice for service of existing equipment for projected economic lifetimes.

Hydrocarbons offer both low cost and comparatively low environmental impact, are commercially available in purities suitable for refrigerant use, and have a long history of use in small systems. The fire and explosion risks limit charge size and thereby capacities. The largest hydrocarbon units (other than in refinery systems using feedstock as refrigerant) have maximum capacities of approximately 400 kW (100 RT), far too small for mine refrigeration, though R-290 (propane) and R-1270 (propylene) frequently are cited as potential replacements for R-22 while R-600a (isobutane) and blends of it are cited as candidates to replace R-134a. Maclaine-cross (1999 and 2002), Calm (2005), and Tadros *et al.* (2006) examined R-601 (pentane), R-601a (isopentane), and blends of them to replace R-123 in centrifugal chillers. Still, no manufacturer is known to offer large-capacity chillers with hydrocarbon refrigerants predicated on safety concerns.

Ammonia (R-717) use is common in surface chillers serving deep mines, particularly to produce very cold chilled water, and gaining further interest to produce ice slurries and/or hard ice for mine cooling. It normally is not used in underground systems predicated on its flammability, even though low, and dermal corrosivity, notably to skin, eyes, and mucous membranes. Chillers using ammonia typically employ reciprocating-piston and more commonly screw compressors, but commercialization in turbo-compressor scale has not been practical thus far due to the need for multiple (generally at least four) stages with centrifugal compressors or for axial turbo compressors, uncommon in refrigeration. Ammonia offers very low cost and, for now, is deemed an acceptable alternative not subject to environmental phaseout.

Water (R-718) use as a refrigerant to produce ice slurries and hard ice has drawn high interest to reduce pumping burdens (Hager and Kamper, 1991; Jahn *et al.*, 1996; Paul, 1996; Ophir, 2007 and 2008; Sheer *et al.*, 2001). Water could be an environmentally-attractive refrigerant candidate subject to attainment of competitive efficiencies, equipment cost, performance, durability, and size. It is nonflammable and has negligible toxicity. Water is a common refrigerant in absorption chillers; but further development and demonstration is needed for mechanical vapor compression (Paul, 1996; Kharazi *et al.*, 2005). The mining industry is evaluating water use as a refrigerant in vapor-compression chillers for underground use, vacuum ice making (addressed below), and alternative use of hard ice to achieve a higher ice (frozen component) to water ratio.

Table 1: Environmental properties of refrigerant candidates for deep mine systems
based on WMO (2010) and Calm and Hourahan (2011)

refrigerant	composition	atmospheric lifetime, τ_{atm} (yr)	ODP	GWP (100 yr)
R-22	chlorodifluoromethane	11.9	0.040	1790
R-123	2,2-dichloro-1,1,1-trifluoroethane	1.3	0.0098	77
R-134a	1,1,1,2-tetrafluoroethane	13.4	~ 0.0	1370
R-290	propane	0.041	0.0	~ 20
R-600a	isobutane	0.016	0.0	~ 20
R-601	pentane	0.009	0.0	~ 20
R-601a	isopentane	0.009	0.0	~ 20
R-717	ammonia	< 0.02	0.0	< 1
R-718	water		0.0	< 1
R-729	air		0.0	0
R-744	carbon dioxide	> 50	0.0	≡ 1
R-1234yf	2,3,3,3-tetrafluoropropene	0.029	0.0	< 4.4
R-1234ze(E)	trans-1,3,3,3-tetrafluoropropene	0.045	0.0	6
R-1270	propylene	0.001	0.0	< 20

Air (R-729) has limited potential in open Brayton cycles (formerly used in some aircraft). While cost and energy effectiveness may increase with depth, air-cycle systems are deemed uncompetitive for deep mines (del Castillo, 1988).

Carbon dioxide (CO₂, R-744) gets frequent mention as a candidate, but there is no known current attempt to develop equipment using carbon dioxide as refrigerant for the capacity ranges involved. Use would require highly-optimized transcritical cycles to approach competitive efficiencies.

Other candidates will emerge (Brown *et al.*, 2010; Calm 2008 and 2011; Kontomaris and Leck, 2009), but the majority are being pursued with limited public disclosure, and equipment using them is not yet available.

Table 1 summarizes the environmental properties of the cited refrigerant candidates.

4. THERMODYNAMIC EFFICIENCY

Design conditions for individual systems vary with mine conditions, system configuration, and climatic conditions. Table 2 summarizes three sets of representative operating conditions for deep mines.

Table 2: Representative mine chiller operating temperatures

system	evaporator		condenser	
	leaving water	average refrigerant	leaving water	average refrigerant
surface chiller (shell-and-tube heat exchangers)	5 °C (41 °F)	2 °C (36 °F)	28 °C (82 °F)	32 °C (90 °F)
surface chiller second stage (plate-and-frame or plate-and-shell heat exchangers)	1.5 °C (35 °F)	-1 °C (30 °F)	28 °C (82 °F)	32 °C (90 °F)
underground chiller (shell-and-tube heat exchangers)	5 °C (41 °F)	2 °C (36 °F)	45 °C (113 °F)	48 °C (118 °F)

Table 3 presents the comparative performance of chiller refrigerants, calculated for ideal cycles using CY-CLE_D (Brown *et al.*, 2009) with updated refrigerant models from Lemmon *et al.* (2010) for R-1234yf, R-1234ze(E), and R-1270 (propylene), at the operating temperatures summarized above. The table presents resulting coefficients of performance (COPs), specific power (power per unit of cooling capacity – a dimensional form of the reciprocal of efficiency commonly used in some countries to express chiller performance), and normalized efficiencies relative to the most common current choice for each of the three conditions. Use of the ideal-cycle models yields limits to attainable thermodynamic efficiency for simple cycles without adjustment for such factors as compressor or motor efficiencies, pumping power, cooling tower fan energy, or control strategies, all generally similar for competitive refrigerants for the same use. In practice, non-ideal motors, compressors, and gear-drives (if used) reduce the efficiencies realized, usually by similar factors for competitive refrigerants. Cycle refinements, such as multistage compression with economizers and inter-stage cooling, partially offset such reductions.

Accordingly, the normalized efficiencies in Table 3 suggest comparative performance of alternative refrigerants in similarly optimized systems and, thereby, implications for reduction of both energy use and energy-related greenhouse gas emissions. These indicators are more meaningful for high-performance chillers, since there is overlap in product efficiency for low-performance (not fully optimized) designs.

As indicated in Table 3, several options can offer higher efficiency than R-134a for surface chillers, though some and especially the hydrocarbons pose safety concerns; manufacturers do not market standard centrifugal chillers using hydrocarbons for this reason. Replacements including service fluids for existing equipment are being developed for both R-123 and R-134a, and at least for R-123 continued use of recovered refrigerant from retired systems and also pre-stocked refrigerant will be allowed in existing equipment. As shown,

Table 3: Comparative refrigerant efficiencies for chillers
(see Table 2 for comparison conditions and text for discussion)

<u>chiller category</u> refrigerant	COP	specific power (kW/RT)	normalized efficiency
<u>surface chillers</u>			
R-22	7.87	0.447	1.00
R-123	8.27	0.425	1.05
R-134a	7.85	0.448	reference 1.00
R-290 (propane)	7.74	0.454	0.99
R-600a (isobutane)	7.98	0.441	1.02
R-601 (pentane)	8.22	0.428	1.05
R-601a (isopentane)	8.17	0.431	1.04
R-717 (ammonia)	8.10	0.434	1.03
R-1234yf	7.57	0.464	0.96
R-1234ze(E)	7.83	0.449	1.00
R-1270	7.71	0.456	0.98
<u>surface chillers second stage</u>			
R-22	7.00	0.502	0.97
R-290 (propane)	6.87	0.512	0.95
R-717 (ammonia)	7.20	0.488	reference 1.00
R-1270	6.85	0.514	0.95
<u>underground chillers</u>			
R-22	4.64	0.758	1.02
R-123	5.02	0.701	1.10
R-134a	4.57	0.770	reference 1.00

R-1234yf – a leading candidate to replace R-134a – is likely to yield lowered efficiency. It is moderately flammable and significantly more expensive than current options. Another developmental refrigerant, R-1234ze(E) with a less extreme cost premium, shows comparable performance and is being pursued alone and in blends. Additional candidates using other low-GWP fluids also are being developed. As shown in Table 3, R-717 (ammonia) remains very attractive in both a single or second stage for surface systems, again using screw rather than centrifugal compressors and typically plate rather than shell-and-tube heat exchangers.

R-123 offers a significant advantage for underground chillers, both in performance and fire suppression ability; it is commercially used as a fire suppressant under other names. Again, R-123 is subject to the HCFC restrictions limiting use in manufacture of new equipment until 2020 or 2030 depending on location. R-134a currently is not subject to phase-out, but such measures are highly likely. Manufacturers expect to offer replacements and service fluids for both low-pressure R-123 and medium-pressure R-134. Based on Table 3 and considering its ODP and high GWP, it is difficult to justify further R-22 chillers in deep mine systems.

The AngloGold Ashanti Mponeng Gold Mine in South Africa is believed to have the largest installation in the world of vacuum ice makers (VIMs) with an aggregate refrigerating capacity of approximately 27 MW (7700 RT). The system pre-cools water with conventional chillers and the nine VIMs then produce ice by first compressing water vapor under vacuum and then flashing it (Ophir, 2008; IDE, 2009; Robbins, 2009). The system uses three generations of equipment installed in increments (the most recent in 2008-2009), suggesting favorable experience as an implied pre-requisite for the later additions. Whereas the first six units are two-stage machines, the three newest are single-stage designs. Data from Robbins (2009) indicate coefficients of performance of 5.3-8.4 for the two-stage VIMs and 11.6-14.7 for the newer single-stage units for

the ice-makers alone, and 2.9-3.6 and 2.7-3.0, respectively, including pumps (surface, not reticulation), cooling tower fans, concentrators, and related power inputs. For comparative purposes, the R-134a centrifugal chillers pre-cooling the VIM inlet water achieve COPs – excluding towers, pumps, and similar power burdens – of 5.7-6.6 (Robbins, 2009).

5. CONCLUSIONS

Predicated on (1) increasing electricity prices especially in many deep mine locations, (2) demand limits or even curtailments on electricity use where applicable, (3) implications for deeper mining, and (4) the desire to be and pressures to be perceived as socially responsible, mining companies and the engineering firms and suppliers serving the mining industry must significantly increase mine chiller efficiency. Amidst regulation of refrigerants or at least those with high GWP as greenhouse gases, it is important to note that the energy-related emissions driven by efficiency and operation are of much greater concern for climate change. The information presented herein offers guidance based on environmental data and limits to attainable efficiency for current refrigerant options. Other than continued use of ammonia (R-717) in surface chillers, including as the second stage chillers and ice makers, the primary current contenders and especially for underground installation are R-123 and R-134a. R-123 faces known phaseout as an HCFC in new equipment (not for continued service use) by 2020 or 2030, depending on country other than in Europe. R-134a faces near-certain phaseout as a high-GWP HFC, but with less defined timing. Replacements and service fluids are anticipated for both R-123 and R-134a, but are likely to be less efficient and to increase costs. Further R-22 installation in large equipment is not allowed in many countries and not recommended for the rest.

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