NASA-TM-82695

A minerals research contract report
December 1981

NASA-TM-82695 19830006420

ASSESSMENT OF ALTERNATIVE POWER SOURCES FOR MOBILE MINING MACHINERY

Interagency Agreement J0100026
NASA Lewis Research Center
NASA TM-82695

BUREAU OF MINES ★ UNITED STATES DEPARTMENT OF THE INTERIOR

Minerals Health and Safety Technology

3/222

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CONTENTS

TABLES

FIGURES

ASSESSMENT OF ALTERNATIVE POWER SOURCES

FOR MOBILE MINING MACHINERY

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SUMMARY

The NASA Lewis Research Center, under U.S. Bureau of Mines program direction, performed an assessment of alternative mobile power sources for mining applications. A wide variety of heat engines and energy systems was initially examined to ascertain which could be considered as potential alternatives to presently used power systems. The present mobile power systems are electrical trailing cable, electrical battery, and diesel - with diesel being largely limited in the United States to noncoal mines. Each candidate power source was evaluated in terms of the following requirements:

(1) Ability to achieve the duty cycle
(2) Ability to meet Government regulations (MSHA certification)
(3) Availability (production readiness)
(4) Market availability
(5) Packaging capability

An initial screening reduced the list of candidates to the following:

(1) Diesel
(2) Stirling
(3) Gas turbine
(4) Rankine (steam)
(5) Advanced electric (batteries)
(6) Mechanical energy storage (flywheel)
(7) Use of hydrogen evolved from metal hydrides

This list of candidates was divided into two classes of alternative power sources for mining applications - heat engines and energy storage systems. A summary of each class follows.

Heat Engines

Heat engines, in general, burn a fuel with ambient air to provide output power. Fuel-burning engine operation results in the emission of various substances that may be harmful to humans. In addition the operation of the engine results in the depletion of oxygen from the ambient air. Therefore ventilation is required for all heat engines, either to reduce the proportion of potentially harmful substances in the ambient air or to restore the oxygen content to a safe level. For any engine burning carbon-bearing fuels, the lowest possible ventilation rate corresponds to that required to reduce carbon dioxide (CO_2) to the level specified in the Code of Federal Regulations (CFR), Title 30 - Mineral Resources. For an engine burning hydrogen, the minimum ventilation rate is based on restoring the oxygen

level to 20 percent by volume. Heat engines do differ, however, in the emission of toxic materials such as carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NO_x), and particulates, and this may present a significant difference in terms of long-term health effects. The continuous combustion engines offer a substantial advantage in this regard over the diesel engine.

A summary of the significant findings resulting from the study follows.

Diesel

Diesel systems have demonstrated high production capability and reduced operating cost in applications where they have been accepted. However, toxic emissions are a concern, and thus diesel systems require much higher ventilation rates than nondiesel systems.

Ventilation rates for most diesel engines are determined by NO_x emissions. Some newer diesels have toxic emissions (including NO_x) low enough to have ventilation rates determined by the CO_2 limit. However, concern with long-term health effects, which has apparently been a significant factor in limiting acceptance of diesels - particularly in coal mines, relates largely to particulate emissions (which are currently unregulated). Techniques that reduce NO_x emissions (primarily exhaust gas recirculation (EGR)) tend to increase particulate emissions. Furthermore reducing ventilation because of a reduction of NO_x would proportionately increase the concentration of particulates in the ambient air. Reduction of particulate emissions and their potential long-term health hazards would appear to be necessary to achieve greater acceptance of diesels in underground mines. Research on particulate reduction now in progress for highway diesels should result in techniques applicable to mine engine usage in a few years.

Consequently, if particulate emissions of mining vehicles become regulated, it will be necessary to determine what modifications must be incorporated in the engine and vehicle. First, however, methods must be established to measure particulate emissions from current equipment. This requires that testing methods be established and that testing facilities be modified. Since it may require considerable lead time to make these changes, work in this area should be started by the Mine Safety and Health Administration (MSHA) soon after a decision has been made to regulate particulates.

Stirling

The Stirling engine could offer significant advantages over the diesel engine in reduction of toxic emissions (especially particulates), in reduction of noise and vibration, and in multifuel capability. However, market availability appears to be a long way off. The engine is in an early development stage for automotive application and is at least 10 years away from the market. Just how long will be required for a heavy-duty engine to be produced is not clear. It may follow the automotive introduction or it may be developed separately for other applications such as stationary or solar power. In any event, near-term availability of the Stirling engine is questionable.

A more detailed design assessment should be made of the adaptability of the automotive Stirling engine as well as of the larger United Stirling of

Sweden 4-275 engine for mining application. The assessment should include evaluation of the effects of mining application duty cycles and life requirements on the rated power. It should also include detailed design of the modifications needed to meet the Federal regulations for both gassy and nongassy mines and determine the effect of these modifications on engine power and efficiency. The results of this design assessment can serve as the basis on which to decide if a Stirling-powered vehicle demonstration is practical.

Gas Turbine

Of the candidate power sources for mining application, the heavy-duty industrial gas turbine (IGT) is the closest to mass production. The gas turbine offers advantages similar to those of the Stirling engine, although the brake specific fuel consumption (BSFC) may be slightly greater and multifuel capability not quite as broad. Gas turbines are now being developed for both light- and heavy-duty highway use. In fact, several companies have heavy-duty (approx 200 to 450 kW) engines in the demonstration phase of development, some of which may be available in the near future. Therefore the Bureau of Mines should give strong consideration to a relatively near term demonstration of a heavy-duty gas-turbine-powered mine production vehicle.

Rankine

Although the (Rankine) steam engine has advantages similar to those of the Stirling and the gas turbine, its low thermal efficiency for motive applications has resulted in cessation of any development for highway application. Although low efficiency is not of itself a key factor in mine vehicle applications, the attendant higher ventilation requirement is undesirable. In any event, it is unlikely that a steam engine adaptable to mine vehicle use will come on the market in the foreseeable future. Therefore it is recommended that the Bureau of Mines and other Government agencies continue to hold in abeyance any more work or decisions on steam-powered mine vehicles. If other alternative engines fail to be feasible or practical, serious reconsideration might be given to reexamining the steam-powered shuttle car.

Energy Storage Systems

In general, non-fuel-burning systems are characterized in terms of their energy storage capacity, which is usually substantially less than is possible with fuel-burning systems. This serves as a stringent limit on production capability. Although a number of energy storage systems are possible, only electrical battery systems have actually been used extensively in underground mines. This study considered a variety of battery systems, flywheel energy storage, and metallic hydride hydrogen storage. A summary of the significant findings follows.

Battery Systems

The extensive development effort now being carried out in batteries and in highway electric vehicle systems in general will be of benefit to mine vehicle applications. Battery electric systems, although greatly improved, will still remain intrinsically low in energy density and will be restricted by recharging requirements. Perhaps an exception is the class of metal-air battery systems now beginning active development. The aluminum-air system has the potential to provide a significant impact. This can only be judged with more information and experience as development proceeds.

By the mid-1980's the attractiveness of battery-powered vehicles for mines should be somewhat improved. Usable energy densities are expected to triple and peak power densities double over those of current lead-acid traction batteries. Recharge times are expected to decrease to about 3 or 4 hours, and useful lives of about 5 years are forecast. These improvements will permit greater design flexibility for future battery-powered mine vehicles. Flameproofing, however, will continue to be a design problem and a safety concern.

Further in the future, successful development of aluminum-air batteries could lead to a battery system comparable to diesel in power and energy capacity but totally free of toxic exhaust emissions. These batteries also should be capable of rapid mechanical recharging in a time comparable to that required for diesel refueling.

It is recommended that the Bureau of Mines continue to keep abreast of the development of new battery systems, in particular nickel-iron, nickel-zinc, and metal-air battery systems.

Flywheel Energy Storage

Flywheel energy storage provides a unique and interesting approach to mine vehicle operation by utilizing rapid recharging once each operational cycle. Analytically the system appears quite feasible. It will be most interesting to see how this system works in practice and what practical problems are uncovered in forthcoming DOE demonstrations. Therefore it is recommended that the Bureau of Mines continue to monitor the demonstration program for a flywheel power system in a mine car application and also keep abreast of composite fiber developments for advanced flywheel systems.

Hydrogen Fuel from Metal Hydrides

Hydride systems used to provide hydrogen fuels to conventional heat engines appear to offer some promise. They offer substantially better energy density than current or near-future battery systems and do not appear to be practically limited in power density. However, considerable development will still be required before all the practical operational and safety problems are solved.

The use of hydrogen offers the potential to eliminate CO and CO_2 emissions and reduce greatly NO_x emissions from heat-engine-powered mine vehicles. The ventilation requirements for such a vehicle would be reduced by at least a factor of 4 from those of present diesel vehicles since the requirements are established only by the need to maintain 20 percent oxygen in the mine air. The use of hydrides appears to be the most practical and least hazardous method for hydrogen storage.

We recommend that the Bureau of Mines closely monitor the DOE-sponsored automotive hydrogen engine and hydride research and also monitor the BOM (Minneapolis)-sponsored activities of Eimco and Ergenics to design a hydride-fueled mining vehicle.

There do not appear to be any significant advantages to using a gas turbine, Stirling, or steam engine rather than a reciprocating internal combustion engine if all are to operate with hydrogen fuel, for they all will have similarly acceptable exhaust characteristics. Therefore any development of a hydrogen-fueled mine engine should be based on reciprocating internal combustion industrial engines, for which a production base already exists.

INTRODUCTION

The Industrial Safety and Training Systems Group of the Bureau of Mines (BOM) Pittsburgh Mining and Safety Research Center of the Department of Interior has been investigating alternative power sources for the mining industry. Because of this interest of the Bureau of Mines in alternative power sources and the NASA Lewis Research Center's extensive engine experience along with its broad capability in propulsion, power, and energy systems, it was advantageous to the Government to have Lewis provide technical support to the BOM program directed toward new power source evaluation for mining applications.

An interagency agreement, Power Sources for Mining Applications - J0100026, between NASA and the Bureau of Mines was signed on October 30, 1979. It covers the following activities: (1) the test and evaluation of a 40-kW (55-hp), four-cylinder, United Stirling P-40 Stirling engine and (2) the accumulation and assessment of data and technology in the area of alternative power sources for mining applications. This report is the result of the second activity.

Mine machinery varies from fractional-horsepower, hand-held tools to gigantic long-wall mining systems that can stretch over 300 m (1000 ft) of mine wall and use 746 kW (1000 hp) or more in operation. The preponderant power source, particularly in coal mines, is electrical. Electricity is nonpolluting (in the mine). Electric power can be used in fixed installations such as ventilation systems or hoisting winches, in quasi-fixed machinery such as continuous or long-wall miners, or in mobile equipment such as haulage or auxiliary vehicles. Electrical input can be through cable or trolley lines or from batteries. Use of diesel power is limited exclusively to mobile equipment. In particular, diesel power is well suited to haulage vehicles such as load-haul-dump machines. Diesels are seeing increasing usage, especially in noncoal, nongassy mines.

This study was intended to assess a variety of alternative power sources potentially applicable to mobile equipment used in underground mining. Since the principal concern of the Bureau of Mines is "to promote health and safety in metal and nonmetallic mining industries" (quote from preamble to Federal Metal and Nonmetallic Mine Safety Act), the assessment was concerned primarily with identifying improved power systems and technological advancements that will increase operational safety and reduce the probability of long-term health hazards. Productivity improvement was also an important part of the assessment. This assessment covered a power range from approximately 18.7 to 224 kW (25 to 300 hp), which includes most in-mine power source requirements. Actual coal-mining machinery (generally 224 kW (300 hp) or more) was not considered in this study. Specifically the applications that were considered were face haulage vehicles and auxiliary vehicles. Face haulage vehicles include shuttle cars, load-haul-dump machines, and various tractor-trailer assemblies. Auxiliary vehicles include personnel and equipment carriers and lubrication trucks.

Tethered systems were not addressed in this study, except as a standard for comparison. Although evolutionary (and relatively minor) improvements in cable systems will probably continue to be made, the intrinsic disadvantages and limitations will remain. Two broad power source areas were examined: heat engine systems, including diesel, rankine - steam and organic, Stirling, and gas turbine - open and closed cycle, and energy storage systems, including batteries, fuel cells, flywheels, accumulators, hydrides, and hybrid systems.

REQUIREMENTS

To establish a basis for this assessment and to define the requirements that must be met by mine machinery systems, fact-gathering visits were made to three major mine equipment manufacturers: Jeffrey Mining Machinery Division of Dresser Industries, Inc. (Columbus, Ohio), Eimco Division of Envirotech Corp. (Salt Lake City, Utah), and Wagner Mining Equipment Co., a Division of PACCAR (Portland, Oregon). From information obtained during these visits and in discussions with Bureau of Mines personnel and from the Code of Federal Regulations (CFR), Title 30 - Mineral Resources, the following desirable characteristics were chosen for any alternative power source:

(1) Shall be capable of meeting all pertinent Federal regulations with regard to safety and health (MSHA certification requirements) without significantly increasing cost or decreasing performance.
(2) Shall be completely mobile, not restrained by cables, trolleys, etc.
(3) Shall not be limited in practical range by either tethered energy supply or by energy storage capability.
(4) Shall be able to work continuously over at least a full shift without having to renew the energy supply.
(5) Shall be able to work on a full-time basis for at least 2 years without a major overhaul or replacement.
(6) Shall not require frequent or skilled maintenance.
(7) Shall produce emissions (including particulates, but excluding CO_2) substantially below those produced by current diesel-powered machines.
(8) Shall reduce noise level at full power at least 5 dB below current CFR levels.
(9) Shall have torque characteristics that allow good "lugging capability," that is, increased torque as engine speed is reduced from nominal operating speed.
(10) Shall be cost effective in production.

On the basis of these desirable characteristics, an attempt was made to establish a set of requirements for mobile mining power sources to be used as a guide to the assessment. Requirements for mine machinery power sources cannot, in general, be spelled out simply. A variety of factors including productivity considerations, Government regulations, and labor relations influence the nature of any requirements that could be presented. In many cases, they are difficult to quantify or they present different aspects for different types of operations. In some areas, there is general agreement - in others, significant divergence. With these cautions, the following list of requirements is offered. Each will be discussed further below, and to the extent possible, quantified.

(1) Ability to achieve a prescribed duty cycle for specific equipment in a specific mining environment
(2) Ability to meet Federal regulations pertinent to safety and health
(3) Availability for production service (includes reliability, ruggedness, durability, and ease of maintenance)
(4) Market availability - industrial or highway production base
(5) Packaging capability - influence of power system on vehicle dimensions

Ability to Achieve Duty Cycle

The first, obvious requirement of any power source is that it be able to do the job. Typically a piece of mining production machinery such as a haulage vehicle should be able to work continuously over at least an entire shift without servicing (except for the prescribed "prepare to mine" time at the beginning of a shift). It should be able to haul product from the face to a point of discharge in a manner so as to minimize its contribution to the cost per ton of product. Current experience indicates that a wide variety of power systems can be applied, although each has its unique advantages and drawbacks. Each system requires some compromise; none is wholly satisfactory.

Trailing-cable systems are pollution free in the mine, do not require petroleum fuels, and can deliver very high power levels. For quasi-stationary machines with a high power demand, such as continuous miners, cable power systems seem to be generally satisfactory. However, these super extension cords limit operational capability for mobile equipment severely. For practical purposes no more than two cable-reel shuttle cars can be operated per section. In general, the haulage capability of two shuttle cars is below the production capability of a continuous miner. This is a major factor limiting the production from room and pillar mining. Range for cable-reel shuttle cars is limited - normally a maximum of 200 m. As much as 400 m is possible assuming backspooling, but this is an undesirable complication. Cable breaks are relatively frequent for mobile machinery. Not only does a cable break result in a significant production time loss, but also safety is severely compromised.

Battery-powered vehicles do have essentially complete mobility. Moreover, they are pollution free (except when being recharged) and require little service time or skill. However, energy density is a key problem for battery systems. The typical lead-acid traction battery has an energy density of about 25 W-hr/kg (0.015 hp-hr/lb). This means that a very high battery weight must be carried to support a full shift of haulage operation. A typical battery-powered tractor-trailer for face haulage (S&S Corp. Model 320 Du-A-Trac) has a battery pack weighing 4220 kg (9300 lb) that provides 100.3 kW-hr energy storage when the batteries are new and in good condition. The machine is powered by a 33.6-kW (45-hp), 128-V electric motor. The available energy storage theoretically allows full-power operation for 3 hours. For a typical coal mine tractor-trailer haulage duty profile (1)[1], the average power level is approximately 40 percent of maximum motor horsepower. This would allow almost 6 hours of working capacity, assuming 80 percent discharge of the batteries, which has been shown to be most cost effective in industrial use. This is, in general, adequate to complete a full shift. Available face time for a typical shift (exclusive of breakdowns) is approximately 310 min (table I). The rest of the time is spent going in and out, preparing to mine, preparing to leave, safety meetings, etc. If two-shift operations are maintained, two battery sets will be required to operate one battery-powered machine since approximately 8 hours is needed for recharging. The charging station must be in a specially ventilated place away from production areas because of hydrogen evolution during charging. Another concern with battery systems is the difficulty of providing complete flameproofing in the event of an accident or roof fall when the battery may be severely damaged. Considerable sparking and/or heat release may cause ignition of mine gases or other combustible materials.

Diesel-engine-powered mine vehicles offer a near-optimum situation as far as mobility, energy storage, and refueling capability are concerned. They have a distinct productivity advantage over cable-powered systems because of mobility and elimination of cable-related operational restrictions and hazards. Their energy storage capability (11 900 W-hr/kg of fuel as compared with 25 W-hr/kg of battery) gives them a distinct working time and power advantage over battery-powered sytems. They allow a substantially longer haulage range than either electrical system. The number of diesel-powered vehicles servicing a continuous miner is not limited, as the cable-powered systems are. This is on the assumption, of course, that adequate ventilation is supplied. Diesel engines, however, have several major disadvantages. These include exhaust emissions, noise, and maintenance requirements. The most severe problems lie in the area of exhaust emissions. Water and catalytic exhaust treatment systems can be used to reduce emissions somewhat. Dilution air is added at the exhaust to reduce concentrations in the immediate vicinity of the vehicle. Finally, mine ventilation must be increased considerably to limit the overall concentration of toxic materials to safe levels. For example, the minimum ventilation requirement for a section operating with no diesel engines is approximately 85 m^3/min (3000 ft^3/min). Introducing a haulage vehicle with a Caterpillar 3306 diesel engine requires (by Federal regulation) an additional 481 m^3/min (17 000 ft^3/min). The use of two or more diesel engines, then, raises ventilation requirements by an order of magnitude. There is considerable controversy, particularly in this country, as to the long-term health hazards related to the use of diesel equipment in underground mines. As a result, their use is severely limited.

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[1]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

Duty cycle requirements are being met today in mines by widely divergent systems. None of them is wholly satisfactory. With the electrical systems, significant compromises in productivity must be made. The great potential of the diesel-powered systems is only partially realized because of concern over long-term health hazards related to emissions.

Although duty cycle requirements for production equipment are of primary concern, other vehicle power requirements must be considered. In general, these are intermittent requirements and do not stress the inherent limitations of the various systems, such as battery capacity or diesel emissions. Some types of intermittent duty vehicles are personnel and equipment carriers, lubrication or service trucks, shotcrete trucks, and drill jumbos or roof bolters (tramming power only). In assessing power system requirements, the major concern should be with continuous production equipment - haulage vehicles - as these do test the inherent limitations of the various systems.

Ability to Meet Government Regulations

The primary purpose of Government regulations pertinent to mining is to provide better working conditions for miners with respect to health and safety. Underground mining has long been recognized as one of the most hazardous industries. Immediate hazards such as roof falls, explosions, and machinery accidents result in many fatal and disabling accidents. Long-term health hazards related to airborne dusts and gases have resulted in incapacitating and life-shortening lung diseases such as silicosis or black lung.

A strong Federal role in mine health and safety began with establishment of the Bureau of Mines in 1910. The promotion of health and safety in the minerals industry by investigating accidents and their causes, along with research and development of special equipment, is a principal activity of the Bureau of Mines. The Federal role in mine safety was greatly extended with the Federal Metal and Nonmetallic Mine Safety Act, Public Law 89-577 (1966) and, in particular, the Federal Coal Mine Health and Safety Act of 1969, Public Law 91-173.

The 1979 edition of Title 30 - Mineral Resources - of the Code of Federal Regulations contains 1342 pages. The portion relating specifically to mine health and safety contains 614 pages, nearly half. These regulations include detailed specific requirements for all manner of equipment and procedures pertinent to mining. Equipment produced for mining use must meet these specifications. To ensure that the Government regulations are met, all mining equipment must be certified by the Mine Safety and Health Administration (MSHA). Requirements are often presented for both performance and design. In many cases, equipment manufacturers find these requirements restrictive and costly. They can have substantial effect not only on the design modifications required for industrial equipment (such as a diesel engine), but also on the mine operational systems (such as greatly increased ventilation requirements to dilute and dispel diesel exhaust).

Taking past experience as a guide, there is good reason to believe that future Federal regulations regarding mine health and safety will become more extensive and more restrictive. For example, the current U.S. noise level limit for machinery is 90 dB at the operator's ear. Sweden now has a limit of 85 dB and apparently is considering a reduction to 80 dB. Some mining equipment manufacturers feel that the United States will also reduce the noise level specification before long. Possible long-term health hazards related to diesel emissions - in particular, when combined with coal dust - may result in even more restrictive regulation of engine emissions in underground mining. Studies involving the effect of the soluble organic fraction of diesel exhaust particulates on human cells suggest that a significant mutagenic effect is possible. This may be a profound deterrent to expanded automotive diesel usage, and it is a further argument against the use of diesel engines underground. If very strict particulate emission standards are set for automotive diesel engines, they may not be attainable, at least not without a potentially critical loss in efficiency. However, the expected detrimental effect on diesel engine efficiency with more stringent emission control - which might preclude extensive automotive usage - should not be a significant factor in mining applications. Nevertheless, should the use of diesels in highway applications be proscribed because of particulate emissions, it is unlikely that diesels will be available for application to mine usage. The relatively small number of diesel engines used for mining applications would not justify either dedicated production or any extensive emissions control research.

The more important Federal regulations concerned with diesel usage in mines are summarized briefly table II. The regulations specifically state that only diesel engines burning diesel fuel will be considered for approval and certification. Gasoline fuel is not allowed in mines because of its low flashpoint and accompanying hazards. This does not necessarily imply that a spark ignition engine cannot be used for mining if it can use high-flashpoint fuel and may even be used in gassy mines if the ignition system can be made explosion proof. It may also be assumed that other heat engines (e.g., steam, Stirling, or turbine) that do not present the hazards regarded as attendant to gasoline engines may be considered. Obviously it must also be assumed that the significant regulations applicable to diesels must also be considered for other heat engines. Furthermore other heat engines may prompt additional regulations pertinent to their specific characteristics. For example, the use of hydrogen as a working fluid in a Stirling engine may be prohibited.

Availability (Production Readiness)

Availability (production readiness) is the portion of total working shift time that a machine is actually on hand, ready to work. This time is affected primarily by the frequency and severity of breakdowns. Any time required for servicing (fueling, battery change, etc.) during a shift would be particularly detrimental in that it would not only detract from availability but also disrupt the rhythm of operations. Figures on availability for various types of haulage vehicles appear to be quite similar. Cable-reel cars average a mechanical delay time of about 25 min per shift, which is approximately 10 percent of the effective face time available per shift. Typically, available face time is approximately 250 min per 8-hour shift. Table I shows a typical breakdown of function times for an 8-hour shift. The nonproductive time includes going in, going out, preparation to mine, lunch, mechanical delay, etc. New diesel-powered vehicles also are available 90 percent of the time or more. With age and wear the availability factor will normally decrease. The lowest tolerable availability is of the order of 75 percent. At this point the machine would have to be replaced or extensively refurbished.

Availability or production readiness is the cumulative result of a number of machine characteristics such as reliability, ruggedness, durability, and ease of maintenance. Reliability is the capacity to perform a particular function on call, repeatedly, without failure - either systematic or random. This is obviously an important factor in availability as related to production machinery. However, it is also a key factor in the performance of nonproductive machinery such as personnel transports or utility vehicles. Poor reliability would not only affect productivity but could also adversely and seriously affect personnel safety in the event of need during an emergency.

The mining environment is a difficult one, in particular for haulage vehicles. Passages are narrow, often low, and poorly lit. Most often the only lights in passageways are those carried by the vehicles or men. Roadways are rough and uneven and often involve fairly steep grades. It is not unusual for vehicles operating underground, particularly haulage vehicles, to hit or scrape walls or pillars. Heavy loads of dense, hard material are dumped - often roughly - on the haulage vehicles. Power systems must endure these shocks and others without damage or malfunction. Obviously ruggedness is also a factor that must be considered in assessing production availability and durability or life.

Durability of a power system relates to the length of time it can perform its required duty cycle reliably and with the requisite availability (minimum, approx 75 percent). As breakdowns or stoppages increase in frequency or the machine's capacity to fulfill its duty cycle requirements falls, the machine becomes too costly to operate and must be refurbished or replaced.

Diesel systems, in general, last about 3000 to 5000 hours of engine operation, which is the equivalent of about 2 years of active production. At this point a major overhaul is required. This may involve cylinder reboring and replacement of all engine moving parts. Often to avoid loss of the entire vehicle over an extended period, the worn engine may simply be replaced with a spare and the replaced engine used as a spare when rebuilt. Electrical systems generally will last longer before major overhaul is required. Of course this does not include the cables or batteries.

Maintenance or repair of any production machinery should entail a minimum effect on production time. This is true for mines as for any production system. This implies that regular maintenance is not required frequently and that it can be done quickly with a minimum of skill or specialized equipment. Furthermore the machine should not be susceptible to operational breakdown or environmental damage. Mining machinery must be especially rugged because of the severe environment.

The underground mine represents a worse situation, as far as maintenance is concerned, than the normal production shop - which is bad enough. Often no facilities for repair can be provided in close proximity to the working sections. The people responsible for maintenance and repair are not necessarily highly skilled or trained in the maintenance of sophisticated systems. In many cases, maintenance jobs are bid for through the miners' union and seniority may be a bigger factor in filling these jobs than capability or experience. In maintenance terms, battery systems, which require small amounts of relatively unskilled maintenance, are preferred to diesel engines, which require frequent and skilled maintenance.

Market Availability

In general, any power source for application to underground mining machinery must be easily available commercially. Spare parts and service must also be readily and widely available. The market for mine machinery is, in general, small compared with other industrial and highway applications. In a good year, approximately 10 000 rubber-tired mine vehicles are manufactured. About 6000 of these are various haulage vehicles - shuttle cars, scoops, and load-haul-dump vehicles (LHD's). The others are roof bolters, personnel carriers, and other utility vehicles. Approximately 2000 of the total are diesel powered.

Deutz Corp., Engine Division - a large manufacturer of diesels used widely in mines - states that engines for mining applications are a small part of a market segment called "municipal applications," which is about 3 percent of their total business. The diesel engines used for mining applications are simply standard highway or industrial engines that have been extensively modified to meet Federal regulations for mining use. More often than not, this is true for other drive-train components such as transmissions and axles. A typical approach to designing a mine vehicle is to survey the components available commercially and then to design a vehicle around these components.

Perhaps the biggest practical problem in introducing a new power system will be getting it produced. For example, the cost of an engine produced just for mining applications would be prohibitively high - probably at least 10 times the cost of current engines. It is highly unlikely that this will be done. To be acceptable for mining applications, any new power source would have to have a substantial production base for industrial or highway applications.

Packaging Capability

The physical size of a power system when modified as needed to meet Federal regulations and packaged in a mine vehicle is of considerable importance. Dimensions in most mines are small - in width and most especially in height. Passage height, particularly in coal mines, is generally equal to seam thickness and can be as little as 61 cm (24 in.). Height is generally the most critical dimension. Vehicles built for low-seam haulage are highly specialized and essentially all electrically powered. Haulage vehicles for high-seam mining are substantially less specialized and quite often use diesel power where allowable. They often closely resemble above-ground earthmoving equipment.

The width of a haulage vehicle is generally more than enough to accommodate any reasonable power system - including battery systems, which require considerable volume for storage. Length also does not appear to be a limiting factor in power system applications, except possibly where excessive power system length may increase the minimum turning radius. Ability to package in a low-height configuration is a definite advantage for a mine vehicle power system. However, very low haulage vehicles - although necessary for low-seam haulage - are at a disadvantage in higher seams. Because of the low body height, both loading efficiency and operator performance are sacrificed.

EVALUATION OF HEAT ENGINE SYSTEMS

A heat engine can be described as a device that produces useful mechanical power from the thermal energy released from the burning of a fuel. Heat engines can be broadly divided into two categories: intermittent combustion and continuous combustion. Otto cycle (spark ignition) and diesel cycles (compression ignition) engines are prime examples of the intermittent combustion type. Typical continuous combustion engines are the Brayton cycle (gas turbine), the Stirling cycle, and the Rankine cycle (steam) engines. The Otto cycle engine is not applicable to underground mine use because of its requirements for high-volatility fuel and the attendant hazards.

Diesel engines are used in underground mines in many countries. Use of diesel engines for mobile hauling equipment in particular has generally resulted in substantial productivity improvement and consequently lower cost per ton of product. Basic operational safety is also better with the diesel engine than with trailing-cable electric machines. However, the potential health effects of diesel emissions have severely limited its use in underground mines in this country, especially in coal mines. Diesel noise may also pose a problem if Federal regulations are changed to lower the acceptable limit.

Continuous combustion engines offer promise of substantially reducing both serious toxicants (HC, CO, NO_x, aldehydes, and particulates) and engine-generated noise. However, no continuous combustion engine is now available commercially that could be applied directly to production mining machinery. Several are now in development and may be available commercially in the future.

The following discussions present the relation of mine ventilation rate to heat engine fuel consumption and assess the characteristics of various heat engines and their applicability to mine usage. Projections as to future market availability are also made.

Ventilation Requirements

All fossil-fuel-burning systems produce exhaust emissions that may include CO_2, CO, HC, NO_x, aldehydes, and particulates. Carbon dioxide production is a function only of the fuel composition and the rate at which the fuel is used. For example, no. 2 diesel fuel is composed of about 87 percent carbon and 13 percent hydrogen by weight. As a result, about 3.19 kg of CO_2 are produced for each kilogram of fuel burned.

The ventilation rate established by the Mine Safety and Health Administration is based on dilution of the exhaust emissions (CO_2, CO, and NO_x) to half the average 8-hour tolerable limit as specified in CFR Title 30 (table II). For ideal combustion, only CO_2 and water would be produced and the ventilation rate would be minimum. In practice, ventilation rates are generally determined by NO_x emissions and may be much higher. Carbon dioxide concentration is limited by the CFR (table II) to 0.25 percent by volume, and therefore a minimum of about 685 m^3 of ventilation air is required for each kilogram of no. 2 diesel fuel burned (10 970 ft^3/lb) (see appendix A). The minimum ventilation rate per rated horsepower, or specific ventilation rate (SVR), is related directly to the engine's brake specific fuel consumption (BSFC) at rated power.

$$\mathrm{SVR}\left(\frac{m^3}{kW\text{-}min}\right) = 0.01142\left(\frac{m^3\text{-}hr}{g\text{-}min}\right) \times \mathrm{BSFC}\left(\frac{g}{kW\text{-}hr}\right) \tag{1a}$$

or, expressed in U.S. customary units,

$$\mathrm{SVR}\left(\frac{ft^3}{hp\text{-}min}\right) = 182.9\left(\frac{ft^3\text{-}hr}{lb\text{-}min}\right) \times \mathrm{BSFC}\left(\frac{lb}{hp\text{-}hr}\right) \tag{1b}$$

This relation is shown graphically in figure 1. The line represents the lower limit of ventilation rate required for any engine operating on no. 2 diesel fuel with CO_2 diluted to 0.25 percent by volume and is representative of all carbon-bearing fuels. Of course, the use of a non-carbon-bearing fuel such as hydrogen could avoid this limitation and, if NO_x emissions were kept low, greatly reduce ventilation requirements. Obviously the handling and storage of such a fuel would require considerable development.

The emission rates of CO, NO_x, and some particulates are not directly proportional to the fuel flow but are dependent on how the fuel is burned. Such things as air-fuel ratio, peak flame temperature, residence time, whether combustion is intermittent or continuous, and whether the fuel is vaporized and mixed with air prior to combustion or introduced in droplet form into the combustor all influence the amount of CO and NO_x formed. The volumes of ventilation air required to dilute CO and NO_x to half the 8-hour threshold limit value (TLV) (50 ppm CO, 12.5 ppm NO_x) are 16.88 m^3/g CO (596 ft^3/g CO) and 41.1 m^3/g NO_x (1452 ft^3/g NO_x). The ventilation requirements for current diesel mine engines are generally NO_x limited. Although formaldehyde in the mine air is limited to 10 ppm (the 8-hr TLV) ventilation requirements are not prescribed because formaldehyde is self-evident if present in objectionable concentrations.

The long-term health effects of currently unregulated compounds produced in the exhaust of diesel engines are now attracting much attention. Particulates are of special concern for many of them are suspected cancer-causing agents. The DOE has shown that the total soluble organic fraction (SOF) of diesel exhaust as well as most of the subfractions of the SOF are mutagenic and possibly carcinogenic. It was found that the subfraction of the SOF with the greatest mutagenic activity is that containing compounds such as substituted polynuclear aromatics (PNA's), phenols, ethers, and ketones. It was also found that promutagens exist as the PNA benzo(a) pyrene (BaP), which needs to be activated metabolically or chemically before it becomes a direct mutagen. It is possible also that a harmful synergistic effect may exist when diesel emissions are combined with the other air-borne particulates found in underground mines, particularly coal mines. Further tests are needed to isolate these fractions, to assess their health effect, and to devise means for measuring these components.

Further legislation may require that the concentration of these compounds be maintained below certain limits. Therefore the engines that tend to produce low levels of these questionable compounds will be better suited for mine use. Continuous combustion engines (Stirling, gas turbine, and steam engines) are desirable from the emissions viewpoint because they generally produce relatively low concentrations of toxic emissions, including particulates.

Diesel

Basic Description

Diesel engines are used extensively in underground mines, including coal mines, in many countries. However, their use in the United States is limited primarily to noncoal mines. Diesel locomotives are the only diesel application certified by the U.S. Mine Safety and Health Administration for use in underground coal mines.

In general, diesel engines for underground mines are versions of existing production engines that have been modified to comply with the Government mining regulations. Since diesel engines for underground use represent only a very small specialized portion of diesel engine production, they tend to be expensive when modified for mining use. In addition, with time, certain models may be unavailable as the engine manufacturers discontinue production of one model and begin production of a new model. If a new engine is substituted, it may require considerable redesign of the vehicle and generally requires recertification of the vehicle by MSHA.

Figures 2 and 3 show two typical diesel mining engines. Table III lists some specifications for mine engines. Diesel engines vary considerably in size and weight depending on horsepower, operating speed, and manufacturer. Included in table III are overall dimensions for typical Caterpillar water-cooled and Deutz air-cooled diesel mine engines without flame arrestors or air exhaust cooling devices. The volume[2] of these engines per brake horsepower (exclusive of the water cooling system and flame arrestor) varies from about 4.5 liters/kW (0.12 ft^3/hp) for engines producing over 200 kW (270 hp) to over 15 liters/kW (0.40 ft^3/hp) for 19-kW (25-hp) engines. Specific weight typically ranges from about 5.25 kg/kW (8.63 lb/hp) for engines above 150 kW (200 hp) to about 12 kg/kW (16 lb/hp) for 19-kW (25-hp) engines.

Diesel mine engines may be either water cooled or air cooled depending on their particular application. Air-cooled engines are normally not used in gassy mines because of the uncertainty of maintaining low surface temperatures. However, some air-cooled engines have been modified with water cooled exhaust manifolds and are certified in gassy, noncoal mines. The overall system weight, including the cooling system, of air-cooled engines tends to be less than that of corresponding water-cooled engines. The cooling system used does not appear to affect significantly the exhaust emissions or fuel consumption.

Diesel engine combustion chambers can be either prechamber, swirl chamber, or open chamber direct-injection types. Examples of the three types are shown in figure 4. Prechamber and swirl-chamber engines employ two-stage combustion with initial burning at rich conditions in a separate combustion chamber and completion of burning at lean conditions in the cylinder proper. Direct-injection engine combustion takes place entirely within the cylinder, also at a lean mixture ratio. Emissions from two-stage combustion engines are significantly lower than those from direct-injected engines.

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[2]Overall maximum rectangular volume based on manufacturer brochures.

Figures 5, 6, and 7 compare CO, HC, and NO_x concentrations over a range of speeds for the Deutz FL912 direct-injection and FL912W two-stage (swirl chamber) combustion engines as a function of brake mean effective pressure (BMEP) (2). The two-stage combustion produces significantly lower and more constant concentrations of all three pollutants. Carbon monoxide is less than half, HC is one-fourth to about one-seventh, and NO_x is about one-third of that for the direct-injection engine. The HC emissions vary differently as a function of BMEP for the two types of engines. The CO emissions in the direct-injection engine vary widely with speed at high BMEP. The HC concentration is maximum at low power and steadily declines as power is increased in the swirl-chamber engine. But HC concentration for the direct-injected engine starts out high and increases to a maximum at about 2-bar BMEP and then declines to a minimum at full power.

Most of the diesel engines used for mining applications are four-stroke-cycle engines and use all three types of combustion chambers. The only certified two-stroke engines use direct injection and have emissions comparable to those of the four-stroke direct-injected engines.

Turbochargers are used on some water-cooled diesel engines but are not generally used on air-cooled engines. Turbocharged engines tend to have higher NO_x emissions and correspondingly higher ventilation rates than normally aspirated engines. However, engines that are turbocharged and employ aftercoolers have emissions comparable to those of normally aspirated engines. The main advantage of turbocharging is an increase in specific power - approaching two times that of naturally aspirated engines.

Combustion of fuel in diesel engines is intermittent and occurs through autoignition due to the high temperature of the air in the combustion chamber after compression. The burning of the fuel and heat release occur when fuel is injected into the combustion chamber near the end of the compression process. The diesel combustion process can be characterized as simultaneous diffusion droplet burning, since each droplet of fuel injected into the combustion chamber is exposed to a local environment that favors spontaneous combustion. The diesel combustion process takes place with excess air. As a result, hydrocarbon and carbon monoxide emissions are generally low. Nitrogen oxides are produced at relatively higher levels. Particulates including soot, sulfur compounds, and other compounds are also produced. Relatively high particulate emissions appear to be characteristic of the diesel combustion process. Data on automotive diesel engines (3) indicate that hydrocarbon emissions generally range from about 1 to 8 g/kg fuel, particulates from 2 to 6 g/kg fuel, and NO_x from 8 to 14 g/kg fuel.

Figures 8 and 9 show the specific ventilation rates for several diesel engines certified for use in underground mines under MSHA schedule 31 (satisfies CFR, Title 30, Part 36 for gassy, noncoal mines) and schedule 24 (satisfies CFR, Title 30, Part 32 for nongassy, noncoal mines), respectively, as a function of their BSFC at rated power. The specific ventilation rates are generally determined by NO_x emissions for the various engines. The trends are (1) for prechamber engines to have significantly lower specific ventilation rates than open-chamber (direct injection) engines, (2) for naturally aspirated engines to have lower specific ventilation rates than turbocharged engines without aftercooling, (3) for turbocharged engines with aftercooling to have specific ventilation rates about equivalent to those of naturally aspirated engines. Note that some engines have ventilation rates near the CO_2 limit. Therefore further reduction of NO_x emissions for these engines would have little effect on their ventilation requirement.

Evaluation Against Requirements

Ability to Achieve Duty Cycle

The diesel engine offers unrestricted mobility and broad power range for mine vehicles. A diesel system has both high energy and high power density without the limitations pertinent to tethered systems. Experience has shown that substantial increase in productivity and reduction in cost are possible with conversion from trailing-cable systems to diesel-powered haulage equipment. The elimination of cables and accompanying breakage problems results in improved safety and operational continuity. When cables are eliminated, the number of vehicles working a section of mine also can be increased (depending on ventilation) because there is no chance of entanglement with cables.

Figure 10 compares full-load torque, engine power, and BSFC as a function of engine speed for three versions of the same diesel engine - naturally aspirated, turbocharged without aftercooling, and turbocharged with aftercooling. The torque characteristics of all three versions are well suited for mining use. Torque rises significantly as speed is reduced from maximum, thus providing for good lugging power. Use of both turbocharging and aftercooling results in a substantial increase in power and improvement in fuel economy over both the naturally aspirated and turbocharged versions of the engine.

Ability to Meet Government Regulations

The Code of Federal Regulations for underground mines requires that diesel emissions (CO_2, CO, and NO_x) be diluted to below the 8-hour tolerable limit. Therefore a substantial increase (possibly as much as an order of magnitude) in ventilation is required when diesel equipment is introduced into a mine to replace trailing-cable electric vehicles.

In addition to the ventilation requirements, for a diesel to qualify for MSHA Schedule 31 approval for operation in gassy, noncoal mines, a number of expensive modifications are required. (See table II for a summary of these regulations.)

Exhaust temperature is limited to 71° C (160° F) by Government regulations. This is generally accomplished by passing the exhaust through a water bath or a spray chamber. This cools the exhaust and also removes some particulates and undesirable components such as soot and some sulfur compounds from the exhaust. Diesel engines used in coal or gassy mines are also required to have provisions for limiting the temperature of the external surfaces of the exhaust system to not more than 204° C (400° F). In actual practice this limit has been lowered to 150° C (302° F). If water-jacketed parts are used, the jackets must be integral with the parts (i.e., not bolted together).

The Federal regulations require diesel engine untreated exhaust to contain not more than 0.25 percent CO for use under provisions of Part 31 or Part 32 of the CFR and not more than 0.30 percent CO or 0.2 percent NO_x

under Part 36 provisions (table II, item 9). To meet these requirements, diesel mine engines generally require some derating of maximum power from their industrial counterpart engines.

The Federal regulations require that provisions be made to dilute the exhaust gas with air before it is discharged from the vehicle. The mixture of exhaust gas and air may not contain more than 100 ppm by volume of carbon monoxide, 25 ppm by volume of oxides of nitrogen (as equivalent nitrogen peroxide), or 10 ppm by volume of aldehydes (as equivalent formaldehyde) under any operating condition. To provide for this dilution, various measures are used. Generally some form of baffle is used to form an ejector to entrain air with the exhaust as well as to distribute flow over a large area at the location of discharge from the vehicle. Some equipment manufacturers design their systems to combine the exhaust gas with the air discharged from the cooling system, thus taking advantage of the cooling fan to dilute the exhaust. Vehicles for use in gassy mines are required to have flame arrestors in both the intake and exhaust systems. Federal regulations are explicit in describing the design details of spaced-plate flame arrestors for diesel engines. The thickness, spacing, and width of the plates are specified. Specifications are also given for the performance of the flame arrestors. They must be capable of withstanding repeated explosions of methane-air mixtures without distortion and without propagating flame outside the engine. If a water chamber is used to cool the exhaust, it can also be used as the flame arrestor, but it must pass the explosion tests for flame arrestors. Figure 11 shows schematically the engine exhaust system used by Jeffrey. It provides effective exhaust cooling, scrubbing, flame arresting, and dilution with engine cooling air.

In the United States each diesel engine intended to power an underground mine vehicle or machine must pass a safety certification test. The test includes measurements of exhaust temperature and emissions. The Mine Safety and Health Administration then assigns a ventilation flow rate to that engine that is based on achieving a safe level of concentration for the worst pollutant measured.

If the vehicle is to be used in a gassy mine, engine explosion tests are also performed. The engine must be capable of withstanding repeated internal explosions of methane-air mixtures without igniting an external natural gas - air mixture and also without deforming or damaging the intake or exhaust systems.

Present MSHA regulations require that diesel engine noise in mine vehicles measured at the operator station not exceed 90 dB. In practice, most diesel mine engines operate near this limit. It is likely that in the near future this noise limit may be lowered to 85 dB. Costly modifications would be required to do this as diesel engines tend to be inherently noisy and the noise is produced from a number of sources (4). Furthermore gassy mine approval allows no electrical equipment except for headlights with a self-contained, sealed power source. A pneumatic or hydraulic engine start system is required. CFR Title 30, Part 31, for diesel mine locomotives is essentially the same except that an explosion-proof electric motor can be used for starting. These modifications, along with emissions treatment equipment, can increase the basic engine cost by a factor of 1.5 to over 5.

Availability (Production Readiness)

Overall availability for new diesel-powered haulage vehicles is as good as that for trailing-cable machines (approx 90 percent) or better. With time and use the availability factor degenerates to the extent that the engine must be replaced or completely refurbished in order to maintain an acceptable level of availability. In general, diesel engines last about 3000 to 5000 hours of engine operation, which is equivalent to approximately 2 years of active two-shift-per-day production. Diesel engines require skilled maintenance, and diesel mechanics appear to be in short supply.

Market Availability

Diesels for mining application are available from the existing production for highway, marine, and industrial use. The mine vehicle market of itself does not provide the volume needed for dedicated production. Unfortunately product changes based on highway, marine, or industrial requirements can affect the availability of an engine for mining. An engine can and has become unavailable after incorporation in a mine vehicle design. This can force vehicle redesign or possibly withdrawal from the market.

Packaging Capability

Currently available diesel mine engines are either inline or V-type engines. They are normally mounted in the upright position. Both types tend to be taller than they are wide. This arrangement does not lend itself to use in vehicles requiring low-seam capability, which is particularly important in coal mines. Minimum height is close to 122 cm (4 ft). (The Jeffrey 410M diesel Ramcar with a 75-hp Deutz engine has an overall height of 109 cm (43 in.).) Some equipment manufacturers have modified engines to operate on their sides. These modifications have had limited success, primarily because of cost and the reluctance of the engine manufacturers to warrant the modified engine. In general, width and length are not a problem.

Potential for Future Improvement

Several of the diesel engines tested and certified by MSHA have ventilation rates near the CO_2 limit (figs. 8 and 9). Current Federal Environmental Protection Agency emissions regulations limit heavy-duty truck engine emissions to 2 g/kW-hr (1.5 g/hp-hr) HC, 13.4 g/kW-hr (10 g/hp-hr) HC + NO_x, and 33.5 g/kW-hr (25 g/hp-hr) CO. Current California regulations limit combined HC + NO_x to 8 g/kW-hr (6 g/hp-hr). Proposed Federal regulations for 1984 will limit HC to 1.7 g/kW-hr (1.3 g/hp-hr), NO_x to 14.4 g/kW-hr (10.7 g/hp-hr), and CO to 20.8 g/kW-hr (15.5 g/hp-hr). These changes should have little effect on mine engine emissions since their limits are currently set at or below these levels. Proposed 1986 regulations would require NO_x to be reduced to 5.4 g/kW-hr (4.0 g/hp-hr) with CO and HC limits unchanged from 1984. These also should have little effect on mine engine emissions because heavy-duty truck regulations are based on average rates over a typical driving cycle while MSHA ventilation requirements are based on the peak emission rates, which may be considerably higher than the averages. At best the 1986 EPA regulations could produce mine engines having CO-limited ventilation requirements of about 5.85 m^3/kW-min (154 ft^3/hp-min). The resultant mine air therefore can be expected to have a NO_x concentration of about 31 percent of the TLV and a CO_2 concentration of about 23 percent of the TLV. These engines may use exhaust gas recirculation (EGR) to reduce NO_x and therefore may have somewhat reduced power and increased fuel consumption.

Particulate standards of 0.335 g/kW-hr (0.25 g/hp-hr) have been proposed for highway diesels beginning in 1986, but standards have not yet been set by MSHA for mine diesels. At the present time there does not appear to be a satisfactory method to reduce particulate emissions significantly. There are two basic approaches to control particulate emissions:

(1) Modify the combustion process to reduce formation of particulates
(2) Process the exhaust to remove particulates before it is released into the atmosphere

Attempts to modify the combustion process such as by altering fuel type, injection timing and pressure, turbocharging, and air thottling have not significantly reduced particulate emissions without also correspondingly increasing NO_x emissions (3). There appears to be an inverse relationship between NO_x and particulates that is a fundamental phenomenon associated with diffusion-limited droplet combustion, a characteristic of the diesel engine. If both NO_x and particulates are to be significantly reduced, it may be necessary to avoid droplet combustion. This will require a radically new and currently undefined approach.

Several methods have been considered for particulate removal from automotive diesel exhaust:

(1) Centrifuge
(2) Water scrubber
(3) Electrical precipitation
(4) Oil bath
(5) Catalysts
(6) Disposable trap
(7) Trap with periodic regeneration or self cleaning through incineration

The centrifuge is not practical because the particles are submicrometer size and too small for dynamic removal.

Water scrubbing requires high water consumption, and disposal is a problem. However, diesel mine equipment generally incorporates a water scrubber to control exhaust gas temperature. If the design of the water scrubber were optimized to achieve high particulate removal efficiency, it might prove to be the most efficient method for reducing particulate emissions from diesel mine equipment.

Electrical precipitation provides a means to concentrate particulate emissions, but the low-maintenance system considered for automobiles still requires secondary treatment of the concentrated dirty gas. Initial test results show operation to be erratic and efficiency to be at best about 50 percent. However, in an application where daily maintenance is feasible (changing and cleaning filters) much better results may be obtained.

Liquid baths using oil have not worked well. They collect particulate matter but tend to trade engine exhaust matter for bath oil. Best efficiency tends to be about 20 percent.

Catalysts for reducing HC in combination with particulate trapping are being considered. However, no suitable catalyst has been found that reduces particulates. High-surface-area pleated-paper filter elements have given about 80-percent particulate reduction. Although they must be changed frequently, daily change could be acceptable in mine equipment. However, the filter materials are destroyed by incineration under some operating conditions, and they tend to block exhaust flow, causing significant increase in backpressure within a short operating time.

Trap materials with a fairly open structure that will trap or collect particulates within this structure are also being considered. Traps do not normally block the exhaust system, and they may have the highest collection capacity for a specific volume. Materials being considered include ceramic-coated metal mesh, ceramic beads, knitted ceramic cloth, and bare metal mesh. Particulate collection efficiency of about 60 percent has been achieved with metal mesh and ceramic beads. Because of the open structure of the material, blowoff of collected particles from this material can occur for some engine operating conditions. Various methods for cleaning and automatically regenerating the trap material are being investigated. These range from cleaning with solvents to automatic incineration effected by microprocessor-controlled throttling of the intake air and retarding of injection to increase exhaust temperature.

It appears at present that the removal of particulates from the exhaust by filtering, trapping, catalytic reaction, or some other treatment of the exhaust is the only practical approach. It is unlikely that particulate emissions from the diesel can be reduced by an order of magnitude without a significant breakthrough in the combustion process and/or in the treatment of the exhaust.

Work done for automotive diesels has shown that EGR significantly reduces NO_x. However, recirculating hot EGR gas can cause significant penalties in fuel economy, power, and smoke. These qualities can be minimized by cooling the EGR. Tests with four-stroke engines indicate that a 10-percent EGR rate results in 25-percent NO_x reduction without adversely affecting fuel consumption or power. Higher recirculation rates result in further reduction in NO_x, but engine performance suffers greatly, particularly at low speed. Two-stroke engines respond similarly to EGR, but since their NO_x emissions tend to be higher than those for four-stroke engines, more EGR is required to reduce NO_x emissions to a given level. Therefore two-stroke-engine performance is degraded more than four-stroke-engine performance.

Turbocompounding appears to be the direction in which commercial diesel engines are headed. The DOE currently is sponsoring work at Cummins to develop the turbocompounded diesel engine (5-6). The turbocompounded diesel offers several advantages:

(1) It produces more power while using less fuel (thereby creating less CO_2 emissions) without increasing thermal or mechanical loading.

(2) NO_x emission control using retarded injection timing and EGR does not affect fuel consumption because exhaust energy can be recycled to provide additional output power.

(3) Low-compression-ratio operation is possible with higher combined system efficiency and less structural noise.

(4) Exhaust gas recirculation can easily be used to reduce NO_x since higher exhaust manifold pressures can be used without sacrificing fuel economy.

(5) The turbocompounded diesel provides much better transient response than single-or two-stage turbocharged engines.

The primary disadvantage of turbocompounding is the increased complexity and associated maintenance problems of the additional turbine and gears. The efficiency of current turbocharged engines is relatively insensitive to the turbomachinery efficiency. However, this is not the case with turbocompounded engines, especially if operated with high pressure ratios. Since a large portion of the engine shaft power is generated by the exhaust turbine, its efficiency directly influences the overall engine efficiency. Considerable development is required to improve the efficiency of the turbomachinery in order to realize the full potential of turbocompounding. The turbocompounded diesel system is shown in figure 12. The concept basically consists of a single-stage turbocharged diesel engine and aftercooler with the addition of a power turbine that extracts additional energy from the exhaust. The energy is then transmitted through a fixed-speed-ratio gearbox directly to the engine output shaft. In this way, energy that would otherwise be lost through a waste gate valve is used to increase the shaft power output of the engine.

Two turbocompound diesel engines built by Cummins have achieved a minimum BSFC of 190 g/kW-hr (0.313 lb/hp-hr) and 196 g/kW-hr (0.323 lb/hp-hr) at rated power while meeting the 1980 California emissions limit for combined brake specific NO_x and HC (5), respectively. Driveby noise was 1 to 2 dB lower than for the baseline engine.

Typical BSFC for basic turbocharged engines is about 231 g/kW-hr (0.38 lb/hp-hr). Further improvement in BSFC is possible through insulating the cylinders, valves, pistons, and exhaust parts as shown in figure 13 to greatly reduce heat flow to the cooling system and thus approach an adiabatic case. The Cummins turbocompounded adiabatic diesel test engine being developed for the U.S. Army (7) has achieved 173-g/kW-hr (0.285-lb/hp-hr) BSFC at a rated power of 335 kW (450 hp). The energy balances of the basic turbocharged diesel, turbocharged plus turbocompounded engine, and adiabatic engine are compared in figure 14. However, despite its potential for improved BSFC, the increased complexity of the turbocompounded and adiabatic diesel engines (and the accompanying more difficult maintenance) may not be warranted in mining applications, where BSFC is not as critical as it is for highway applications. Also, adiabatic engines will not be available until the 1990's. A predicted schedule for production of adiabatic engine systems is shown in figure 15.

Roessler (4) discusses the potential for reducing diesel noise. It is important to recognize that substantial noise reduction by treatment of a single source is possible only if that source dominates. Many separate noise sources contribute to overall diesel engine noise. For effective noise control, all these sources must be treated simultaneously. Table IV lists some of the major parameters contributing to diesel noise and shows their potential noise reduction. The diesel engine is inherently noisy. Current regulations limit noise to 90 dB, which is the 8-hour permissible exposure level. Future regulations may limit diesel noise to 85 dB (as in Sweden) or possibly less. Extensive effort in diesel noise reduction may be required.

Noise treatment may also affect engine performance, emissions, or weight. For example, a reduction in combustion noise through the use of a low-turbulence prechamber can result in an increase of as much as 14 percent in fuel consumption. Increasing injection rate to lessen ignition delay can decrease NO_x by 40 percent. Complete encapsulation of the engine appears to have the potential for the greatest noise reduction, but it will add to engine weight and cost and will make access to the engine difficult. The work at Cummins (5,6) has shown that some noise reduction also can be made through turbocompounding without adversely affecting weight and performance.

Recommendations

The most significant deterrent to more extensive diesel use in mining appears to be potential health effects due to emissions. Projected improvements in diesel engine emissions, if the proposed 1986 EPA standards are adapted, may reduce the problems with NO_x. It can be expected that ventilation rates will be determined largely by CO limits. However, particulate emissions - now unregulated - appear to entail a significant potential health hazard. Particulate emissions are a key part of the argument against diesels now being presented by the United Mine Workers (UMW) and others. In particular, a health concern is presented for the combination of particulate emissions and coal dust. It appears then that a significant reduction in particulate emissions would be an important factor in extending diesel usage in underground mines.

Measurements to determine the particulate emissions from current diesel mining equipment are not part of the current MSHA certification procedure. It is possible that existing engines with water bath exhaust treatment already have exhaust particulate emissions considerably lower than the commercial engines from which they were derived. When and if particulate emissions of mine vehicles become regulated, a necessary first step in determining what modifications must be made to the vehicles is to measure particulate emissions from current equipment. This requires that test methods be established and that the appropriate modifications be made to the test facilities at MSHA. These test methods should provide for testing with the complete exhaust system to encourage the mine equipment manufacturers to improve the net engine particulate emissions through innovative design of the exhaust cooling system. Since it may require considerable lead time to make these changes, work in this area should be begun by MSHA at the earliest possible date.

Stirling

Basic Description

Although it was invented in the early 1800's, the Stirling engine was not developed to a compact, efficient engine until recent years. This was primarily due to lack of knowledge of thermodynamics, lack of analytical techniques and high-speed computers to aid in the design of Stirling engines, and lack of materials with sufficient strength at high temperatures with which to build them.

The conventional internal combustion engines (diesel and Otto cycles) produce mechanical power in the following manner: Air is compressed at a low temperature, requiring expenditure of work. A fuel and air mixture is heated by rapid combustion. The mixture expands from a high temperature and work is performed. The hot gas exhausts and is replaced by fresh, cool air. The difference between the expansion work performed and the compression work expended is then the net work available from the cycle.

The Stirling engine, like the steam engine, is an external combustion engine. The Stirling engine works in a similar manner to the conventional internal combustion engine in terms of compression and expansion, but it differs from a conventional engine in two fundamental respects. Heat is supplied continuously and externally, and the working gas - which is usually hydrogen or helium - operates in a completely closed system. A simple model of the Stirling process is shown in figure 16(a). It consists of two pistons, one operating in the cold-side cylinder and the other working in the hot-side cylinder. The working gas, which is enclosed between the pistons, moves continually back and forth between the hot and the cold sides and is alternately heated and cooled. The gas passes through a regenerator, which removes heat and stores it when the gas moves from the hot to the cold side and returns the heat when the gas moves in the opposite direction.

The theoretical pressure-volume curve (fig. 16(b)) and actual pressure-volume curve (fig. 16(c)) are also shown. The Stirling engine characteristically operates with a pressure ratio of 2 or lower and currently has a maximum cycle temperature of about 720° C (1330° F). To have a reasonable power density, the Stirling engine must operate at high pressure; typically up to 20-MPa (2900-psi) peak cycle pressure.

To achieve low specific weight, the double-acting principle is used in most of today's Stirling engines. In the double-acting arrangement (fig. 17), the pistons have two functions: They move the gas back and forth between the hot and cold spaces, and they transmit mechanical work to the drive shaft. The pistons in a double-acting Stirling engine each operate simultaneously in two cycles: The hot upper surface of one piston is coordinated with the cold undersurface of the next piston, and so on. At least three pistons are required to achieve thermodynamic coordination. Optimal efficiency is achieved by using four to six cylinders. The cylinder can be arranged in many ways; in-line, V, and square arrays are most common. The square array is shown in figure 18. It offers several advantages over the V and in-line arrangements. A single circular-shaped combustor can be used to supply heat to all the cylinders. The heater heads for each cycle can be identical. The cold-gas connecting passages can be made short and identical. This arrangement can be adapted to either a crankshaft U-drive or a swashplate drive as shown in figure 19. A V-engine configuration is also possible. However, it is less desirable because the heater heads and passages cannot be identical. Figure 20 is a cross-sectional view of the U-drive United Stirling P-40 engine showing the major components. Since the Stirling engine uses a closed cycle, it requires

(1) Seals to prevent leakage of the working gas (usually hydrogen) past the piston rods

(2) Heaters and coolers to transmit heat into and out of the cycle

(3) An external heat system to supply heat energy from the fuel to the heaters. The external heat system comprises the combustion chamber, where fuel and air are mixed and burned, and an air preheater, which removes heat from the high-temperature exhaust leaving the heaters and transmits that heat to the incoming combustion air. An air blower (not shown in the figure) is also needed to supply air for combustion.

Also not shown in the figure are several auxiliary systems that are necessary to operate the engine. These include a cooling water system, air-fuel mixture control system, a power control system, and a starting system. Figure 21 shows the P-40 engine equipped for test installation in an automobile.

Since the fuel is burned externally, the Stirling engine can operate on a wide variety of fuels. Almost any liquid or gaseous fuel that is reasonably clean burning can be used. For example, Stirling engines can run on gasoline, kerosene, diesel oil, jet fuel, alcohol, LNG, LPG, natural gas, or hydrogen. The use of any of these fuels generally entails only relatively minor modifications in the air-fuel system of the engine. Fuels with similar heating values and viscosities, such as gasoline, kerosene, and diesel oil, can be directly interchanged. Also, it should be possible to operate a Stirling engine on solid fuel such as micrometer-sized pulverized coal if a suitable fuel delivery system can be devised.

Stirling engine performance compares favorably with that of diesel engines. Figure 22 shows the power and torque curves for the United Stirling 4-275 engine (8). Of particular interest is the large rise in torque as the engine speed is reduced. Torque increases about 25 percent when the speed is reduced from 2200 rpm to 1000 rpm. The full-load brake specific fuel consumption with diesel fuel is shown in figure 23. Best full-load fuel economy is about 235 g/kW-hr (0.39 lb/hp-hr) at full load (1000 rpm). This is about the same as a "good" diesel mine engine. At 2200 rpm (maximum rated power) the BSFC is about 275 g/kW-hr (0.452 lb/hp-hr). This is well within the range of fuel consumption for diesel engines currently approved for use in U.S. mines. Table V shows part-load fuel consumption. The increase in BSFC at half load is less than 15 percent.

The Stirling engine combustor operates in a continuous-flow mode. Liquid fuel is introduced into the combustion chamber as droplets with about 25 percent excess air present. The CO emissions are mainly controlled by the amount of excess air. About 25 to 30 percent excess air is required to minimize CO. Specific CO emissions of 2 g/kg fuel or about 0.55 g/kW-hr (0.41 g/hp-hr) or less are possible for a Stirling mine engine. Oxides of nitrogen emission levels are potentially high at this lean combustion condition. Hydrocarbons, aldehydes, smoke, and particulates are normally very low. Two methods are used to control NO_x emissions (9): exhaust gas recirculation (EGR) and combustion gas recirculation (CGR). Both involve recirculation of exhaust gas back to the combustion chamber. Figure 24(*a*) shows the EGR system. EGR consists of returning exhaust gas leaving the engine to the combustion blower inlet. This dilutes the combustion process with essentially inert gas and thus reduces the peak combustion temperature and hence NO_x production.

CGR (fig. 24(b)) is similar to EGR in that exhaust gas is used to dilute the combustion process. But the recirculation occurs within the engine. Gas ejectors, activated by the incoming preheated air, entrain exhaust gas leaving the heater. With this arrangement the air preheater handles only the airflow and not the recirculated flow. Therefore the flow-related energy losses in the preheater are reduced from the EGR arrangement. Pressure drop losses in the combustor are higher for the CGR system mainly because of the ejector requirements. The net result is that the CGR system should have slightly better fuel economy than the EGR system.

Since the Stirling engine uses a closed cycle, the indicated power is independent of the combustion process. Therefore the use of either EGR or CGR has very little effect on shaft power. In contrast, diesel power is reduced significantly by EGR.

The lower limits of exhaust emissions depend on several design parameters. These include the power range of the engine, the power consumed by the combustion air blower, the degree that the fuel is vaporized and mixed with the air prior to combustion, combustor geometry, the degree of control of the air-fuel ratio (a/f), the amount of EGR or CGR flow, heater operating temperature, and air preheater effectiveness. The trend is for the concentration of NO_x to be reduced as EGR or CGR is increased. However, this also results in slightly higher fuel consumption as a result of increasing blower power requirements. Ultimately, the maximum airflow and EGR are limited by the combustor flow capacity. NO_x levels of about 2.5 g/kg fuel, or 0.69 g/kW-hr (0.51 g/hp-hr), should be possible for a heavy-duty Stirling engine suitable for mine use. This is about one-eighth of the proposed 1986 Federal NO_x limit for heavy-duty highway diesels.

Potential Mining Modifications

To make a Stirling engine suitable for operation in gassy mines, a number of modifications are required. Flameproofing of the Stirling engine will require inlet and exhaust flame arrestors similar to those used on diesel engines. The preheater-combustor assembly (fig. 20), which is normally constructed of relatively thin sheet metal, will probably have to be made of much heavier gage material in order to withstand the possible explosion overpressures. The insulation sandwiched within the sheet metal of the external heating system must also be capable of withstanding repeated explosions without being deformed. In addition, it must have appropriate provisions for pressure venting without propagating flames to the surrounding atmosphere. Therefore the insulation should be totally enclosed in heavy-gage metal. Since the external heating system encloses a relatively large volume, explosion proofing will probably result in a significant increase in engine weight.

To maintain all external surface temperatures below 150° C (302° F), it may be necessary to redesign some areas of the preheater-combustor. For example, because there is little insulation in the vicinity of the fuel nozzle, surface temperatures on the nozzle mounting flange are relatively high. Since the uncooled exhaust temperature can exceed 200° C (392° F), the surface temperatures of the exhaust pipes normally exceed the 150° C (302° F) requirement for gassy mines. Both of these conditions can be remedied by adding insulation and/or by water jacketing. This again will increase engine weight. It is not possible to estimate the relative increase in engine weight associated with these modifications without first doing a detailed design analysis.

The current Federal regulations restrict the use of electrical equipment on mine vehicles for gassy mines. Vehicles for gassy, noncoal mines are allowed only explosion-proof self, contained headlamps. The starter motors must be hydraulic or pneumatic powered. Coal mine locomotives are allowed to use explosion-proof electric starting motors. The Stirling engine requires two starting motors, some form of ignition system for starting, and electronic controls. Modifications to these components will be required to make them explosion proof. If a Stirling engine were to be used in mining applications, new sections for the Code of Federal Regulations that recognize its specific characteristics would have to be written. However, most of the requirements for diesel engines could be applied directly.

Evaluation Against Requirements

Ability to Achieve Duty Cycle

A Stirling engine, sized and designed properly, could handle haulage duty cycles well. There appears to be no basic reason why a heavy-duty Stirling engine could not do the haulage job well. However, the automotive Stirling engine is being developed to operate with the relatively light loading encountered in the automobile duty cycle. To use an automotive engine in a mining application, where the duty cycle requires a much greater average percentage of the engine maximum power, the engine power must be derated to have the life expectancy required of production mining equipment. Consideration must be given to the number of power cycles required and to the average stress levels encountered. The heater tube stress-rupture life for an automotive Stirling engine is designed for a relatively low average power level (approx 20 percent of maximum power). An engine intended for mining applications must be designed for high average power (up to 75 percent of maximum power). An automotive engine would have to be considerably derated in cycle pressure and/or temperature to have acceptable life in the mining application. Since the automotive Stirling currently being developed will produce only about 67 kW (90 hp) maximum, it is highly unlikely that a derated version of that engine can be put to haulage use in a mine. Its power capability will be too low. It is more likely that a mine engine will evolve from a heavy-duty industrial engine possibly from the United Stirling 4-275 engine (fig. 25).

A Stirling engine for mine use will probably use helium as the working fluid. This will eliminate the need for additional explosion-proofing considerations that would be encountered with hydrogen. A NASA-funded study to evaluate the Stirling engine for a stationary power source has recently been completed (9). The study includes evaluating the effect of operating with helium rather than with hydrogen. Figure 26 compares the indicated power and cycle efficiency of an engine optimized to run on hydrogen with those for an engine optimized to run on helium. Both engines are based on the automotive Stirling engine and are optimized for operation at 1800 rpm, and both produce 37.5 kW (50.2 hp) at 1800 rpm when modified for stationary use. For speeds to 1800 rpm, the helium engine produces slightly greater power at low speed than the hydrogen engine, but the power for the helium engine drops off sharply when the speed exceeds 1800 rpm. Therefore the lugging characteristics of the helium engine tend to be better than those of the hydrogen engine. The maximum cycle efficiency for both engines occurs at about 1000 rpm. The maximum efficiency with hydrogen is about 1.5 percentage points better than that with the helium engine. At 1800 rpm the hydrogen engine efficiency is 2.5 percentage points better than the helium engine efficiency.

Ability to Meet Government Regulations

The toxic emissions (CO, NO_x, aldehydes, and particulates) are much lower for a Stirling engine than for a diesel. Carbon monoxide emissions are expected to be from one-half to one-fifth of those for a diesel. Oxides of nitrogen emissions are expected to be almost an order of magnitude lower than those of a diesel. Although data for aldehyde emissions are not available, it is apparent from the lack of odor in the Stirling exhaust that aldehyde emissions are low. Particulate emissions data are not available for Stirling engines, but indications are that they are significantly lower (possibly by several orders of magnitude) than those for a diesel.

Ventilation requirements for the Stirling engine will be defined by CO_2 emissions, which ultimately are determined by the fuel consumption. Stirling engine fuel consumption is expected to be about the same or slightly higher than that of a "good" diesel. Therefore the ventilation requirement for the Stirling will be about the same as the theoretical minimum for a CO_2-limited diesel. At this time, only a very few diesel engines have reached this optimum point. Most mine-certified engines have ventilation rates from 2 to 4 times the rate required to dilute CO_2. Since the Stirling ventilation rate will be about the same as that for a CO_2-limited diesel, the concentration of toxic emissions in the mine will have the same relation as that of the emissions rates for the Stirling and diesel engines - Stirling CO about 0.31 diesel CO, Stirling NO_x about 0.19 diesel NO_x, and Stirling particulates possibly orders of magnitude lower than those of a diesel that meets the proposed 1986 EPA standards. As a result, Stirling may prove much more acceptable than diesel to the people who have to work with them in underground mines.

A significant reduction in noise should be possible with the Stirling engine. Although the present U-drive configuration used in the 4-95 (P-40) and 4-275 engines tends to produce significant gear-generated noise, it does not represent the final form of the automotive Stirling engine. Vehicle noise measurements for an Opel Rekord with a diesel engine and with an unmuffled P-40 Stirling engine are summarized in figure 27 (11). Three different tests were made. For all tests the Stirling engine noise was significantly less (up to 12 dB) than the diesel noise. It is reasonable to project that a Stirling mine engine could easily meet any future Federal noise requirements even if they are set as low as 80 dB at the operator's station.

Availability (Production Readiness)

There are, at present, little or no data on which to base a firm assessment of Stirling engine production readiness for mine haulage vehicles. Projections must be based on the limited amount of experience to date and on the basic nature of the engine.

The Stirling engine has potential for a high degree of availability. This is primarily because it uses a closed cycle, which is not subject to contamination from combustion products or exposure to the atmosphere. It does not require frequent oil changes and the wear rates should be low. However, it is composed of many components and complicated systems, both mechanical and electrical, that potentially can fail. The reliability of the components has not been demonstrated to a high degree of certainty. The present engines are complicated to repair and require specially trained and skilled technicians. The reliability and repairability of the Stirling engine must be improved significantly if the Stirling is to be used for automotive applications or for mining. We do expect improvement of this nature in our current automotive engine development, as it is also vital to highway applications.

Market Availability

Obviously, no Stirling engine that could be applied to mine haulage use is available on the market now. Experimental engine development for automotive engines is now being carried out by the team of Mechanical Technology, Inc., United Stirling, and American Motors General under the auspices of DOE and NASA. Assuming successful development and commercialization and the normal industry development time leading to market availability, the first automotive Stirlings will not be available until the early 1990's. It is unlikely that engines for heavy-duty highway use would be available for several more years.

A more optimistic approach to near-term heavy-duty Stirling availability would come through the development of Stirling engines for solar, stationary, and other nonhighway heavy-duty use. A number of applications of that general nature, including marine, industrial and a variety of congested area applications - such as mining, indoor material handling, and downtown urban buses and trucks - might be combined to form a sufficiently large market (10 000 to 20 000 engines per year) to justify manufacture in reasonable volume and at reasonable price. The analogy could be drawn with general aircraft engines, which are roughly at that production level. Although their cost is substantially higher than the cost of automobile engines, it is not exorbitant for the application.

United Stirling is producing their 4-275 engine in very small quantities with intentions of selling them to such a market. These engines are still in the developmental stage and, as yet, very expensive.

Packaging Capability

The Stirling engine packageability appears to be similar to that of a diesel engine. Compared to the Caterpillar 3304NA (table III) diesel engine of the same power, the United Stirling 4-275 is about the same height and width but 36.5 percent shorter (fig. 28), its specific weight (weight/power) is about 12 percent lower, and its specific volume (volume/power) is about 38 percent lower.

A swashplate configuration could offer a much lower profile if this were made a design requirement, since the cylinder, heater head, and drive system are arranged horizontally in line with the output shaft. This configuration would be attractive for low-seam haulage vehicles. Engine height could be reduced to about one-half that of a U-drive engine. Unfortunately there is no current active development of a swashplate engine.

Recommendations

The Stirling engine appears to offer considerable potential to reduce toxic emission levels in underground mines. Therefore the current automotive development effort aimed at commercialization of Stirling engines should be monitored closely.

In addition, a more detailed design assessment should be made of the adaptability of the automotive Stirling as well as the United Stirling 4-275 to mining applications. The assessment should include evaluation of the effects of mining application duty cycle and life requirements on the rated power. It should also include detailed design of the modifications needed to meet the Federal regulations for both gassy and nongassy mines and determine the effect of the modifications on engine power and efficiency. The results of this design assessment can serve as the basis on which to decide if a demonstration Stirling-powered haulage vehicle is practical.

Gas Turbine

Basic Description

The heat engine based on the Brayton cycle, mechanized in the commonly known form of the gas turbine engine, is widely used for a variety of stationary, industrial, and aircraft shaft-power applications. For a number of years, it has also been in exploratory development for a variety of vehicular applications, namely automobiles, trucks, and buses.

Figure 29 illustrates a simple single-shaft Brayton-cycle engine and process diagram. The compressor induces the flow of working fluid (air) and increases its pressure. Fuel is mixed with the air and burned in the combustor. The high-pressure, high-temperature gas is then expanded through the turbine to produce work. Part of the work is used to drive the compressor and the remainder is available for shaft power. The "ideal" cycle diagram (fig. 29(b)) shows two isentropic and two constant-pressure processes taking place in the cycle. In the actual engine, nonisentropic adiabatic processes take place in the compressor and turbine, with some pressure loss occurring in the combustor and exhaust ducting.

In these applications the Brayton cycle is "open," that is, without recirculation of the working fluid (air). In a "closed" Brayton cycle the working fluid is recirculated and is not involved in combustion. The working fluid is not normally air. Two heat exchangers must be added to the components shown in figure 29(a), and an external source of heat similar to the combustion system for the Stirling cycle must replace the combustor. Because of this added complexity, cost, and weight, and because a production base for closed-cycle Brayton engines is not likely to exist from which to obtain engines for the mining industry (since they are not in common usage, are not commonly available, and are not actively being developed for other applications), the closed cycle was not considered herein as practical for the mine vehicle application.

Only a regenerated form of the Brayton cycle is being considered for the vehicular engines (fig. 30) in order to minimize the fuel consumption and exhaust temperatures. The regenerator provides for recovery of exhaust heat that is transferred to the compressed air prior to combustion. The resulting thermodynamic efficiency of the cycle with regeneration is comparable to the efficiencies of the diesel and Stirling engines, as will be shown later. Hence the amount of waste heat and CO_2 discharged to the atmosphere is comparable for all three engines. However, the gas turbine differs uniquely from the other cycles and engine types in that almost all the waste heat is limited to the exhaust. Thus the engine requires no radiator. This increases the amount of water required for exhaust cooling for the mining application as compared with other engine types.

The fuel economy for the regenerative Brayton cycle usually optimizes at a low enough cycle pressure ratio to require no more than one or two compressor or turbine stages. Centrifugal compressors are used in the vehicular engines, axial turbines in the bus or truck engines, and radial turbines in the automotive engines. At present there is a major emphasis being placed on the development of ceramic materials and fabrication techniques for the turbines. The rewards, if successful, will be a reduction in engine cost and a reduction in fuel consumption (and CO_2 emissions) of 15 percent for bus and truck engines to 45 percent for automotive engines, as compared with present gas turbine engines with metal rotors. Ceramic regenerators are already in common usage in these engines.

Two basic shaft arrangements are used in the vehicular gas turbine engines: the single-shaft arrangement shown in figure 30(a), and the two-shaft arrangement shown in figure 31. In the single-shaft engine, the compressor, turbine, and power output are all on one shaft. In the two-shaft arrangement, two turbines are used: one to drive the compressor through the "gasifier" shaft, and the other to drive the power output shaft. Because the compressor is driven independently of the power output shaft, its ability to deliver working fluid to the power turbine is independent of the speed of the output shaft. This difference results in a significant difference in the range of output speeds and torque characteristics for the two different shaft arrangements (fig. 32). The maximum-to-idle output speed ratio is approximately 2 for the single-shaft engine and approximately 3 to 6 for the two-shaft engine, as compared with approximately 4 for a comparable diesel. The maximum torque occurs at maximum speed for the single-shaft engine and at the minimum output shaft speed for the two-shaft engine, as compared with intermediate speed for the diesel. The effect of these engine differences on transmissions requirements are discussed later.

Evaluation Against Requirements

Ability to Meet Duty Cycle

The power, duty cycle, and life requirements used herein for evaluating the potential suitability and merits of a gas turbine engine for a load-haul-dump mine vehicle were derived from (1,12). They are representative of an LHD with an 8200-kg (18 000-lb) load-carrying capacity and are listed in the form of the parameters shown in table VI for section A and C types of operations (1) in a mine. They are compared in this table with the goals for the advanced automotive gas turbine engines (AGT) currently under development at Detroit Diesel Allison (DDA) and Garrett Division of AiResearch (the AGT-100 and 101) under the DOE-funded, NASA Lewis-managed heat engine program and with the goals for a heavy-duty industrial gas turbine (IGT) for truck and bus application (the DDA-404 engine), part of which is funded and managed under this same program.

It is apparent in table VI that the AGT engines are sized to produce only slightly more than half of the maximum power required for the LHD. Paired engines could meet the maximum power requirement. However, two of the operating requirements that affect engine life and durability (time at maximum power and average power over the duty cycle) are much more severe for the LHD than for the AGT. Therefore the AGT was not considered suitable or easily adaptable for LHD use. This is not to say that the AGT should not be considered for auxiliary mine vehicle applications. The advantages of such applications lie in potentially lower toxic emissions than diesel engines.

It is also apparent in table VI that the IGT has more than enough power to meet the maximum power requirement for the LHD. It should also meet the basic durability requirements when fully developed. The IGT appears to represent a class of vehicular gas turbine engines that is potentially well suited to the LHD requirements. The characteristics of the particular IGT used herein, the DDA-404 engine for line-haul trucks and city transit buses (13-14) are used for convenience and are assumed to be representative of the general class of heavy-duty vehicular gas turbine engines. IGT and diesel mine engines are compared in table VII. The IGT compares favorably in size and weight with the diesel engines in current LHD use, even though there is a 2:1 difference in peak power capability. In fact, the IGT is lighter and lower and occupies less volume than either diesel engine. The additional volume and weight of a radiator for the diesels, and of additional water for exhaust treatment for the gas turbine, if required, are not shown.

The heavy-duty gas turbine engines that may be available for mining applications will most likely be of the two-shaft configuration, primarily because of the torque characteristics. Characteristic torque-speed curves for one- and two-shaft gas turbine (GT) engines and the diesel engine are shown in figure 32. The one-shaft configuration does not provide favorable torque characteristics for heavy-duty applications and would require a complex transmission system. The two-shaft engine, on the other hand, provides an excellent torque characteristic - even better than those of the diesel engine. Maximum torque occurs at zero output shaft speed, presenting the potential of operating without a torque converter.

The fuel economy of the IGT operating derated to meet the duty-cycle power and durability requirements for the LHD application would be approximately comparable to that of diesel engines currently in use. The brake specific fuel consumptions of the 224-kW (300-hp) IGT and naturally aspirated diesel engines suitable for LHD application and ranging in rated power from 111.9 to 141.7 kW (150 to 190 hp) are compared in figure 33. Although the IGT would be operating well below its maximum power capacity, its fuel economy over the range for the LHD would be approximately comparable to that of the diesels shown.

On the whole, a heavy-duty gas turbine engine such as the DDA-404 would appear to be an excellent candidate for powering mine haulage vehicles.

Ability to Meet Government Regulations

The peak undiluted concentrations of toxic emissions (CO, HC, NO_x, and particulates) from the gas turbine engine will be substantially lower than those from the majority of currently certified diesel engines. The ventilation requirements will be set by CO_2 emissions and will be equivalent to the best diesel engine now available. (At least one diesel engine has been certified for mine usage that has a CO_2-limited ventilation rate.) However, the great majority of certified diesel engines have ventilation rates that are NO_x- or CO-limited and that range from about 1.2 to 5 times the CO_2-limited minimum ventilation (figs. 8 and 9).

The gas turbine engine is an inherently quieter engine than the diesel. Tests were made by Detroit Diesel Allison comparing sound levels for diesel- and gas-turbine-powered transit buses during acceleration and deceleration (14). These measurements were made at 15 m (50 ft) from the buses and showed the gas turbine engine to be as much as 8.8 dB quieter than the diesel during acceleration. There should be no concern with the gas turbine engine meeting current noise level restrictions. Moreover, it should be able to reach lower noise levels, if required in the future, more easily than the diesel.

There would appear to be no fundamental reason why gas turbine engines could not be adequately flameproofed and explosion proofed for operation in gassy mines. However, the large mass of airflow required for gas turbine operation (approx 4 times that for a diesel) may complicate the design of intake and exhaust flame arrestors and may introduce excessive pressure drops that would reduce engine efficiency and power. On the other hand, the gas turbine's lower exhaust temperature will simplify design. The larger internal volumes for the gas turbine as compared with the diesel may also complicate explosion proofing. Considerable structural stiffening may be required that will increase weight. A detailed design study would be required to define exactly what penalties in engine performance and engine weight, if any, would be incurred in providing the required flameproofing and explosion proofing.

The arrangement of components in a gas turbine engine can have a large effect on the temperature of its external surfaces. There are two basic types of component arrangements. In one, all the external surfaces (with the exception of the combustor dome and exhaust duct) are exposed to engine temperatures no greater than the compressor discharge temperature. As a result, these surfaces get no hotter than approximately 232° C (450° F) at maximum power and 93° C (200° F) at idle. This type of component arrangement is currently being used in the AGT-101 development program and is shown in figure 34. Only a small amount of external insulation would be required to reduce these surfaces to 150° C (302° F), the accepted operational temperature limit for mine applications. Additional insulation over the combustor dome and exhaust duct, with possibly an upgrading of their material to a higher temperature alloy, or the addition of water jackets would be required.

The other types of turbine engine configurations characteristically have large portions of the engine housing, as well as the combustor inlet and exhaust duct, exposed to high gas temperatures. The heavy-duty IGT engine is characteristic of this type of component arrangement and is shown in figure 35. Nearly all the external surfaces would require water jacketing or the addition of insulation to stay below the required surface temperature. Either approach would require modifications to the basic engine and thus some degree of development effort. If external insulation were added, the iron housing, combustor inlet, and exhaust duct would probably require upgrading to a higher temperature alloy. If water jacketing were used, the water would draw heat from the engine and thus increase engine specific fuel consumption and the CO_2 content in the exhaust. Adding external insulation would have the opposite effect.

Derating the IGT engine by 50 percent from 224 kW (300 hp) to 112 kW (150 hp), as noted previously for the LHD application, would increase rather than decrease the temperature of the gas in contact with the engine housing for this type of component arrangement. These temperatures, along with measured wall temperatures, are shown in figure 36. Surface temperature control should also be a subject of a detailed design study along with flameproofing and explosion proofing to define specifically what would be required and what the effect would be on engine performance, weight, and external dimensions.

Cooling the gas turbine exhaust to the required outlet temperature (71° C, 160° F) will require approximately twice the heat rejection to the exhaust cooling water as is required for the diesel. The increase is approximately equal to the heat rejected by the diesel to the cooling water and the radiator. The gas turbine does not use water convective cooling and a radiator; all the heat is rejected through the exhaust. However, some degree of convective cooling may be required to keep gas turbine surface temperatures below required maximum values. Again, the exhaust cooling requirements would have to be considered as part of a total system design study to define the modifications needed for mining applications.

Availability (Production Readiness)

The design specifications for the industrial gas turbine engine (DDA-404) appear to be sufficient to meet the needs of mine haulage vehicles. Although statistical data on actual operation with gas turbine engines in heavy-duty vehicular applications is not yet available, experience with gas turbines in other applications - including aircraft - shows reliable, long-term service with relatively low maintenance. We can assume that this experience would carry over to highway use and to underground mining, that availability of the gas turbine will be comparable to that of the diesel, and that service life - time between overhauls - may be substantially longer.

Market Availability

No gas turbine engines directly applicable to mine vehicle usage are now available on the commercial market. However, several engines in the 224- to 448-kW (300- to 600-hp) class are now in development, with commercial availability expected in the late 1980's. These engines are being developed primarily for highway use in buses and trucks. Industrial Turbines International (ITI) (a consortium made up of The Garrett Corp., Mack Truck, Inc., and Klockner-Humboldt-Deutz A.G.) has developed a 410-kW (550-hp) truck-bus gas turbine engine that is now being tested in heavy-duty highway trucks (15). Their objective is to have this engine in production during the

1980's. Detroit Diesel Allison Division of General Motors has a heavy-duty highway gas turbine, the DDA-404. It has been extensively road tested in buses and trucks. It is now being used as the base engine for the DOE-NASA Ceramic Applications in Turbine Engines (CATE) program, which is aimed at developing and utilizing ceramic components in an existing gas turbine so as to demonstrate operation at higher turbine inlet temperatures and consequently higher efficiencies. No decision has been made yet to begin production development.

It appears quite likely that one or more large 224- to 448-kW (300- to 600-hp) gas turbine engines will be on the market by 1990. The current DOE-NASA automotive gas turbine development program is aimed at providing the technical basis for a decision by an automobile engine manufacturer to begin prototype engine development. Should all proceed favorably, automotive gas turbines would be on the market in the early 1990's.

The heavy-duty highway engines discussed above should be the earliest valid source of gas turbines for mining applications. In general, they would have to be derated for most applications. However, as shown in table VII, they would still be competitive with the diesel engine in size, weight, and specific fuel consumption. It can be expected that somewhat smaller engines, 112 to 224 kW (150 to 300 hp), for heavy-duty use will be developed after successful introduction of the larger engines. However, commercial availability of these engines may not come until well into the 1990's.

Packaging Capability

As shown in table VII, the DDA-404 industrial gas turbine engine is smaller and lighter than two diesel engines currently in use for powering LHD's, even though it has twice the rated horsepower. However, requirements for flameproofing, explosion proofing, and controlling surface temperature will probably increase weight and package dimensions and may also reduce fuel economy. As discussed previously, the specific modifications required and their effect on engine size, weight, and performance would have to be the subject of a detailed design study. In any event it would appear that the gas turbine engine is quite competitive with the diesel in terms of packaging. In fact, the gas turbine has proven to be distinctly superior to diesel engines in size and weight for applications over about 150 kW (200 hp).

Recommendations

Of the heat engine alternatives to diesel for mining, the two-shaft industrial gas turbine is the closest to production. Therefore the Bureau of Mines should give strong consideration to a relatively near-term demonstration of a gas-turbine-powered mine production vehicle, possibly a load-haul-dump type. The necessary first step of such a demonstration would be a vehicle design study

(1) To select an appropriate prototype gas turbine and production mine vehicle
(2) To assess the modification required to both the vehicle and engine to meet Federal regulations

(3) To assess vehicle performance, production capability, fuel consumption, ventilation requirements, concentrations of toxicants, production availability, service life, cost of manufacture, and operating cost

Steam Engine

Basic Description

Steam engines are one of a class of heat engines that operate on the basis of the Rankine thermodynamic cycle. Such engines utilize a change in phase of the working fluid between liquid and vapor in the conversion of heat into mechanical work. For example, in a steam engine demineralized water is heated in an externally heated boiler to produce high-pressure steam. The hot steam then expands through a turbine or against a piston to produce useful shaft work. After expansion the lower pressure steam condenses in an externally cooled heat exchanger at nearly constant pressure back into water, which is then pumped through to the high-pressure boiler to complete the cycle.

In an internal combustion engine, such as a diesel, fuel burning takes place explosively, creating high pressures and noise, and is relatively difficult to control. Steam engines, in contrast, burn their fuel external to the cycle at nearly atmospheric pressure, similar to the Stirling engine, in a steady and more easily controlled way. Both emissions and engine noise can be greatly reduced. Burners can be designed for a variety of fuels by providing long flame paths and large volumes to oxidize the fuel completely. This results in very low hydrocarbon and carbon monoxide emissions. Nitrogen oxides are also relatively easily controlled with exhaust gas recirculation because of the low operating pressures. However, the steam engine operating on the simple Rankine cycle described above and at moderate temperatures (approx 540° C) has a relatively low efficiency of about 15 percent. The implication of this is large heat rejection requirements and high weight and bulk for a given power output. Moreover, ventilation rates can be high at full-power operation even though toxic emissions are low because of the requirement to reduce CO_2 content to 2500 ppm (half the threshold limit value). Steam engine ventilation rates would be more than twice as high as for an optimum diesel (CO_2 limited) - 6 m^3/kW-min (159 ft^3/hp-min) as compared with 2.6 m^3/kW-min (69 ft^3/hp-min) - because of the higher BSFC (517 g/kW-hr (0.85 lb/hp-hr)) for the steam engine as compared with 230 (0.38) for the diesel. However, steam engine ventilation rates would be comparable to those of many current certified diesels, which are generally NO_x limited.

Steam engines have a long history and are highly developed. Their principal applications today are in large electric power-generating plants. Before the advent of modern internal combustion engines, steam engines did find applications in the transportation industry: namely, in ships, railroad locomotives, and, to a small extent, automobiles. During the 1970's, Rankine-cycle engines, including the steam engine, were resurrected and considered as a low-exhaust-emission alternative for automobile powerplants. Through sponsorship of the U.S. DOE and its predecessor agencies, four independent contractors performed preprototype system developments (16). The State of California also sponsored the development of compact prototype steam vehicles as part of its Clean Car Project. Major private developments were those of Jay Carter Enterprises and Saab-Scania of Sweden. The Carter steam-powered Volkswagen was the first to meet the original 1976 Federal emission standards without add-on devices. This automotive research confirmed most of the expected advantages and disadvantages. In particular, high power with the closed cycle does result in a heavy, bulky package with large areas for condensers and system auxiliaries. Proven advantages are clean exhaust, high power output per unit of cylinder displacement, and high stall torque. Most of this automotive development work terminated in the mid 1970's in favor of other alternative powerplant developments that offered higher fuel economy potential, namely, the Stirling engine and the gas turbine.

In 1975, Scientific Energy Systems (SES), one of the automotive steam engine developers, was contracted by the U.S. Bureau of Mines to design and build a demonstration steam-powered shuttle car. Contract management was later transferred to DOE. Under the program, Jeffrey Mining Machinery Division of Dresser Industries developed the shuttle car, and SES developed the steam engine assembly. After completion of the steam engine tests, SES sold their engine research and development interests to Foster-Miller Associates. Foster-Miller completed the final report (17). A summary of this program is given below.

Summary of SES Program

The original goal of the program was to certify and demonstrate the feasibility of a steam-powered shuttle car in an underground coal mine. However, the program was reduced in scope and terminated after 6 hours of steam engine dynamometer testing and separate surface testing of the newly developed vehicle with a diesel engine substituted for the steam engine. Although development delays precluded certification and vehicle installation, the limited testing was felt to be sufficient as a proof-of-principle demonstration. The general conclusions of the program were that the steam engine is a technically feasible alternative powerplant for underground mine vehicles and that the steam engine is economically competitive but with an estimated higher initial cost.

The steam engine developed by SES for the mining study was an adaption of their earlier automotive steam engine, which used a four-cylinder piston expander with a total displacement of 2213 cm^3 (135 in^3) and produced up to 95 kW (127 hp) at a speed of 2250 rpm. For the mine car application, speed was limited to 1600 rpm with a design maximum output of 56 kW (75 hp). Figure 37 shows a schematic of the engine. Figure 38 shows the general layout of the steam-powered Jeffrey RAMCAR[3], and figure 39 a sketch of the engine mounted in the Jeffrey-designed tractor. The complete steam powerplant was mounted on a removable pallet for ease of engine replacement. The condenser and the air and oil cooler heat exchangers are located across the front of the vehicle (fig. 39) with engine-driven fans blowing forward through each heat exchanger. The three major assemblies

[3]Registered trademark, Jeffrey Mining Machine Division, Dresser Industries, Inc.

behind the heat exchangers are the four-cylinder piston expander on the left, the cylindrical burner-boiler in the center, and the cylindrical burner - air filter on the right.

The steam engine adaptation for mining retained the automotive boiler-outlet temperatures of 540° C (1000° F) and pressure of 6.9 MPa (1000 psia). This resulted in only a modest peak efficiency; however, this efficiency or specific fuel consumption is retained over a wide power range. In contrast, the diesel specific fuel consumption rises at part power. Therefore steam engine overall fuel usage would not be much greater than diesel fuel usage for a typical shuttle car duty cycle.

A diesel engine requires an exhaust scrubber to attain acceptable exhaust temperatures; a steam engine does not. However, a steam engine still has more components than a diesel engine; and, because each cycle function is carried out in a separate component that must be controlled to match the demands of the next component, the steam engine requires a more elaborate control system than does the diesel engine. Steam engine controls must regulate expander power and water, fuel, combustion air, and cooling air flow rates. Modifications made on the automotive steam engine for mining applications are as follows:

(1) Burner and boiler assembly - The burner was redesigned to operate on diesel fuel rather than gasoline. A small preheat burner was added for clean startups. Porous metal flame arrestors were added to both the burner inlet and exhaust, and an inlet-air filter and blower were also added to prevent fouling. Half of the air blower flow was ducted around the burner for cooling (fig. 37). The assembly has an explosion-proof housing with a water-cooled connection between the boiler and the expander.

(2) Piston expander - For low-profile packaging, the four-cylinder expander was inclined at 15° to the horizontal. The explosion-proof cooling jacket was extended over the expander block and its hot valve and cam area. An accumulator (not shown in the schematic of fig. 37) stores cooling water under pressure during engine operation and continues the cooling flow for several minutes after shutdown.

(3) Condenser - A new, more durable design was employed that uses conventional truck radiator cores. The three side-by-side cooling fans were made of epoxy and fiberglass to prevent sparks in case of an accident. An oil-water separator (not shown in fig. 37) was also added to the expander exhaust to minimize fouling from piston-ring oil carryover.

(4) Water pump - The automotive pump flow control was changed from the electric solenoid valve to a hydraulic-power bypass valve for an intrinsically safer design.

(5) Engine controls - A major redesign was needed to provide additional safety. High-voltage power was limited to the starter motor, the ignition, and the main-flow shutoff valves for the fuel, water, and hydraulic fluid. A computer was designed to provide all control logic and placed in an explosion-proof box. The one complete steam engine that was assembled did meet the performance and emissions objectives of the program during its limited dynamometer testing. The results are summarized in table VIII (17). Mechanical development problems during the tests were relatively few. The major hindrance to testing was related to the control system. Subsequent analysis suggests that the control logic was correct but that the

transducers in the system for temperature, pressure, and actuator control need improvement in their reliability, installation, and reponse rates.

Production rate and cost comparisons between the steam-powered car and a conventional tethered car were made by Jeffrey and independently by Penn State. Jeffrey results are given in tables IX and X (17). This study did not take credit for the higher unloading speeds that are possible with the steam-powered vehicle nor for the other improvements available with a free-ranging vehicle. In spite of the steam car's higher first costs, the 38 percent improvement in productivity results in a payback period of 11 months for the additional investment. Penn State's results confirmed an economic advantage for the steam car even with its tram speed reduced to that of the conventional car.

Evaluation Against Requirements

As a result of the work at SES, the steam engine has been shown, in principle, to be a viable alternative heat engine for mine shuttle cars. Furthermore a steam-powered mine vehicle should be capable of meeting current Government safety requirements with good design practice and adequate ventilation. However, steam engine ventilation rates will be at least as high as those for most current diesels and far higher than those for an optimum diesel engine that is CO_2 limited. A steam engine has the packaging flexibility to fit low-seam shuttle car applications. Low emissions, odors, noise, and exhaust temperatures, without scrubbers or cooling devices, have been demonstrated. It also has high torque at low speed. Its load capacities and estimated overall operating costs are comparable to those of a diesel-powered vehicle. Initial steam engine costs are estimated to be high, and its fuel consumption somewhat higher, than those for a diesel engine. One drawback, as compared with a diesel engine, is that the steam engine requires a more complicated control system. And proof of satisfactory controls for a steam-powered mine car remains to be demonstrated.

The major flaw in producing steam engines that would be suitable for mining applications is the lack of a large-volume application in another sector of the transportation industry. There are no large-volume production lines for steam engines. And it would seem unlikely that the mining industry by itself could support the overall costs of a limited production facility.

Recommendations

It is recommended that the Bureau of Mines and other Government agencies continue to hold in abeyance any more work or decisions on steam-powered mine vehicles. If other alternative engines fail to be feasible or practical, serious reconsideration might be given to resuming development on the basis of the earlier steam-powered shuttle car demonstrations.

EVALUATION OF ENERGY STORAGE SYSTEMS

Mine vehicles that use electric energy can be based on two sources: stationary and mobile. A tethered electric vehicle has a stationary source of electricity to which it is tied by means of an "extension cord." Within the limitations of the connecting cord, the performance of this type of vehicle is independent of the physical characteristics of the electric power source. The size, weight, and efficiency of the generating plant do not affect the vehicle. On the other hand, an untethered vehicle must carry its energy source "on board" as mobile stored energy. The weight and size of the storage system as well as its energy capacity and its power capacity now become factors affecting the vehicle performance. The energy density of the energy storage system is the key factor in the consideration of possible alternative power sources for mine vehicles. In general, for haulage vehicles, battery power density potential is essentially equivalent to that of diesel systems and is not an overriding consideration.

Lead-acid battery-powered haulage vehicles have been used in mines for some time. However, they are severely limited in load-carrying capacity, power, and range because the batteries are capable of storing only about 25 W-hr/kg (11.3 W-hr/lb). In contrast, diesel-powered vehicles get their energy from a liquid fuel with an energy density of about 12 000 W-hr/kg (5440 W-hr/lb). The time required for energy source replenishment is also an important factor. With lead-acid batteries, recharging time can be 8 hours or more and this would necessitate duplicate energy supplies. Although energy storage systems are desirable from the standpoint of low pollution, they require greatly improved energy density, recharging time, and life to achieve broad applicability in mining use.

The following sections discuss alternative energy storage systems that can be considered as reasonable candidates for underground mining. These include advanced battery systems, flywheel energy storage systems, and hydride fuel storage.

Battery Systems

Basic Description

Lead-acid electrical storage batteries are currently the alternative to diesel engines for unconstrained mine vehicles. In contrast to diesel engines, they have the advantages of producing power quietly and simply with small amounts of relatively unskilled maintenance. They also do not add significantly to mine ventilation requirements. However, energy density is low for battery systems. As a result, to support a full shift of haulage operation before battery recharging is needed, very high battery weight must be carried (see Requirements, Ability to Achieve Duty Cycle).

The useful life of lead-acid batteries is a function of the amount and rate of discharging, primarily because of the progressive blocking of electrodes with nonconductive lead sulphate as the battery is discharged. Characteristically, discharging in excess of 80 percent of capacity shortens battery life significantly. In applications, energy density and useful life are traded off to fit the intended use. Lead-acid battery systems for electrically powered experimental cars (18) provide an energy density of 42 W-hr/kg (19 W-hr/lb) with a life of about 400 charge-recharge cycles. Lead-acid batteries for a typical mine haulage vehicle application, the S&S Corp. Model 320A Du-A-Trac, have a lower energy density of 24 W-hr/kg (10.9 W-hr/lb) but also a longer useful life of about 1000 cycles. Thus the surface application tends to minimize battery weight to favor vehicle range at the expense of battery life, while the mining application accepts higher weights to achieve longer life. Power density for lead-acid batteries is a function of the amount of active material that can be effectively used in the battery package. Current lead-acid batteries for both of these applications have peak or initial power densities of about 100 W/kg (1.061 hp/lb).

Mine use of these batteries is also complicated by about an 8-hour recharge time and the evolution of hydrogen gas during recharge, which requires a safe recharge facility with adequate ventilation. Because of the long recharge time, a two-shift mine usually requires at least two sets of batteries for each vehicle. One additional safety concern with batteries is that they cannot be switched off in case of a major accident. When crushed, they can release sparks and considerable heat. Complete flameproofing of battery systems has been difficult.

In spite of their drawbacks, battery systems are expected to play an increasing role in transportation propulsion applications. Considerable research and development has been and is being aimed at improving lead-acid batteries and providing practical alternative electrochemical battery combinations with better operating characteristics. Bristow (19) lists some of these development activities both here and abroad. Potential battery improvements, with emphasis on mine shuttle car applications, are summarized here.

Projected Battery Improvements

Progress in improved battery programs has been slower than anticipated. However, commercialization of three improved battery types is expected by the mid-1980's. These types include improved lead-acid, nickel-zinc, and nickel-iron batteries. Higher energy and power densities and shortened recharge times are expected for each of these improved batteries. Both the nickel-iron and nickel-zinc batteries should have less sensitivity to discharging and therefore longer useful lives.

Other battery combinations, such as sodium-sulphur, lithium - metal sulphides, and zinc-chlorine, have been operated under laboratory conditions. Although these advanced combinations offer potentially attractive energy and power densities, they also require extensive developments and/or major breakthroughs before any possible commercialization date can be forecast. The advanced combinations also do not appear attractive for mining use because they all use dangerous or highly corrosive chemicals. Furthermore the sodium-sulphur and lithium - metal sulphide batteries require operating temperatures of 270° C (518° F) or higher, which add to the safety and handling problems.

Another class of advanced batteries, now in the early stages of development and offering potentially attractive energy and power densities, is metal-air batteries, namely zinc-air, iron-air, and aluminum-air. The metal-air batteries use basic electrolytes that are somewhat less hazardous than acid. They also can be shut down quickly by stopping the airflow.

Characteristics are presented in table XI for the three most promising near-term battery types. Energy and power densities are given for both current and improved versions of each type. Current battery costs are also presented relative to those for lead-acid batteries. In addition, some projected performance data based on (20) for aluminum-air batteries are given for comparison. The last column in the table summarizes important features of these battery types. The projected improvements in energy and power density for lead-acid batteries represent about a 50-percent increase over current traction batteries. These improvements are expected through greater utilization of active material in the batteries. With better charging equipment and some form of cooling during recharge, it should be possible to reduce charging time by a factor of 2, or to about 4 hours. No major improvements in useful life are projected for the improved lead-acid batteries since they are expected to remain sensitive to the amount and rate of discharge.

Nickel-iron batteries have been in use for many years in applications where long life and ruggedness have been critical. Their development stopped when lead-acid batteries became available. Interest has been renewed, and two nickel-iron battery systems are being developed in this country. Westinghouse is experimenting with a battery system that incorporates pumping of the potassium hydroxide electrolytes. Because of the weight of the circulation system, an energy density of about 40 W-hr/kg (18 W-hr/lb) is projected. The other development is being conducted by Eagle-Picher on a conventional nickel-iron battery with a projected energy density of about 55 W-hr/kg. Both of these developments are expecting useful lives of at least 5 years with no sensitivity to deep discharging. It is also hoped to demonstrate about a 3-hour recharge time for this battery type. Presently these characteristics have yet to be fully verified. Nickel-iron batteries cost about twice as much as current lead-acid batteries and characteristically give off large quantities of hydrogen during recharge, thus using more water and needing greater maintenance attention.

Although there are no commercially available nickel-zinc batteries at this time, they appear attractive. A practical energy density of about 80 W-hr/kg (36 W-hr/lb) is thought to be possible, with a correspondingly high power density of about 200 W/kg (0.12 hp/lb). The main gas given off during recharge is oxygen and it should be possible to seal these batteries completely. Inherently, nickel-zinc batteries should not be sensitive to discharge and thus also offer potentially long useful life. It is also hoped that very rapid recharging will be possible. One of the main development problems has been deterioration of the zinc electrodes during recharging, causing internal short circuits and reduced battery life. Some success in solving this problem has been achieved under laboratory conditions. Nickel-zinc battery costs are about 2.5 times that of current lead-acid batteries, and their costs are expected to remain high.

Although they are in the very early stages of development, metal-air batteries offer much higher energy densities and higher power densities. Lithium, aluminum, magnesium, and calcium are the main candidates. Their potential chemical energy densities, based on the weight of reactants only, are competitive with those of liquid petroleum fuels. They range from about 2.5 to 3.8 kW-hr/kg (1.1 to 1.7 W-hr/lb) (21). Diesel fuel, when used in an engine with about 30-percent average efficiency, has an effective energy density of about 3.6 kW-hr/kg (1.6 kW-hr/lb).

Metal-air batteries are actually primary batteries (essentially fuel cells) in that they generally cannot be recharged electrically. They are recharged mechanically by replacing the reactants that are consumed in producing electricity. As a rule, water is added and the product of reaction is removed from the electrolyte several times before the metal is totally consumed and must be replaced. Thus the effective energy content of the battery per water charge is limited not by the mass of metal but by the amount of water in the battery. However, the water recharge can be accomplished very easily. Because the battery consumes air, about 0.2 m^3/kW-min (5.4 ft^3/hp-min), ventilation air is required to maintain mine air quality at 20 percent oxygen (see appendix A). Typical diesel ventilation rates are 20 to 50 times greater. As determined from small-scale single-cell test data, a hypothetical aluminum-air battery system designed for automotive use would have an energy density of about 300 W-hr/kg (136 W-hr/lb) (20), based on the water recharge cycle. This design would give three recharge cycles before aluminum depletion. The energy density and number of water recharges possible can be varied over a wide range. A haulage vehicle battery would be designed to minimize operating cost for a given operational cycle. Figure 40 shows a schematic of the aluminum-air cell and construction detail of an experimental cell. Figure 41 is a schematic diagram of a complete aluminum-air battery system.

The major problem areas to overcome are to develop

(1) A low-cost, long-lasting air cathode
(2) A method to refuel the aluminum rapidly
(3) An optimal, cost-effective aluminum alloy with low parasitic corrosion loss
(4) A method to minimize corrosion loss of the aluminum during standby
(5) The hardware to continuously and selectively remove, drain, and store the product of reaction (hydrargillite crystals)

Assuming continued effort and successful development, these batteries could be ready for commercial use in the early 1990's.

Evaluation Against Requirements

The projected battery system improvement shown in table XI should permit greater flexibility and utility in the design of future mine vehicles. In an earlier section of this assessment under Requirements, Ability to Achieve Duty Cycle, it was indicated that the current battery-powered S&S Corp. Model 320 Du-A-Trac is capable of operating over a full shift (6 hr) before recharging. Table XII shows the effects on work capacity of replacing the current lead-acid batteries used in this vehicle with the projected improved battery systems. Although the improved lead-acid batteries should be capable of nearly two shifts of operation before recharging, they are still expected to be sensitive to the rate and depth of discharging. And the available face times for lead-acid batteries reflect brand new operation. It would appear more likely that the improved lead-acid battery capacity would be used to prolong useful life and to reduce replacement or annual operating costs. Both of the improved nickel-iron and nickel-zinc battery systems, on the other hand, should be less sensitive to discharging and capable of at least two-shift operations without recharging. From an operational point of view, this would eliminate the need to change battery sets between each shift and would cut down on mine inventory of battery sets. Overall economics, however, will depend on the magnitude of the higher costs that are expected for the improved systems. Although they are not developed, aluminum-air batteries have potential for substantial improvement in the more distant future, as shown in table XII. Aluminum-air batteries occupying the same volume as the 4220 kg (9300 lb) of lead-acid batteries in the Model 320 Du-A-Trac would provide energy for about 14.5 shifts of operation before adding water and 44 shifts before replacing the aluminum anodes. Furthermore the aluminum-air batteries would weigh between 910 and 1360 kg (2000 and 3000 lb); thus also providing an opportunity to increase the load capacity of the vehicle without increasing the gross vehicle weight.

Alternatively, the improved batteries could also be used in single-shift operations to drive higher powered motors in the same tractor and thus provide greater haulage capacity or allow operation at steeper grades or under poor floor conditions.

The improved lead-acid batteries would be capable of powering about a 45-kW (60-hp) drive motor; the nickel-iron batteries, a 67-kW (90-hp) motor; and the nickel-zinc, a 75-kW (100-hp) motor or better. A detailed economic-mission analysis would be needed to examine all of the potential trade-offs. However, a battery-powered tractor with a 67-kW (90-hp) drive motor would represent a sizable step toward the capacity of a diesel-powered vehicle - the Jeffrey 410H diesel, for example, with 109 kW (146 hp) and 10 100 kg (22 250 lb) of rated capacity - and its attractive productivity. However, in spite of these projected improvements, these battery systems will probably still be limited to relatively light-duty applications - particularly in low-seam mines. They will most likely not be able to compare with diesel-engine-powered machines in rugged, heavy-duty, all-terrain operations.

In contrast, aluminum-air batteries - if they fulfill their promise - will have sufficient energy density to allow more than two-shift operation of a 410H type of mine vehicle per water change with power comparable to that of a diesel. Depending on battery design, operation for several days or maybe weeks would be possible before the aluminum anodes would require replacement.

The main concern with battery operation in mines is safety and, in particular, preventing sparking or heat release if the batteries are crushed in an accident. Flameproofing will continue to be a design challenge in the improved systems. The aluminum-air battery may be more easily flameproofed since it requires airflow and electrolyte circulation. The battery is easily deenergized by stopping the airflow or by draining the electrolyte. Care must also be exercised in handling procedures for these batteries since all four types use a corrosive and toxic electrolyte: sulfuric acid in the lead-acid batteries, potassium hydroxide in both the nickel-iron and nickel-zinc batteries, and sodium hydroxide in the aluminum-air batteries.

Outlook and Recommendation

The attractiveness of battery-powered vehicles for mines should be somewhat improved by the mid-1980's. Usable energy densities of secondary batteries (electrically rechargeable) are expected to triple, and peak power densities to double, over those of current lead-acid traction batteries. Recharge times are expected to decrease to about 3 or 4 hours and useful lives of about 5 years are forecast. These improvements will permit greater design flexibility for future battery-powered mine vehicles. Flameproofing, however, will continue to be a design problem and a safety concern.

If successful, the development of the mechanically rechargeable aluminum-air battery could make battery-powered mine vehicles production competitive with diesel-powered vehicles in terms of production capacity and recharging ease. Flameproofing of aluminum-air batteries should be less complicated than for lead-acid batteries, since the battery tends to shut down when damaged.

It is recommended that the Bureau of Mines continue to support the development of new battery systems and in particular those associated with lead-acid, nickel-iron, and nickel-zinc batteries. In addition, the development effort with aluminum-air batteries should be followed to ascertain whether the promise implicit in the concept can be achieved in practice.

Flywheel Energy Storage

Basic Description

Flywheels are capable of absorbing and releasing energy at very high rates by using the kinetic energy of a rotating mass. The amount of stored energy is limited by the strength and shape of the flywheel material. Most successful flywheel tests so far have used shaped steel disks, with resulting energy storage densities of the order of 10 to 20 W-hr/kg (4.5 to 9 W-hr/lb) (19) based on flywheel mass alone. A practical flywheel energy storage system, however, requires a vacuum enclosure to reduce windage losses and thereby prevent rapid loss in speed, a suitable mounting arrangement with bearing supports to absorb both flywheel- and application-induced loads, adequate containment material for safety in case of wheel rupture and disintegration, and a means for transmitting flywheel energy to the application. These system needs can result in a useful energy density nearly a factor of 10 lower than those achieved with the flywheel alone. System power density is only limited by the type of transmission that is used and its design capacity for power transfer.

Some tests have used flywheels made with composite fiber materials. Composite materials potentially offer strength-density ratios, and hence energy densities, about 10 times that of steel. However, high strengths for the fiber composite only occur in one direction. Careful fiber alignment, compromising directional strength to accommodate both the radial and tangential stresses that are expected in the wheel, reduces the advantage over steel to about 4:1. One further system advantage for composites is that they disintegrate slowly into cotton-like fluff when overstressed rather than burst into large pieces as steel does as it fails. This feature allows a composite flywheel system to be designed with 15 to 30 percent of the weight of steel flywheel containment. Currently, however, the state of the art of composite flywheels has not advanced much beyond small-size laboratory demonstrations.

Flywheel systems are currently being examined and tested for their practicality in a variety of transportation applications. Bristow (19) summarizes these activities here and abroad. But of particular interest to the mining industry is the flywheel-powered shuttle car evaluation (22) that was conducted by General Electric and the follow-on demonstration program under DOE contract to FMC.

Summary of GE Analysis

The program at General Electric evaluated the practicality of a flywheel system as a power source for shuttle cars in an underground coal mine. Energy storage needs were analytically determined for broad ranges of bottom conditions and seam heights by using the Underground Mine Haulage Simulator developed by Pennsylvania State University and the Bureau of Mines. The longest tramming route in a typical six-cut entry plan was used in the calculation. Seam heights of 1.2 to 2.4 m (4 to 8 ft) were considered, with loaded vehicle weights to about 18 metric tons (20 short tons) (payloads to 7 metric tons (7.75 short tons)). Results were also compared against measured data for mine shuttle cars. The conclusion was that 90 percent of all conditions could be satisfied with 4.5 kW-hr (6 hp-hr) of usable energy for each tramming round trip. The study also showed that 3.0 kW-hr (4 hp-hr) would satisfy about 80 percent of the conditions for the longest tramming path and that 7.5 kW-hr (10 hp-hr) would be needed for the worst case.

The analysis was centered on the 4.5-kW-hr (6-hp-hr) usable energy requirement, and a variety of flywheel energy storage systems and required charging systems were analyzed. The general conclusions of the study were that the mine shuttle car requirements could be fulfilled with a flywheel energy storage system designed within the present state of the art and that there are sufficient economic and safety benefits to warrant a mine demonstration. The selected conceptual power source (fig. 42) consisted of a motor-alternator mated to a conical steel flywheel on a common shaft mounted vertically with ball bearing supports in a vacuum capsule. The motor-alternator was sized to accept 4.5 kW-hr (6 hp-hr) of energy in 80 sec (203-kW input power) and is a solid-rotor synchronous machine with both ac and dc windings on the stator. The motor-alternator converts wayside electric power at the unloading point into flywheel energy and also converts flywheel energy to electric power to the shuttle car during each tramming run for both propulsion and auxiliary system needs. The flywheel produces 4.5 kW-hr (6 hp-hr) of useful electric power while its speed drops from 10 000 to 5000 rpm. About 180 kg (400 lb) of containment material was placed around the periphery of the 109-cm (43-in.) diameter, 454-kg (1000-lb) flywheel. The flywheel capsule is operated in a partial vacuum at a pressure of 69 to 345 Pa (0.01 to 0.05 psia) to minimize windage losses. Cooling circuits are wrapped around the vacuum capsule to remove heat losses from the motor-alternator-flywheel assembly and thereby provide acceptable operating temperatures. The flywheel capsule is freely mounted in a second and final enclosure (fig. 43) on spherical bearings that allow $\pm 20°$ movement of the capsule from the normally horizontal plane of the flywheel and minimize gyroscopic forces on the flywheel bearings. The final enclosure then is shock mounted into a shuttle car.

Adequate space for the selected 4.5-kW-hr (6-hp-hr) flywheel power system was found in the engine or battery compartment of several current tractor-trailer cars. Because of diameter restrictions, the selected power system could not be fitted into the cable-reel space of a conventional tethered shuttle car. It was noted, however, that it may be possible to fit a 3.0-kW-hr (4-hp-hr) flywheel power system into the conventional car. Preliminary sizing also showed that at the same diameter as the 4.5-kW-hr (6-hp-hr) flywheel, a double steel disk design could provide 6.0 kW-hr

(8 hp-hr) of useful energy with only about a 9.5-cm (3.72-in.) increase in capsule height (figs. 44 and 45).

For demonstration purposes, it was recommended that the 4.5-kW-hr power system be used in the experimental four-wheel-drive Jeffrey demonstration Ramcar discussed earlier in the steam engine section. The Jeffrey Mining Machinery Division of Dresser Industries, under subcontract, investigated and made preliminary layouts for the flywheel installation. The enclosed flywheel package was placed on the front left side of the existing chassis (figs. 46 and 47). About a 30.5-cm (12-in.) high dome, rising above the normal hood line, was required to accommodate the package. Flywheel system electronic controls were fitted conveniently behind the power package. Flywheel package cooling needs were satisfactorily integrated with the torque-converter - transmission oil loop and the cooling fan for the car's 56-kW (75-hp), 500-V electric drive motor.

An electrical charging station at the unloading point was recommended as part of the study. The station required a 250-kVA feedline from a 750-kVA mine power center, about a 0.85-m^3 (30-ft^3) enclosure for a load-commutating inverter, and an assembly consisting of a car alignment guideway, a vehicle connector, and an automatic engagement actuator for the vehicle connector. The study showed that the mine power center could accommodate the vehicle load at 500 V without a serious voltage drop and thus would not adversely affect the other mine equipment. Charging spinup time with average bottom conditions was about 30 sec and, in the worst case, no more than 90 sec. Such times are compatible with normal unloading times for mine cars. Static O-ring seals were used for the flywheel capsule enclosure, and no more than four capsule penetrations were needed: namely, two electrical connector ports, a bearing lubrication port, and a vacuum pumping port. It was believed that the required flywheel capsule vacuum could be maintained for at least one mine shift. However, some type of vacuum pumping system will be needed as ancillary equipment to occasionally reevacuate the flywheel capsule.

The economic part of the General Electric analysis compared the conceptual flywheel-powered vehicle with a conventional tethered shuttle car, a diesel car, a battery car, and the experimental steam-powered shuttle car. Typical overall results are summarized in table XIII. The diesel-powered car in the comparison had about twice the payload capacity of the other cars. This fact caused the diesel car to have the highest annual operating cost and yet the lowest cost per ton. The spreads in costs for the other car types were believed to be within the accuracy of the calculations. Therefore it was concluded that the flywheel power system should be cost competitive with existing and other alternative systems.

Evaluation Against Requirements

Flywheel power systems have the potential for quiet, nonpolluting, and relatively safe operation when provided with adequate safeguards. The General Electric study has shown that a flywheel power system can meet mining duty cycle requirements and is economically viable. And, as with any of the alternative power systems for free-ranging vehicles, mine safety and productivity are enhanced through the elimination of trailing cables and two-car limitations.

The main potential hazards projected for flywheel systems are a sudden release of stored kinetic energy and high-voltage shocks from the required electrical subsystems. Mine safety standards, including inspection and maintenance, should minimize electrical shocks. And good design practice should ensure flywheel containment in case of disintegration. However, there still could be a fire, and perhaps an explosion, if a flywheel-powered vehicle were crushed in an accident. Sparks from the sudden stop of the flywheel in an accident could ignite the bearing lubricating oil and the hydraulic fluid used in the transmission and cooling circuits.

For normal mine duty, flywheel power systems appear to offer very few complications. They are compatible with existing mine power centers for their charging needs and can be designed to fit within existing mine vehicles. The conceptual design and vehicle installation in the General Electric study did partially block the driver's forward view. Further design work might eliminate this potential problem. Vacuum pumping needs for the flywheel system should be more easily handled than diesel fueling or battery charging and recharging. Stalled flywheel vehicles, as recommended in the study, could be towed with a spare car.

Obviously, the true feasibility of the concept will depend on the demonstration program. But, if flywheel power systems are found to be practical, their production costs should be low enough to be supported by mining applications alone.

Recommendations

It is recommended that the Bureau of Mines continue to monitor the demonstration program for a flywheel power system in a mining car application and also keep abreast of composite fiber developments for advanced flywheel systems.

Use of Hydrogen Fuel from Metal Hydrides

Hydrogen as a fuel for mine engines has two significant advantages over conventional petroleum fuels. The first is the complete absence of CO_2, CO, HC, aldehydes, and particulates in the products of combustion; the second is that hydrogen can be produced from a variety of source materials including coal and water. However, hydrogen either as a gas or as a liquid presents significant storage problems because of its low density and its very low liquid temperature. Metal hydrides present a unique opportunity for storing hydrogen at reasonable pressures and temperatures. Hydrogen fuel can be stored in a metal hydride at normal room temperature and at low pressure with a density about the same as that of liquid hydrogen. Although further development is needed, hydride storage is potentially a safe and practical approach to supplying hydrogen fuel to a mine engine.

Since 1977 Eimco Mining Machinery and Ergenics Division of MPD Technology Corp., a wholly owned subsidiary of International Nickel, Inc., have worked jointly to develop a hydride-storage, hydrogen-fueled engine system for mining vehicles. The Denver Research Institute has been hired to test the engine and the on-board hydride fuel system. In August 1980, the Bureau of Mines (Minneapolis) entered into a 6-month cost-sharing contract with Eimco to design a mine vehicle powered by a hydrogen-fueled engine. The design is to emphasize safety and includes all aspects of vehicle operation and fuel handling in nongassy underground mines.

The DOE views hydrogen as a long-term potential alternative fuel for automotive use and is sponsoring research on hydrogen-fueled engines as well as on various means for storing hydrogen, including hydrides. The following discussions are intended to describe briefly the effect of hydrogen on ventilation requirements, the characteristics of various heat engines operating on hydrogen fuel, the characteristics of various hydrides that might be used for hydrogen storage, and a typical hydride fuel system.

Hydrogen Fuel Ventilation Requirements

Although the use of hydrogen fuel eliminates CO and CO_2 emissions, it does not eliminate the need for ventilation. The oxygen used to burn the hydrogen comes from the mine air and must be replaced in order to maintain at least 20 percent oxygen concentration in the mine air. This defines the minimum ventilation rate. Of course, this assumes control of thermal NO_x to a low level. As was the case for CO_2-limited, hydrocarbon-burning engines, there is a direct relation between the minimum ventilation requirement and the rate at which fuel is consumed. For every kilogram of hydrogen burned, 465 m^3 of air is required (7450 ft^3 air/lb H_2). Figure 48 is a comparison of the specific ventilation rate required for H_2 fuel with that for no. 2 diesel fuel as a function of brake specific fuel consumption. Calculations used to arrive at these curves are shown in the appendix. On the basis of a lower heating value for hydrogen of 33 300 W-hr/kg (51 530 Btu/lb) and for no. 2 diesel fuel of 11 900 W-hr/kg (18 584 Btu/lb), an engine using hydrogen fuel would consume only about 36 percent of the weight of fuel as an engine having the same thermal efficiency operating with no. 2 diesel. The minimum ventilation required for the hydrogen-fueled engine is about one-fourth that of the diesel-fueled engine. For example, an engine with 30-percent thermal efficiency requires 280 g/kW-hr (0.4605 lb/hp-hr) of no. 2 diesel fuel. If the engine is CO_2 limited, it requires at least 3.198 m^3/kW-min (84.22 ft^3/hp-min) of ventilation air to dilute the exhaust to 0.25 percent CO_2. An engine operating on hydrogen requires 100 g/kW-hr (0.1645 lb/hp-hr) of hydrogen and only 0.776 m^3/kW-min (20.43 ft^3/hp-min) of ventilation air to maintain at least 20 percent O_2 concentration in the mine air.

Hydrogen-Fueled Heat Engines

Hydrogen is a potential fuel for intermittent combustion engines (spark ignition or diesel) or for continuous combustion engines (gas turbine, Stirling, or steam). However, the high autoignition temperature of hydrogen discourages compression ignition in a diesel engine because the compression ratio required would be too high to be practical. Continuous combustion engines could be operated on hydrogen with only relatively minor changes to the combustion systems. Aircraft gas turbine engines have been operated on hydrogen by NASA with good results for power and efficiency. However, NO_x emissions were not controlled or measured. Little or no work has been done with either Stirling or steam engines with hydrogen as a fuel. A number of experimenters have tested spark ignition engines with hydrogen. Some of the pertinent results and their implications to mine vehicle propulsion are discussed here.

The principal reason for using hydrogen is to reduce or eliminate potentially harmful emissions and greatly reduce the need for mine ventilation. The use of hydrogen, of course, eliminates CO, HC, CO_2, aldehydes, particulates, sulfur compounds, and other emissions related to hydrocarbon fuel composition. However, thermally generated NO_x is still a potential problem. At equivalence ratios near stoichiometric, NO_x levels with hydrogen can be equal to or greater than those generated with hydrocarbon fuels. Figure 49 shows specific NO emissions as a function of equivalence ratio. (The equivalence ratio is defined as the ratio of the actual fuel-air ratio to the stoichiometric or chemically correct fuel-air ratio.) These data were generated on a CFR engine with hydrogen injection (23). For near-stoichiometric air-fuel mixtures, NO_x emissions reach 10.7 to 12.1 g/indicated kW-hr (8 to 9 g/indicated hp-hr). This is over 3000 ppm of NO in the exhaust and would require over 7.6 m^3/kW-min (200 ft^3/hp-min) of ventilation air to bring the diluted exhaust NO content to 12.5 ppm. Figure 49 also shows NO emissions near zero at low equivalence ratios (below 0.4). Tests made at the Denver Research Institute with a Caterpillar 3304N diesel engine modified for hydrogen operation (fig. 50) covered in detail this low-equivalence-ratio range. Figure 51 (24) shows the effect of very low equivalence ratio on NO_x generation. At equivalence ratios below about 0.41, the NO_x content of the exhaust for both naturally aspirated and turbocharged engines was well below the mine-air-quality NO_x limit (25 ppm). At higher equivalence ratios, exhaust NO_x content rose sharply.

It is possible to reduce NO_x emissions substantially at high equivalence ratios (near stoichiometric) through the use of water injection or exhaust gas recirculation. Tests at Billings Energy Research Corp. (25) indicate that NO_x emissions can be reduced significantly with water injection. Figure 52 shows the effect of water injection on a hydrogen bus engine.

Hydrogen engine tests by Hawthorne Research and Testing, Inc. (26) evaluated both water injection and EGR effects on NO_x. The effects of water injection and EGR on NO_x concentration as a function of brake mean effective pressure are shown in figures 53 and 54, respectively. Both reduce NO_x, but water injection is more effective. Both methods result in peak NO_x concentrations that would require ventilation at least equal to what is required for an optimum (CO_2 limited) diesel. The use of EGR causes a reduction in volumetric efficiency and a corresponding loss in power. Water injection does not have a significant effect on engine power.

Hydrogen has the unique and desirable property of being able to burn efficiently over a broad range of equivalence ratios. This makes possible operation at low equivalence ratios, which results in very low NO_x formation. Unless low NO_x emissions are achieved and ventilation rates reduced to the theoretical minimum for a heat engine (oxygen replacement), the benefits of using hydrogen as a fuel will be diminished.

Operation at low equivalence ratios results in reduced engine power output. At 0.45 equivalence ratio, BMEP for a normally aspirated engine is only 345 to 414 kPa (50 to 60 psi), which is 241 to 276 kPa (35 to 40 psi) less than for the same engine operated with diesel fuel. The richer fuel mixtures that would allow increased power result not only in undesirably high NO_x emissions, but also in backfiring and rough combustion. Therefore the hydrogen engine developer must address the problem of achieving a satisfactory power level through other methods. Some of the methods suggested are

(1) Increased engine displacement
(2) Supercharging
(3) Increased compression ratio
(4) Increased engine speed
(5) Direct cylinder injection

The problem of backfiring experienced with hydrogen due to its unique properties must also be solved. The work being done at Denver Research Institute suggests that backfiring can be suppressed in a laboratory engine by careful control and maintenance. However, they feel that a truly marketable engine - one that is practical in the mine environment - will require the development of a fuel injection system.

Further research on hydrogen-fueled engines at Denver Research Institute (24) shows that turbocharging is an effective method of increasing power output while maintaining low NO_x emissions and avoiding backfiring (fig. 55). Turbocharging combined with aftercooling to maintain low intake manifold temperatures showed even better results. The engine tested was rated at 61.9 kW (83 hp) for diesel operation, naturally aspirated. Oxides of nitrogen emissions at rated conditions were 6.7 g/kW-hr (5 g/hp-hr). It delivered only 37.3 kW (50 hp) with hydrogen when operated at low equivalence ratio (approx 0.5) to maintain NO_x emissions below 0.5 g/kW-hr (0.37 g/hp-hr). With the same restrictions on maximum NO_x generation, a turbocharged engine delivered 56 kW (75 hp), and an aftercooled, turbocharged engine delivered 67.1 kW (90 hp). In each case, the NO_x-limited power level was below the backfire-limited power level.

The preceding discussion was concerned only with intermittent combustion engines. Continuous combustion engines (gas turbine, Stirling, and steam engines) could also be used with hydrogen fuel. Oxides of nitrogen control would probably have to be handled differently than with the spark ignition engine. The steam engine, which does not use an air preheater, could possibly use either lean combustion or EGR to provide the combustion dilution necessary to reduce temperatures and lower NO_x generation. The Stirling engine uses an air preheater that typically heats the incoming combustion air to above the hydrogen autoignition temperature. Therefore a homogeneous lean mixture could probably not be achieved before ignition. A combustion system using EGR could probably be developed that would allow low NO_x emissions with hydrogen fuel in a Stirling engine. To improve efficiency, the gas turbine also uses a regenerator to preheat the combustion air, and therefore a homogeneous lean combustion mixture does not appear feasible. Furthermore EGR is not practical because of the greatly increased compression work resulting from the higher compressor inlet temperature. Specific techniques for controlling NO_x emissions to low levels in a hydrogen-fueled gas turbine would have to be developed.

Hydride Storage of Hydrogen

Hydride storage is a chemical means of storing hydrogen as a bed of solids at ambient temperature and near-atmospheric pressure with a hydrogen density about the same as that of liquid hydrogen. A metallic hydride is formed by the simple reversible reaction of a solid metal (Me) with gaseous hydrogen in which a solid metal hydride MeH_x is formed.

$$Me + \frac{x}{2} H_2 \rightleftarrows MeH_x \tag{2}$$

In effect the metal becomes a solid "sponge" for hydrogen that can be repeatedly charged and discharged at will.

The general properties of hydrides are as follows:

(1) Hydrogen can be stored with densities greater than that of liquid hydrogen, 0.07 g/cm^3 (4.37 lb/ft^3) without refrigeration or loss of fuel for an indefinite time.

(2) The process is fully reversible. In general, hydriding and dehydriding can be performed indefinitely without deterioration of H_2 storage capacity.

(3) Heat energy must be supplied to the hydride to liberate hydrogen. Since the process is reversible, the hydride also must be cooled while being recharged with hydrogen.

The absorption and release of hydrogen depends on pressure and temperature according to characteristic curves such as those shown in figure 56 for a mischmetal-nickel-aluminum compound (27). As hydrogen enters the metal, pressure increases at constant temperature along an S-shaped curve. Usually, much of the hydrogen is absorbed in a region where there is little pressure change, corresponding to the plateau of the curve. This plateau moves up with an increase in temperature. As shown in figure 56, the plateau is often sloped slightly and the plateau limits are not always sharp. Almost always there is some pressure hysteresis between absorption and desorption (see fig. 56 curves at 25° C). The hysteresis is small for most hydrides.

The plateau pressure P_p is related to the absolute temperature T by the van't Hoff equation

$$\ln P_p = \frac{2}{x} \frac{\Delta H}{RT} + C \tag{3}$$

where x is defined in equation (2), ΔH is the entropy change (heat) of the hydriding reaction, R is the universal gas constant, and C is a constant related to the entropy change of the hydriding reaction. Figure 57 (28) shows the desorption pressure - temperature relation for several hydrides.

The properties of hydrides can be modified by adding various alloying metals. In this way it is possible to tailor a hydride to a specific application. Table XIV (data from (28) to (30)) lists the characteristics of several commercially available hydrides and compares their energy densities with those of diesel fuel, liquid hydrogen, and gaseous hydrogen. The DOE hydride program to develop lightweight hydrides has concentrated on development of a magnesium-base hydride with low desorption temperature. The weight of magnesium hydride is about five times the weight of diesel fuel with the same fuel energy. The volume of magnesium hydride (exclusive of container) is about three times that of the energy-equivalent diesel fuel. The lowest equilibrium temperature obtained thus far by alloying is slightly over 200° C (392° F). The heat energy required for dehydriding is about 30 percent of the fuel energy. Figure 58 (31) shows the exhaust temperature of a naturally aspirated hydrogen-fueled engine. Assuming that the waste heat from the engine contains 50 percent of the fuel energy, the exhaust temperature must be at least 500° C (932° F) in order to supply all the heat required to liberate the hydrogen from the hydride. However, for equivalence ratios less than 0.5, the engine exhaust temperatures do not exceed 450° C (842° F). This indicates that much development is still required to match the hydride heating requirements to the energy available in the exhaust. The equilibrium temperature must be reduced to increase the availability of the exhaust heat, and/or the heat of desorption must be decreased to reduce the amount of energy required from the exhaust.

The Eimco-Ergenics development has concentrated on use of low-temperature iron-base and nickel-base alloys. These alloys have equilibrium temperatures near normal room temperature and require only about 10 to 15 percent of the fuel heat energy for desorption. However, they are heavy - 20 to 30 times the weight of diesel fuel with the equivalent fuel energy.

Hydride storage tends to be relatively safe as compared with other means of storing fuel. The small void volume and low pressures involved mean there is little gaseous H_2 immediately available for catastrophic release in a tank rupture situation. The endothermic self-limiting nature of the desorption reaction also tends to limit the rate of accidental discharge after rupture. However, some unique care must be taken with hydride storage. Active hydride powders can be mildly pyrophoric on sudden exposure to air. They will begin to glow like coal a few minutes after being suddenly exposed to air. Tests made by Ergenics showed that penetration of a hydride tank by a bullet was followed by a controlled release of hydrogen that burned for a few seconds until cooling of the container suppressed the dehydriding reaction and the flame went out.

Very high pressure can be generated if a hydride is accidentally overheated. Hydride containers must have adequate pressure relief devices to protect against fire or other potential accident situations. To prevent accumulation of H_2 in the mine, the pressure relief system must also include a catalytic reactor to oxidize the hydrogen before it is released into the mine. The BOM-sponsored work at Eimco is primarily intended to design a safe and practical hydride-fueled mine vehicle. All aspects of H_2 safety are to be considered.

Description of Hydride Fuel Storage System

One possible configuration for a hydride fuel storage system is shown in figure 59 (30). The hydrogen fuel is stored in a reservoir containing a low temperature hydride, iron-titanium hydride. The reservoir is constructed as a heat exchanger so that the engine waste heat carried by the cooling water can be used to heat the hydride. The hydrogen fuel that has been released from the hydride is then fed to the engine. Refueling is accomplished by introducing hydrogen gas at a slightly elevated pressure through a refueling port while circulating engine coolant to cool the hydride. Waste heat from the exhaust is an alternative source for heating the hydride. A higher temperature hydride such as magnesium hydride might then be used. Figure 60 (31) shows a reservoir configuration that might operate by using exhaust heat.

Evaluation Against Requirements

Ability to Achieve Duty Cycle

The hydride system is an amalgam of the advantages of a diesel engine and the disadvantages of a battery system. All the advantages of a diesel largely pertain to the hydrogen-fueled engine. Although specific power (defined as the engine power divided by cylinder displacement) is 35 to 40 percent less for a naturally aspirated hydrogen-fueled engine than for a diesel, this lost power and more can be regained with turbocharging and aftercooling. Essentially, it can be expected that the hydrogen-fueled engine will perform in most respects in the same manner as a diesel engine.

The disadvantages arise from the requirements for adequate fuel storage and fuel recharging. In this respect the hydride system more closely resembles a battery system - although significantly more energy can be stored. Take, for example, a 75-kW (100-hp) rated engine driving a tractor-trailer coal-hauling machine. If we assume an average horsepower requirement over the duty cycle of 56 kW (75 hp) with a 30-percent engine efficiency and a total working time of 310 min per shift (table I) plus 50-min fuel reserve, the total diesel fuel required is 107.5 liters (28.4 gallons). This fuel weighs 93.9 kg (207 lb) and occupies 0.11 m^3 (3.8 ft^3). A lead-acid battery system to provide this level of energy would be totally impractical. To operate a 75-kW (100-hp) motor at 75-percent average capacity for 360 min would require over 14 000 kg (30 900 lb) of batteries. Obviously, energy density is a major drawback for battery-powered systems.

Power density generally is not a problem with the hydride system. It is simply a matter of delivery system design. Energy density is far better than that of battery systems, although it cannot approach that of diesel fuel. Assume that iron-titanium hydride ($FeTiH_{1.95}$) is to be used. It has a combination of properties - hydrogen capacity, density, desorption temperature, and cost - that appear to make it a desirable choice at this time. It has a mass energy density of 583 W-hr/kg, a volume energy density of 3.20 W-hr/cm^3, a desorption temperature of about 0° C (32° F), and a reasonable alloy cost. For 56-kW (75-hp) average power, 30-percent engine efficiency, and 360 min of operation (336 kW-hr, 450 hp-hr), a total of 1919 kg (4230 lb) of hydride is required. The hydride at 100 percent density would occupy 0.35 m^3 (12.4 ft^3). If we allow additional volume for encapsulation, expansion space, hydrogen flow passages, and heat exchangers, we can assume a total required volume twice that of the hydride itself - 0.70 m^3 (24.7 ft^3). This volume can be held in two spherical-ended cylinders 0.61 m (2 ft^2) in diameter and 1.40 m (4.58 ft) long. If we assume welded steel construction with a wall thickness of 3.18 mm (1/8 in.), the cylinders would weigh a total of 133 kg (293 lb). If we approximately double this weight to allow for capsules, heat exchangers, plumbing, etc., the total hydride system weight would be approximately 2190 kg (4820 lb).

The hydride system resembles the battery system in that it is heavy and bulky when compared with a simple diesel fuel tank. But recharging is only a slightly more complex and time-consuming process than filling a diesel fuel tank. And energy and power densities are significantly better than those for battery systems. The hydride system can deliver over three times the average power for the same working period for just over half the weight of a heavy-duty battery system. Recharging should take substantially less time than for a battery system. It may be feasible to recharge at shift beginning without disturbing the work output. On the other hand, it may be more desirable simply to exchange full for empty cylinders. An operational analysis would be required to define the best approach.

Ability to Meet Government Regulations

Combustion of hydrogen results in a complete absence of CO, CO_2, aldehydes, and particulates. The only products of hydrogen combustion are water and a small amount of NO_x. Tests with unthrottled H_2-fueled internal combustion engines have demonstrated exhaust NO_x concentrations of less than 5 ppm. With water injection, NO_x concentration was reduced to 2.5 ppm. No ventilation is required to dilute NO_x since it is less than 1/5 the threshold limit value. The ventilation required to operate the engine would be that required to maintain 20 percent O_2 concentration in the work area. For engines with the same thermal efficiency, an engine operating on diesel fuel would require at least four times the ventilation of an engine operating with hydrogen fuel. This is for an optimum (CO_2 limited) diesel. Most diesels operating in mines now would require from 8 to 16 times the H_2 engine ventilation airflow. By diluting the H_2 engine exhaust to meet the 20 percent O_2 requirement, the NO_x concentration can be reduced by nearly an order of magnitude from that in the engine exhaust (i.e., to about 1/50 the TLV).

Hydrogen safety is the primary concern in underground mines. Hydrogen's flame velocity is 10 times that of methane, and its ignition energy is only 7 percent of that required to ignite methane. This means that flame traps or flameproofing designed for methane will be totally inadequate for hydrogen. This would apply to any equipment in the vicinity of possible hydrogen leaks. Hydrogen is the hardest to contain of all gases. In its atomic form it is the smallest of all atoms and in this ionized form is capable of diffusing through solid materials. Hydrogen systems require careful mechanical design and proper selection of materials to avoid hydrogen leaks and buildup of flammable mixtures. Hydrogen will disperse and dilute to safe levels very quickly in the presence of adequate ventilation. However, catalysts such as palladium can be used to oxidize it quickly if controlled venting is required inside mines. The use of hydride storage greatly reduces the amount of hydrogen that can be leaked since hydrogen is stored at low pressure and requires heat addition to be released.

A new set of Federal regulations pertaining to hydride-hydrogen engine systems would have to be written. These would have to recognize the special requirements for hydrogen system safety and the need for engine ignition systems. However, they would in other respects be very similar to current diesel engine regulations and would recognize the potential hazards.

Availability (Production Readiness)

Since the hydrogen engine is currently in a state of development, there are no meaningful data on durability, reliability, maintainability, or other factors relating to availability. However, there is no reason to believe that the hydride-hydrogen engine system will be significantly different from the diesel in terms of production readiness.

Market Availability

Development testing has been carried out with both diesel and spark ignition engines modified for hydrogen use. A spark ignition engine would be less costly initially and should require less modification. It is possible that either heavy-duty diesel or spark ignition engines being built for industrial, highway, or marine use could be modified for hydrogen operation in underground mines. In that case, market availability would be similar to that of present diesel engines.

Packaging Capability

The hydrogen engine will take more space than the current diesel, if only to accommodate the turbocharger-aftercooler system. A naturally aspirated engine would need a larger displacement at the same power and would be larger. The hydride system will take up more room than the diesel fuel tank. All in all, the system will be larger and somewhat more difficult to package, particularly if the hydride storage system is to be removable for recharging. However, it does not appear that the increased system size will be a severe problem, although minimum vehicle height may be slightly greater than for a diesel.

Remarks and Recommendations

The use of hydrogen offers the potential to eliminate CO, CO_2, and particulate emissions and greatly reduce NO_x emissions from heat-engine-powered mine vehicles. The ventilation requirements for such a vehicle would be reduced by at least a factor of 4 from those for present diesel vehicles since they are established only by the requirement to maintain 20 percent O_2 in the mine air.

The use of hydrides appears to be the most practical and least hazardous method for hydrogen storage. The unique properties of hydrogen present potential safety hazards for both the vehicle and the mine that cannot be handled with equipment and designs suitable for methane. However, the experience of NASA in the space program (32) indicates that hydrogen can be handled safely if appropriate equipment and procedures are employed.

We recommend that the Bureau of Mines monitor closely the DOE-sponsored hydrogen engine and hydride research, and also monitor the BOM (Minneapolis)-sponsored activities of Eimco and Ergenics to design a hydride-fueled mining vehicle.

There do not appear to be any significant advantages to using a gas turbine, Stirling, or steam engine instead of a reciprocating internal combusion engine if all are to operate with hydrogen fuel, for they all will have similarly acceptable exhaust characteristics. Therefore any development of a hydrogen-fueled mine engine should be based on reciprocating internal combustion industrial engines, for which a production base already exists.

CONCLUDING REMARKS

In conclusion, there does not appear to be any new near-term system concept that will revolutionize mobile mining machinery. However, there are a number of areas in which definite improvement can be foreseen. Diesels will be improved: Particulate emissions and other undesirable aspects of diesel engines will be reduced substantially with continuing development for the broader highway application. Continuous combustion engines, such as the Stirling and the gas turbine, which have many desirable features, may become available as a result of development for highway application. The pressure of development for highway application also will make available much better batteries and electric vehicle systems.

In the more distant future, successful development of a hydride fuel storage system could provide a means for substantially reducing heat engine exhaust emissions and hence ventilation requirements. Furthermore successful development of aluminum-air batteries could lead to a power source ideally suited for use in mobile mine equipment - one that is comparable to a diesel system in terms of mobility, power, and energy capacity but totally free of toxic exhaust emissions.

APPENDIX - VENTILATION REQUIREMENTS FOR ENGINES OPERATING IN UNDERGROUND MINES AND TUNNELS AND USING DIESEL FUEL AND HYDROGEN

The MSHA ventilation requirements for underground diesel engines (Code of Federal Regulations, Title 30, Parts 32 and 36) are based on dilution of exhaust emissions to the following volume concentrations:

(1) NO_x - 12.5 ppm as equivalent NO_2
(2) CO_2 - 0.25 percent
(3) CO - 50 ppm

If air is used to dilute exhaust emissions, the concentration C is then

$$C = \frac{V_e}{V_{air}} \tag{A1}$$

or by rearranging

$$V_{air} = \frac{V_e}{C} \tag{A2}$$

where V_e is the volume of emittant and V_{air} is the volume of air. For an ideal gas the equation of state is

$$pv = R_0T \tag{A3}$$

where p is in atm, v is in liters/g-mole, and R_0 is the universal gas constant, 0.0820544 atm-liters/g-mole. Rearranging this equation gives the volume of one mole of gas as

$$v = \frac{R_0T}{p} \tag{A4a}$$

Assuming the standard condition of p = 1 atm and T = 288.15 K (59° F), the volume of one mole of gas at standard conditions is

$$v_0 = 0.0820544 \left(\frac{\text{atm-liters}}{\text{g-mole K}}\right) \times \left(\frac{288.15\ \text{K}}{1\ \text{atm}}\right) = 23.644 \left(\frac{\text{liters}}{\text{g-mole}}\right) \tag{A4b}$$

or

$$v_0 = 0.023644 \left(\frac{\text{m}^3}{\text{g-mole}}\right) \tag{A4c}$$

or in U.S. customary units

$$v_0 = 378.74 \left(\frac{ft^3}{lb\text{-}mole}\right) \tag{A4d}$$

The volume occupied by the mass m of a gas at standard conditions is then

$$V = \frac{mv_0}{M} \tag{A5}$$

where M is the molecular weight. Substituting for V_e in equation (A2) gives

$$V_{air} = \frac{m_e v_0}{M_e C_e} \tag{A6}$$

Rearranging equation (A6) yields the volume of ventilation air required per gram of emittant as

$$\frac{V_{air}}{m_e} = \frac{v_0}{M_e C_e} \tag{A7a}$$

Substituting for v_0 by using equation (A4c) gives the allowable concentration and molecular weight for NO_x (assumed to be NO_2), CO_2, and CO as

$$\frac{V_{air}}{m\ NO_x} = \frac{0.023644 \left(\frac{m^3}{g\text{-}mole}\right)}{46.0055 \left(\frac{g\ NO_x}{g\text{-}mole}\right) \times 12.5 \times 10^{-6}} = 41.12 \left(\frac{m^3 air}{g\ NO_x}\right) \tag{A7b}$$

or in U.S. customary units

$$\frac{V_{air}}{m\ NO_x} = 1452 \left(\frac{ft^3 air}{g\ NO_x}\right) \tag{A7c}$$

$$\frac{V_{air}}{m\ CO_2} = \frac{0.023644 \left(\frac{m^3}{g\text{-}mole}\right)}{44.00995 \left(\frac{g\ CO_2}{g\text{-}mole}\right) \times 0.0025} = 0.2149 \left(\frac{m^3}{g\ CO_2}\right) \tag{A7d}$$

or in U.S. customary units

$$\frac{V_{air}}{m\ CO_2} = 7.589 \left(\frac{ft^3}{g\ CO_2}\right) \tag{A7e}$$

$$\frac{V_{air}}{m\ CO} = \frac{0.023644 \left(\frac{m^3}{\text{g-mole}}\right)}{28.01055 \left(\frac{g\ CO}{\text{g-mole}}\right) \times 50\text{x}10^{-6}} = 16.88 \left(\frac{m^3}{g\ CO}\right) \tag{A7f}$$

or in U.S. customary units

$$\frac{V_{air}}{m\ CO} = 596.2 \left(\frac{ft^3}{g\ CO}\right) \tag{A7g}$$

The NO_x and CO emissions produced by a fuel-burning engine are dependent on many factors, and they tend not to be directly related to the fuel flow. On the other hand, if sufficient oxygen is present and the combustion reaction is nearly complete, the CO_2 produced is in direct proportion to the fuel flow and the fraction of carbon present in the fuel.

For example, by mass, no. 2 diesel fuel is composed of about 87 percent carbon and 13 percent hydrogen and typically has a lower heating value of about 43 kJ/g (18 500 Btu/lb). The mass ratio of hydrogen to carbon therefore is

$$(H/C)_{mass} = \frac{0.13}{0.87} = 0.1494 \tag{A8}$$

By volume this is

$$(H/C)_{volume} = (H/C)_{mass} \times \frac{M_C}{M_H} = 0.1494 \times \frac{12.01}{1.008} = 1.780 \tag{A9}$$

Assuming air to be 21 percent O_2 and 79 percent N_2 by volume, the general equation for complete combustion of a chemically equivalent fuel with air can then be written as

$$CH_{H/C} + n\ (O_2 + 3.76\ N_2) \rightarrow \frac{1}{2}\left(\frac{H}{C}\right) H_2O + CO_2 + \left[n - \left(1 + \frac{H}{4C}\right)\right] O_2 + 3.76\ n\ N_2 \tag{A10}$$

One mole of CO_2 is produced for each mole of fuel.

The CO_2 index is then

$$CO_2 \text{ index} = \frac{\text{Mass } CO_2}{\text{Mass fuel}} = \frac{\text{Moles } CO_2 \text{ x Mol. wt. of } CO_2}{\text{Moles fuel x Mol. wt. of fuel}} \tag{A11a}$$

For a fuel with an H/C volume ratio of 1.780, the chemically equivalent fuel with one carbon atom has a molecular weight of 13.805. Substituting into equation (A11a) gives

$$CO_2 \text{ index} = 1\left(\frac{\text{mole } CO_2}{\text{mole fuel}}\right) \text{x} \frac{44.00995\left(\frac{\text{g}}{\text{g-mole } CO_2}\right)}{13.805\left(\frac{\text{g}}{\text{g-mole fuel}}\right)} = 3.188\left(\frac{\text{g } CO_2}{\text{g fuel}}\right) \tag{A11b}$$

or in U.S. customary units

$$CO_2 \text{ index} = 1446\left(\frac{\text{g } CO_2}{\text{lb fuel}}\right) \tag{A11c}$$

The amount of CO_2 produced per kilowatt hour can be expressed as specific CO_2.

$$\text{Specific } CO_2 = CO_2 \text{ index x BSFC} \tag{A12a}$$

For no. 2 diesel fuel

$$\text{Specific } CO_2\left(\frac{\text{g}}{\text{kW-hr}}\right) = 3.188\left(\frac{\text{g } CO_2}{\text{g fuel}}\right) \text{x BSFC}\left(\frac{\text{g fuel}}{\text{kW-hr}}\right) \tag{A12b}$$

or in U.S. customary units

$$\text{Specific } CO_2\left(\frac{\text{g}}{\text{hp-hr}}\right) = 1446\left(\frac{\text{g } CO_2}{\text{lb-fuel}}\right) \text{x BSFC}\left(\frac{\text{lb fuel}}{\text{hp-hr}}\right) \tag{A12c}$$

By combining equations (A7d) and (A12b) the specific ventilation rate is expressed as a function of BSFC.

$$CO_2 \text{ specific ventilation rate}\left(\frac{\text{m}^3}{\text{kW-hr}}\right) = 0.6851\left(\frac{\text{m}^3}{\text{g fuel}}\right) \text{x BSFC}\left(\frac{\text{g fuel}}{\text{kW-hr}}\right) \tag{A13a}$$

$$CO_2 \text{ specific ventilation rate } \left(\frac{m^3}{kW\text{-}min}\right) = 0.01142 \left(\frac{m^3\text{-}hr}{g\ fuel\text{-}min}\right) \times BSFC \left(\frac{g\ fuel}{kW\text{-}hr}\right)$$

(A13b)

In U.S. customary units, from equations (A7c) and (A12c),

$$CO_2 \text{ specific ventilation rate } \left(\frac{ft^3}{hp\text{-}hr}\right) = 10\ 970 \left(\frac{ft^3}{lb\ fuel}\right) \times BSFC \left(\frac{lb\ fuel}{hp\text{-}hr}\right)$$

(A13c)

$$CO_2 \text{ specific ventilation rate } \left(\frac{ft^3}{hp\text{-}min}\right) = 182.9 \left(\frac{ft^3\text{-}hr}{lb\ fuel\text{-}min}\right) \times BSFC \left(\frac{lb}{hp\text{-}hr}\right)$$

(A13d)

The parts of the CFR, Title 30, relating to diesels also require that the mine air contain at least 20 percent oxygen. Since operation of a fuel-burning engine depletes the oxygen content of the air, sufficient ventilation must be provided to maintain the required oxygen level. Considering an engine operating in a mine, the overall combustion process is equivalent to all of the ventilation air passing through the engine.

Referring again to the general combustion equation (A10), the concentration of O_2 in the dry mine air downstream of the engine is

$$O_2 \text{ percent} = \frac{100 \times \left[n - \left(1 + \frac{H}{4C}\right)\right]}{1 + 3.76\ n + \left[n - \left(1 + \frac{H}{4C}\right)\right]} \qquad (A14)$$

If the O_2 concentration in the downstream mine air is to be 20 percent,

$$n = 20.83 + 4.167\ H/C \qquad (A15)$$

The number of moles of air required per mole of $CH_{H/C}$ fuel or oxygen ventilation index is then

$$\frac{\text{moles air}}{\text{mole } CH_{H/C}} = 4.76\ (20.83 + 4.167\ H/C) = 99.16 + 19.83\ H/C \qquad (A16a)$$

For diesel fuel $(H/C)_{vol} \cong 1.780$.

$$\frac{\text{moles air}}{\text{mole diesel fuel}} = 99.165 + 19.833\ (1.78) = 134.47 \tag{A16b}$$

Substituting equation (A4c) and the molecular weight of $CH_{1.78}$ diesel fuel gives

$$\frac{\text{Volume air}}{\text{Mass fuel}} = \frac{134.47 \left(\frac{\text{mole air}}{\text{mole fuel}}\right) \times 0.023644 \left(\frac{m^3}{\text{g-mole air}}\right)}{[12.01 + 1.78\ (1.008)] \left(\frac{g}{\text{g-mole fuel}}\right)}$$

$$\frac{\text{Volume air}}{\text{Mass diesel fuel}} = 0.2303 \left(\frac{m^3\ \text{air}}{\text{g fuel}}\right) \tag{A16c}$$

or in U.S. customary units

$$\frac{\text{Volume air}}{\text{Mass diesel fuel}} = 3689 \left(\frac{ft^3\ \text{air}}{\text{lb fuel}}\right) \tag{A16d}$$

Therefore

$$O_2 \text{ specific ventilation rate} = \frac{\text{Volume air}}{\text{Mass fuel}} \times \text{BSFC} \tag{A17a}$$

Substituting equation (A16c) and the BSFC for diesel fuel gives

$$O_2 \text{ specific ventilation rate} \left(\frac{m^3}{\text{kW-hr}}\right) = 0.2303 \left(\frac{m^3\ \text{air}}{\text{g fuel}}\right) \times \text{BSFC} \left(\frac{\text{g fuel}}{\text{kW-hr}}\right) \tag{A17b}$$

or

$$O_2 \text{ specific ventilation rate} \left(\frac{m^3}{\text{kW-min}}\right) = 3.838\text{x}10^{-3} \left(\frac{m^3\ \text{air-hr}}{\text{g fuel-min}}\right) \times \text{BSFC} \left(\frac{\text{g fuel}}{\text{kW-hr}}\right) \tag{A17c}$$

In U.S. customary units this is

$$O_2 \text{ specific ventilation rate } \left(\frac{ft^3}{hp\text{-}min}\right) = 61.48 \left(\frac{ft^3 \text{ air-hr}}{lb \text{ fuel-min}}\right) \times \text{BSFC} \left(\frac{lb \text{ fuel}}{hp\text{-}hr}\right)$$

(A17d)

For hydrogen fuel the equation for complete combustion within the mine can be written as

$$H_2 + n\,(O_2 + 3.76\ N_2) = H_2O + \left(n - \frac{1}{2}\right)O_2 + 3.76\ n\ N_2 \tag{A18}$$

The concentration of O_2 in the dry air downstream of the engine is then

$$O_2 \text{ percent} = \frac{100\left(n - \frac{1}{2}\right)}{\left(n - \frac{1}{2}\right) + 3.76\ n} \tag{A19}$$

For 20 percent O_2 in the downstream air, solving equation (A19) for n yields $n = 8.333$. Therefore the moles of air per mole of H_2 are

$$\frac{\text{moles air}}{\text{mole } H_2} = 8.333 \times 4.76 = 39.67 \tag{A20}$$

Substituting equation (A4c) and the molecular weight of H_2 gives

$$\frac{\text{Volume air}}{\text{Mass } H_2} = \frac{39.67\left(\frac{\text{mole air}}{\text{mole } H_2}\right) \times 0.023644\left(\frac{m^3}{\text{mole air}}\right)}{2.016\left(\frac{g}{g\text{-mole } H_2}\right)} = 0.4653\left(\frac{m^3}{g\ H_2}\right)$$

(A21a)

or in U.S. customary units

$$\frac{\text{Volume air}}{\text{Mass } H_2} = 7453\left(\frac{ft^3 \text{ air}}{lb\ H_2}\right) \tag{A21b}$$

Substituting equation (A21a) and BSFC into equation (A17a) for H_2 fuel gives

$$O_2 \text{ specific ventilation rate} \left(\frac{m^3}{kW\text{-}hr}\right) = 0.4653 \left(\frac{m^3 \text{ air}}{g\ H_2}\right) \times BSFC \left(\frac{g}{kW\text{-}hr}\right)$$

(A22a)

$$O_2 \text{ specific ventilation rate} \left(\frac{m^3 \text{ air}}{kW\text{-}min}\right) = 7.755\text{x}10^{-3} \left(\frac{m^3\text{-}hr}{g\ H_2\text{-}min}\right) \times BSFC \left(\frac{g}{kW\text{-}hr}\right)$$

(A22b)

or in U.S. customary units

$$O_2 \text{ specific ventilation rate} \left(\frac{ft^3 \text{ air}}{hp\text{-}min}\right) = 124.2 \left(\frac{ft^3 \text{ air-hr}}{lb\ H_2\text{-}min}\right) \times BSFC \left(\frac{lb}{hp\text{-}hr}\right)$$

(A22c)

For the aluminum-air battery the overall equation for the chemical reaction within a mine can be written as

$$Al + \frac{3}{2} H_2O + n\ (O_2 + 3.76\ N_2) = Al\ (OH)_3 + \left(n - \frac{3}{4}\right) O_2 + 3.76\ n\ N_2 \qquad \text{(A23)}$$

The dry concentration of O_2 in the downstream air is then

$$O_2 \text{ percent} = \frac{\left(n - \frac{3}{4}\right) \times 100}{\left(n - \frac{3}{4}\right) + 3.76\ n} \qquad \text{(A24)}$$

For 20 percent O_2, solving for n yields $n = 12.5$. Therefore the moles of air per mole of aluminum are

$$\frac{\text{moles air}}{\text{mole Al}} = 12.5 \times 4.76 = 59.5 \left(\frac{\text{moles air}}{\text{mole Al}}\right) \qquad \text{(A25)}$$

$$\frac{\text{Volume air}}{\text{Mass Al}} = 59.5 \left(\frac{\text{moles air}}{\text{mole Al}}\right) \times \frac{23.644 \left(\frac{m^3 \text{ air}}{\text{kg mole air}}\right)}{26.9825 \left(\frac{\text{kg Al}}{\text{kg mole Al}}\right)} = 52.14 \left(\frac{m^3 \text{ air}}{\text{kg Al}}\right)$$

(A26)

Multiplying equation (A26) by the energy yield from aluminum, about 4.25 kW-hr/kg Al, gives the specific ventilation rate (SVR) as

$$\mathrm{SVR}\left(\frac{\mathrm{m}^3}{\text{kW-hr}}\right) = 52.14\left(\frac{\mathrm{m}^3\ \text{air}}{\text{kg Al}}\right) \times \left(\frac{\text{kg Al}}{4.25\ \text{kW-hr}}\right) = 12.27\left(\frac{\mathrm{m}^3\ \text{air}}{\text{kW-hr}}\right),\ \text{or } 0.2045\left(\frac{\mathrm{m}^3}{\text{kW-min}}\right) \tag{A27a}$$

or in U.S. customary units

$$\mathrm{SVR} = 12.27\left(\frac{\mathrm{m}^3\ \text{air}}{\text{kW-hr}}\right) \times 35.3147\left(\frac{\mathrm{ft}^3}{\mathrm{m}^3}\right)$$

$$\times\ 0.746\left(\frac{\text{kW}}{\text{hp}}\right) = 323.2\left(\frac{\mathrm{ft}^3}{\text{hp-hr}}\right),\ \text{or } 5.39\left(\frac{\mathrm{ft}^3}{\text{hp-min}}\right) \tag{A27b}$$

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TABLE I. - TYPICAL COAL MINE SHIFT

TIME DISTRIBUTION

[Total shift time available, 480 min.]

	Time, min
Travel in	30
Prepare to mine	30
Service equipment	20
Lunch	30
Miscellaneous	10
Prepare to leave	20
Travel out (and early out)	30
Subtotal - fixed times lost	170
Mechanical delay:	
Mining machine breakdowns	35
Support equipment breakdowns	25
Subtotal - mechanical delays	60
Total nonproductive time	230
Total face time for mining	250

TABLE II. - CONDENSED SUMMARY OF MINE SAFETY REGULATIONS FOR DIESEL-POWERED VEHICLES

[From Code of Federal Regulations, Title 30 - Mineral Resources, revised as of July 1, 1979.]

Parameter	Diesel haulage vehicles		Diesel
	Noncoal, nongassy mines (Ref: Part 32)	Noncoal, gassy mines (Ref: Part 36)	Mine locomotives (Ref: Part 31)
Flashpoint	140° F	140° F	150° F
Starting	Electric motor, etc.	Pneumatic or hydraulic; electricity prohibited	Explosion-proof electric motor or other safe device
Intake and exhaust manifolds	----------------------	Four times explosion test pressure or 125 psi, whichever is less; flanged with metal gaskets	125 psi or explosion pressure, whichever is greater; flanges equivalent to class I electrical
Intake and exhaust flame arrestors	----------------------	No flame propagation to outside	No flame propagation to outside
Engine joints	----------------------	Flanged with metal or metal-clad gaskets; no flame propagation; explosion proof	--------------------
Exhaust cooling	160° F; water box or spray	170° F; automatic shutoff at or below 185° F; water box or spray, or both, water capacity for 8 hr at 1/3 load; minimum quantity, 1 hr at maximum load times 8/3	160° F; automatic shutoff between 180° F and 190° F; water box or spray, or both, or other means that provide equivalent cooling
Surface temperature (engine and exhaust)	----------------------	400° F;[a] integral water jackets; automatic shutoff at 212° F; insulation, not allowable	400° F; integral water jackets; insulation not allowable if absorbs oil, etc.; water spray close to outlet
Dilute exhaust gas (approx 10 ft downstream of vehicle)	0.5 percent CO_2; 100 ppm CO; 25 ppm NO_x; 10 ppm aldehydes	0.5 percent CO_2; 100 ppm CO; 25 ppm NO_x; 10 ppm aldehydes	100 ppm CO; 25 ppm NO_x; 10 ppm aldehydes
Undiluted exhaust gas	0.25 percent CO	0.3 percent CO; 0.2 percent NO_x	0.25 percent CO
Fuel supply system	1.5 mm (1/16 in.) thick, welded; vent to atmosphere; fuel shutoff valve	1.5 mm (1/16 in.) thick, welded; self-sealing filler; vent to atmosphere; capacity, 4 hr at full load, continuous duty; fuel shutoff valve	1.5 mm (1/16 in.) thick, welded; self-sealing filler; vent to atmosphere; fuel shutoff in operator's compartment
Electrical equipment	Fuses; conductors rated at 110 percent; battery box (routine requirements)	Nothing allowed except headlamp with self-contained sealed power source	Extensive detailed requirements for explosion-proof containers, wires, bolts, flanges, bearings, etc.

[a]150° C (302° F) generally used in actual practice.

TABLE III. - SPECIFICATIONS FOR SOME DIESEL MINE ENGINES

Manufacturer	Model	Maximum power		Speed, rpm	Dry weight		Overall dimensions						Specific weight[a]		Specific volume[a]	
		kW	hp		kg	lb	Length		Width		Height		kg/kW	lb/hp	liters/kW	ft^3/hp
							mm	in.	mm	in.	mm	in.				
Caterpillar	3304NA	74.6	100	2200	744	1640	1276	50.3	754	29.7	1000	39.4	9.97	16.40	12.9	0.341
	3304T	123	165	2200	751	1655	1276	50.3	820	32.3	1000	39.4	6.10	10.03	8.52	0.225
	3306NA	112	150	2200	930	2050	1575	62.0	780	30.7	1011	39.8	8.31	13.66	11.1	0.292
	3306T	187	250	2200	980	2160	1504	59.2	782	30.8	1171	46.1	5.25	8.64	7.38	0.195
	3306T	134-201	180-270	2200	980	2160	1575	62.0	782	30.8	1171	46.1	7.30-48.6	12.0-8.0	10.7-7.16	0.283-0.189
Deutz	F2L410	9-18.7	12-25	3000	146	322	522	20.6	510	20.1	690	20.1	16.32-7.832	26.83-12.88	21.0-9.90	0.543-0.261
	ABL714	116	156	2200	935	2061	1155	45.5	1235	48.6	1010	39.8	8.033	13.2	12.4	0.326
	F6L413FW	104-207	139-277	2300	595	1311	1006	39.6	1022	40.3	898	35.4	5.73-2.88	9.43-4.73	8.93-4.48	0.235-0.118
	F8L413FW	138	185	2300	757	1668	124.7	49.1	↓	↓	901	35.5	5.48	9.02	8.34	0.220
	F10L413FW	172	231	2300	925	2039	141.2	55.6	↓	↓	942	37.1	5.37	8.83	7.90	0.208
	F12L413FW	207	277	2300	1090	2403	157.6	62.1	↓	↓	942	37.1	5.27	8.68	7.36	0.194
	BF12714	127-282	170-378	2300	1450	3196	1568	61.8	1235	48.6	916	36.1	11.43-5.14	18.8-8.46	14.0-6.30	0.369-0.166

[a]Values given are for the basic engine only and do not include additional equipment needed to meet Federal regulations.

TABLE IV. - DIESEL NOISE SOURCES AND ABATEMENT POTENTIAL (4)

Parameter	Treatment	Typical noise reduction, dB	Comment
Pressure rise rate	Modify combustion process	3 to 4	Affects other parameters
Ignition delay	Increase injection rate	3 (full load)	40 Percent decrease in NO_x
Fuel composition	Increase cetane number	4 (peak torque)	10 Percent increase in NO_x
Prechamber turbulence	Low-turbulence prechamber	5 to 6 (2/3 load)	14 Percent increase in SFC
Piston slap	Polymeric piston inserts	4 to 5	Durable polymer required
	Reduce clearances	2 to 3	
Timing gears	Use belt drive	3 to 4 (peak torque)	
Oil pan and panels	Stiffen or isolate	1 to 4	Weight penalty
	Shield	5 to 10	Weight penalty
Overall engine	Encapsulate engine	10 to 15	Engine access must be ensured

TABLE V. - UNITED STIRLING 4-275 ENGINE PART-LOAD

FUEL CONSUMPTION (8)

[The figures relate to diesel fuel; fuel consumption at low idling speed, 1.1 - 1.3 kg/hr (2.4 - 2.8 lb/hr); lubricating oil consumption, negligible.]

Load	Speed, rpm					
	1000		1500		2000	
	Part-load fuel consumption					
	g/kW-hr	lb/bhp-hr	g/kW-hr	lb/bhp-hr	g/kW-hr	lb/bhp-hr
1/1	235	0.39	240	0.39	260	0.43
3/4	245	.40	245	.40	270	.44
1/2	270	.44	270	.44	290	.48

TABLE VI. - NOMINAL POWER, DUTY CYCLE, AND LIFE DURABILITY GOALS

Engine requirement	Application				
	Mine LHD[a]		AGT[b]	IGT[c]	
	Section A[d]	Section C[d]		Truck	City bus
Maximum power, hp	150	145	85,130	300	300
Time at maximum or close to maximum power, hr	750	650	100	1700	(e)
Average duty cycle power, kW (hp)	86 (115)	45 (60)	7.5 (10)	112 (150)	15-225 (20-30)
Number of startups	930	930	12 000	1100	19 000
Number of full acceleration-decelerations	120 000	40 000	21 600	50 000	525 000
Life or time to major overhaul, hr	4000	4000	3500	12 000	10 000

[a]Mine load-haul-dump vehicle of 8165-kg (18 000-lb) capacity.
[b]Advanced automotive gas turbine engines: AGT 100 and 102, 63.5 kW (85 hp) and AGT 101, 97 kW (130 hp).
[c]Industrial heavy-duty vehicular gas turbine engine, DDA-404.
[d]Refers to duty cycles for mine sections described in (1).
[e]Not available.

TABLE VII. - ENGINE SIZE, WEIGHT, AND NOMINAL PERFORMANCE

[Obtained from manufacturers' specification sheets.]

Engine	Type	Application	Power		Specific fuel consumption at 150 hp		Weight, kg	Length[b]		Height[b]		Width[b]		Volume[b]	
			kW	hp	g/kW-hr	lb/hp-hr		cm	in.	cm	in.	cm	in.	m^3	ft^3
DDA-404	IGT	Truck or bus	224	300	267	0.44	1800	119	47	91	36	79	31	0.86	30.35
Deutz F8L714	Diesel[a]	LHD vehicle	112	150	261	0.43	2060	117	46	102	40	124	49	1.48	52.18
Caterpillar 3306	Diesel[a]	LHD vehicle	112	150	225	0.42	2050	157	62	99	39	76	30	1.19	41.98

[a]Naturally aspirated.
[b]Radiator not included.

TABLE VIII. - STEAM ENGINE GOALS AND TEST RESULTS

Characteristic	Engine goals	Test results
Maximum net power, kW (hp)	56 (75)	54 (72)
Starting time to idle speed, min	1	1
Maximum fuel flow, kg/hr (lb-hr)	34 (75)	27.7 (61)
Best BSFC, g/kW-hr (lb/bhp-hr)	609 (1.0)	486 (0.8)
Maximum surface temperature, °C (°F)	150 (302)	132 (270)
Maximum exhaust temperature, °C (°F)	150 (302)	104 (220)
Battery capacity	Three starts	More than three starts
Burner emissions concentrations:		
CO_2 (max/avg), percent	15	14.7/13.8
CO (max/avg), g/hp-hr	1.5	1.3/1.2
NO_x (max/avg), g/hp-hr	0.4	[a]0.2/[a]0.2
Smoke less than -, percent opacity	15	Trace
Engine dimensions on pallet:		
Weight, kg (lb)	680 (1500)	Not measured
Length, m (ft)	2.34 (7 2/3)	2.34 (7 2/3)
Width, m (ft)	2.06 (6 3/4)	2.06 (6 3/4)
Height, m (in.)	0.56 (22)	0.56 (22)

[a]Measured 0.2 g/hp-hr of NO_x, but component tests suggest that 0.35 to 0.4 is more realistic.

TABLE IX. - STEAM CAR AND TRAILING-CABLE CAR PRODUCTIVITY

[Jeffrey study for two cars with 300-ft haulage.]

Characteristic	Steam car	Trailing-cable car
Number of cars	2	2
Distance hauled, m (ft)	91.4 (300)	91.4 (300)
Tram speed, km/hr (miles/hr)	8.5 (5.3)	5.6 (3.5)
Trips per car per shift	35	40
Payload per car, tons	9	6
Shift haulage per car, tons	318	230
Increased haulage per car:		
Per shift, tons	88	----------
Per shift, percent	38	----------
From speed, percent	15	----------
From payload, percent	21	----------

TABLE X. - STEAM CAR AND TRAILING-CABLE CAR ECONOMICS

[Jeffrey study for two cars with 300-ft haulage.]

Characteristic	Steam car	Trailing-cable car
Operating time:		
Shifts per day	2	2
Days per week	5	5
Shift haulage per car, tons	318	230
First cost for one car and support equipment, dollars	126 000	77 000
10-year first-cost difference amortization (per year per car), dollars	4900	------
Cost of consumables (per year per car), dollars	7294	7123
Cost of maintenance parts (per year per car), dollars	9908	11 300
Total annual cost differential (per year per car), dollars	3679	------
Profit potential of increased production: typically $1.30/ton (per year per car), dollars	56 940	------
Profit: potential less cost differential (per year per car), dollars	53 261	------
Annual return on first-cost differential, percent	109	------
Payback time on first-cost differential, months	11	------

TABLE XI. - CHARACTERISTICS OF CURRENT AND IMPROVED

ELECTRICAL STORAGE BATTERIES

Battery type	Usable energy density, W-hr/kg	Peak power density, W/kg	Relative cost	Important features
Lead-acid:				Recharge may be cut in half to 4 hours
Current	26	100	1.0	Continuing discharge sensitivity
Improved	40	150	?	Emits H_2 during recharge
Nickel-iron:				Potential for deep discharge
Current	45	130	2.0	Three-hour recharge possible
Improved	55	150	?	Emits large amount of H_2 in recharge
Nickel-zinc:				Mainly emits O_2 in recharge
Current	60	130	2.5	Should not be sensitive to discharge
Improved	80	200	?	Rapid recharge possible
Aluminum-air	[a]300	150-200	?	Rapid mechanical recharge comparable to diesel refueling

[a]Dependent on battery design constraints (20).

TABLE XII. - EFFECT OF BATTERY IMPROVEMENTS ON WORK CAPACITY FOR A TYPICAL TRACTOR-TRAILER HAULAGE VEHICLE[a]

Battery type	Available face time per charge,[b,c] hr	Number of work shifts
Current lead-acid	[d]6.0	1.2
Improved lead-acid	10.0	1.9
Improved nickel-iron	13.7	2.6
Improved nickel-zinc	19.9	3.8
Aluminum-air	[e]74.8	14.5

[a]S&S Corp. Model 320 Du-A-Trac; useful load, 7 to 10 tons; battery package weight, 9300 lb (4218 kg); drive motor, 45 hp (33.6 kW) at 128 V.
[b]Assumes only fixed delay times as shown in table I. Total face time exclusive of breakdowns is 310 min/shift. Average duty cycle power is 40 percent of rated maximum power.
[c]Available face time is calculated on the basis of fixed battery system weight and ratio of energy density for the improved battery types to that for the current. Eighty percent discharge was assumed for all batteries.
[d]Current lead-acid battery is assumed as S&S Corp. Model 320 battery pack. For a weight of 9300 lb (4218 kg), it delivers 100.3 kW-hr of energy for an energy density of 23.7 W-hr/kg.
[e]Assumes the aluminum-air battery occupies the same volume as the current lead-acid batteries.

TABLE XIII. - SUMMARY OF GE RESULTS FOR ESTIMATED SHUTTLE CAR ANNUAL OPERATING COSTS AND COST EFFECTIVENESS

Shuttle car type (source)	Load capacity (rated)		Annual operating cost, $/yr	Cost[a] per ton mined, $/ton
	kg	lb		
Flywheel-powered tractor trailer (GE analysis)	3515	7750	18 400	16.19
Conventional tethered car (Joy 18SC13DC)	4309	9500	19 200	16.48
Battery-powered tractor trailer (Jeffrey 404L RAMCAR)	6100	13 450	20 300	16.17
Diesel-powered tractor trailer (Jeffrey 410H RAMCAR)	10 093	22 250	29 800	15.55
Steam-powered tractor trailer (Jeffrey experimental)	3515	7750	20 600	16.66

[a]Total production cost assuming two-car face haulage with 30-sec unloading time.

TABLE XIV. - CHARACTERISTICS OF SOME COMMERCIALLY AVAILABLE HYDRIDES

	Equilibrium temperature at 1 atm (28), °C	Dissociation heat (29), ΔH W-hr/kg H_2	Ratio of dissociation heat to low heat of H_2 combustion	Available hydrogen mass (29), percent	Mass energy density,[a] W-hr/kg	Volume energy density[b] (30), W-hr/cm^3
$FeTiH_{1.95}$ (Hy-Stor 101)[c]	0	-3900	0.13	1.75	583	3.20
$Fe_{0.9}Mn_{0.1}TiH$ (Hy-Stor 102)	2	-4000	.12	1.79	596	-----
$Fe_{0.8}Ni_{0.2}TiH_{0.6}$ (Hy-Stor 103)	74	-5650	.17	1.21	403	-----
$CaNi_5H_3$ (Hy Stor 201)	42	-4400	.13	1.39	463	-----
$Ca_{0.7}M_{0.3}Ni_5H_3$ (Hy-Stor 202)	-8	-3700	.11	1.60	533	-----
$Ca_{0.2}M_{0.8}Ni_5H_3$ (Hy-Stor 203)	-50	-3350	.10	1.08	360	-----
MNi_5H_3 (Hy Stor 204)	-55	-2900	.087	1.41	470	-----
$LaNi_5H_3$ (Hy-Stor 205)	13	-4300	.13	1.43	476	-----
$LaNi_{4.7}Al_{0.3}H_3$ (Hy-Stor 207)	45	-4700	.14	1.36	453	-----
[d]$MNi_{4.5}Al_{0.5}H_3$ (Hy-Stor 208)	-7	-3900	.12	1.20	400	-----
$MNi_{4.15}Fe_{0.85}H_3$ (Hy-Stor 209)	-32	-3500	.10	1.15	383	-----
Mg_2NiH_4 (Hy-Stor 301)	253	-8900	.27	3.16 (30)	1052	2.70
MgH_2	287	-10 700	.31	7.0 (30)	2332	3.36
Liquid hydrogen	---	-------	----	100	33 300	2.33
Gaseous hydrogen (at 1500 psi)	---	-------	----	100	33 300	.266
Diesel fuel	---	-------	----	-------------	11 900	9.92

[a]Mass energy density = Available hydrogen mass x LHV of hydrogen.
[b]Does not include containment.
[c]Trademark of HPD Technology Corp.
[d]M = mischmetal.

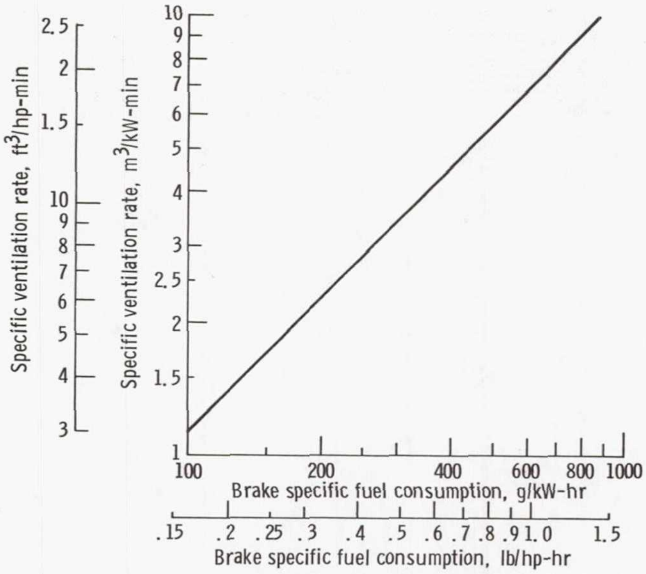


Figure 1. - Minimum specific ventilation rate (SVR) vs. brake specific fuel consumption (BSFC) at rated power for engines operating on no. 2 diesel fuel with CO_2 dilution to 0.25 percent by volume.

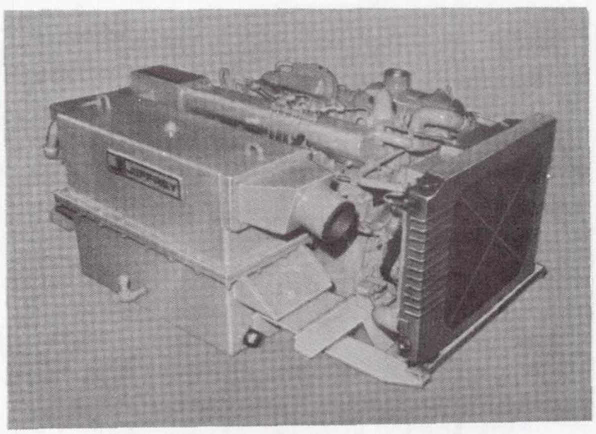


Figure 2. - 146-Horsepower Caterpillar engine package with exhaust scrubber.

1 12-Volt alternator
2 Exhaust diffuser
3 Catalytic converter
4 Mounting frame, cushioned
5 Transmission
6 Transmission oil cooler
7 Hydraulic pump

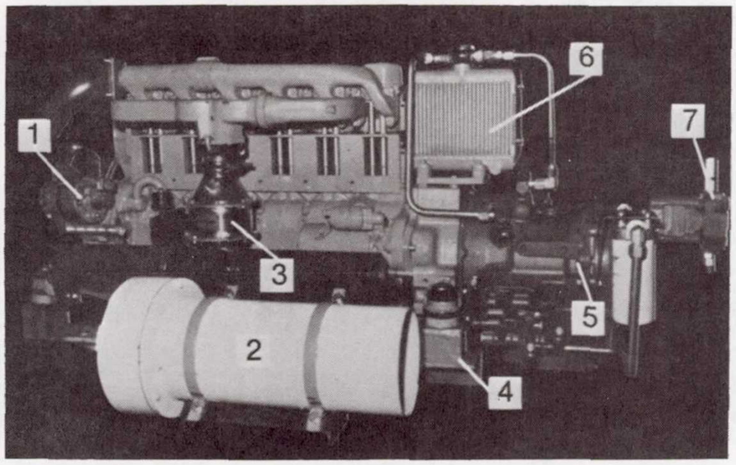


Figure 3. - Deutz air-cooled, six-cylinder, 75-hp schedule 24 engine package.

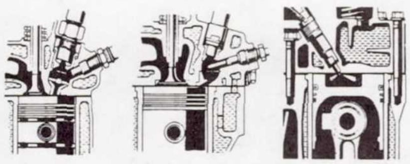


Figure 4. - Different combustion systems used in diesel engines.

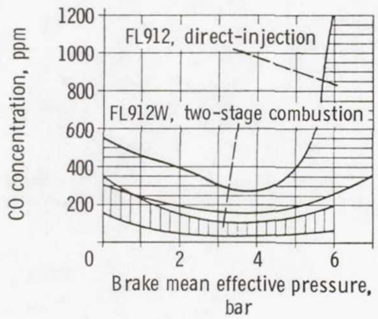


Figure 5. - CO concentrations with direct injection compared to two-stage combustion.

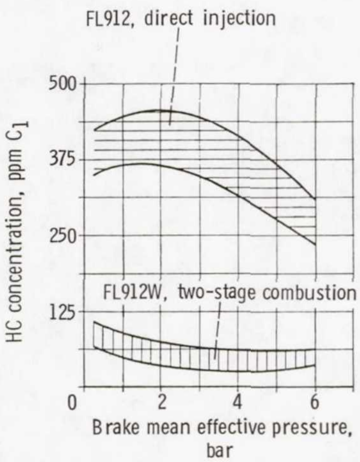


Figure 6. - HC concentrations with direct injection compared to two-stage combustion.

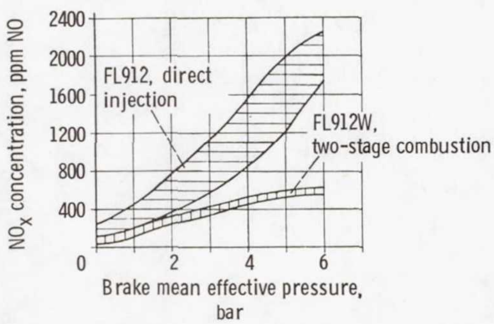


Figure 7. - NO_x concentrations with direct injection compared to two-stage combustion.

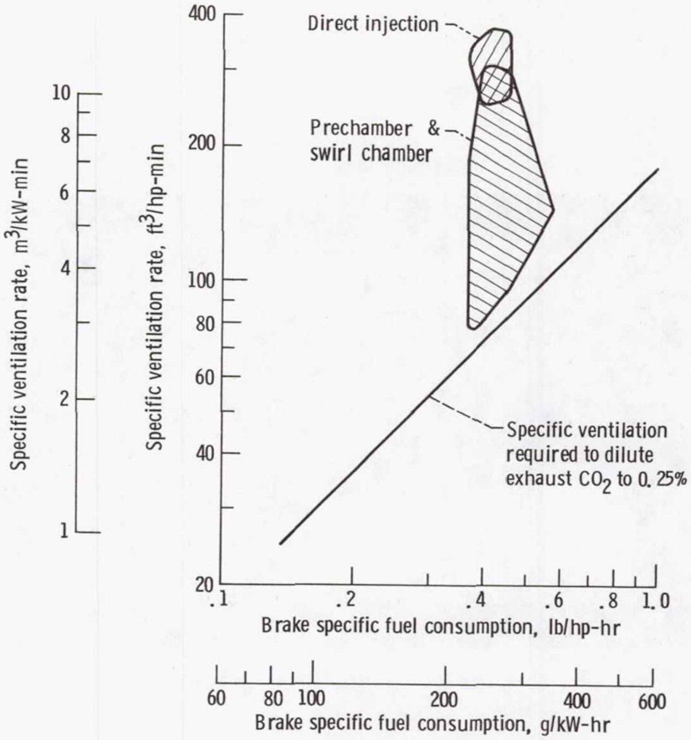


Figure 8. - Specific ventilation rate of diesel engines certified for CFR Part 36 (schedule 31, for gassy noncoal mines and tunnels).

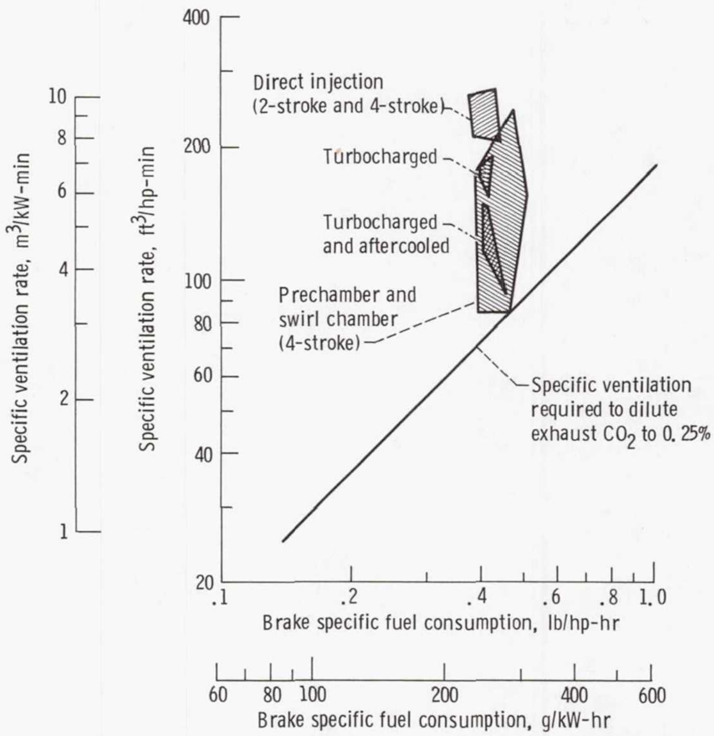


Figure 9. - Specific ventilation rate of diesel engines certified for CFR Part 32 (schedule 24, for nongassy noncoal mines and tunnels).

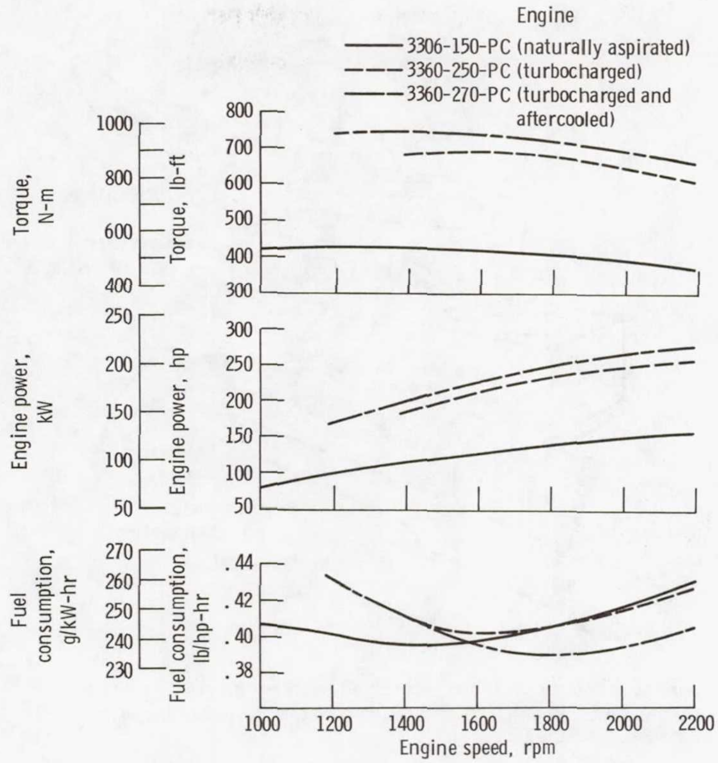


Figure 10. - Comparison of performance of three versions of the 3306 Caterpillar prechamber diesel operating at full power.

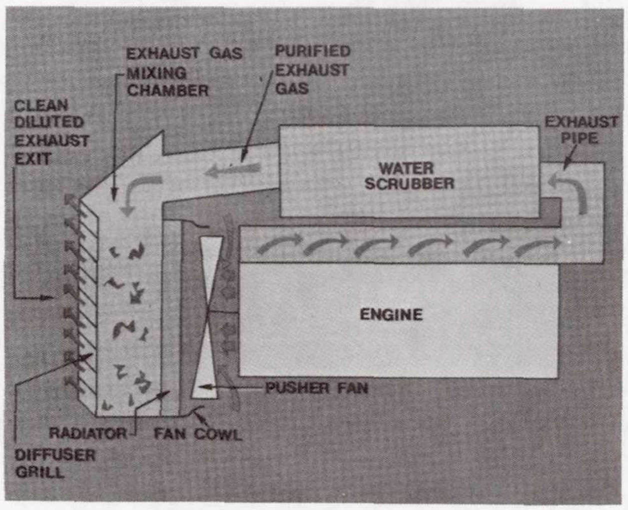


Figure 11. - Jeffrey exhaust conditioning system.

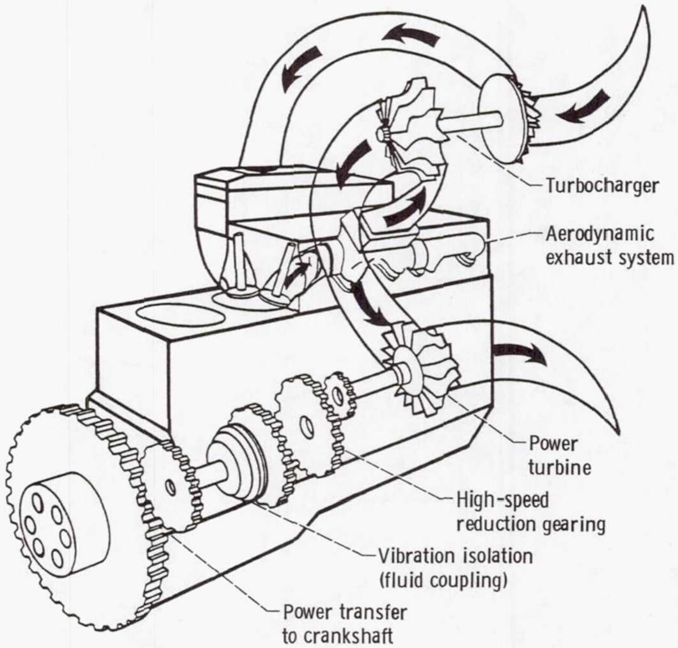


Figure 12. - Cummins NH turbocompounded diesel engine. (A hybrid diesel-turbine system in which piston power is supplemented by turbine power recovered from the exhaust gas.)

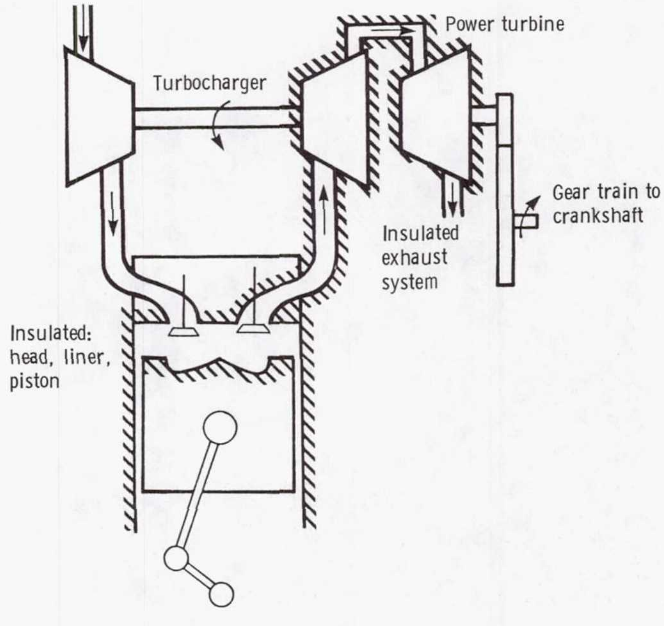


Figure 13. - Adiabatic diesel engine.

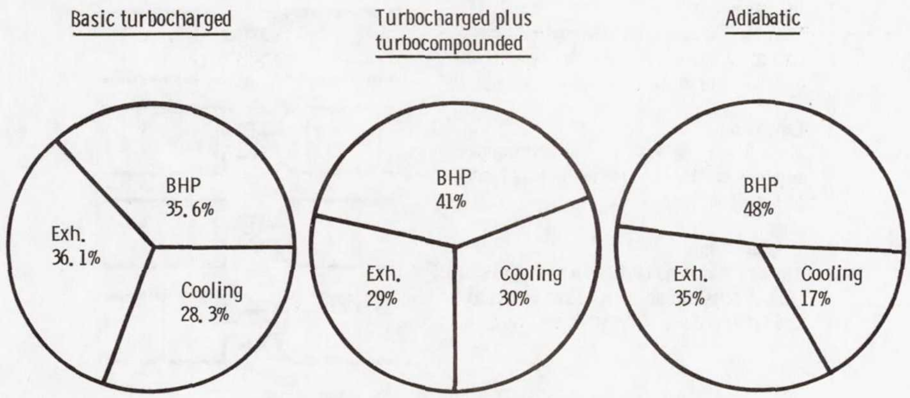


Figure 14. - Energy balance comparison (diesel engine).

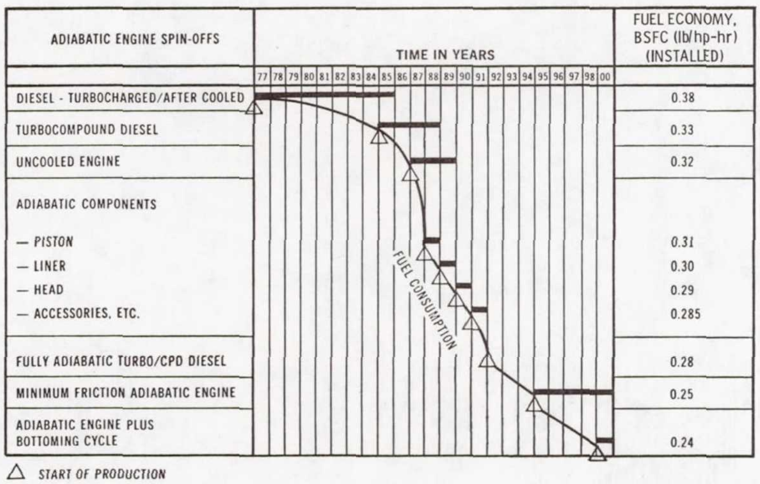


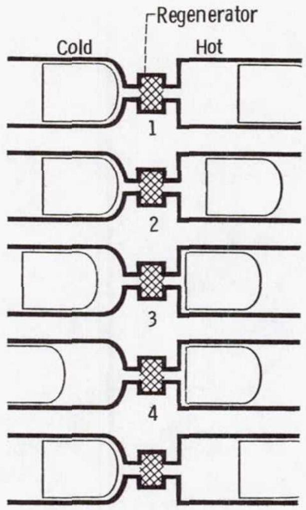
Figure 15. - Predicted production date of adiabatic engine spin-offs from U. S. Army engine programs.

1-2 Compression
Work is supplied by compressing the working gas on the cold side; the gas is cooled at low pressure.

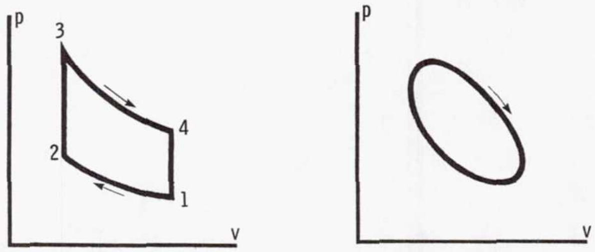
2-3 Displacement
The gas is moved from the cold to the hot side at constant volume. The regenerator gives off stored heat. Pressure increases.

3-4 Expansion
Work is performed when the working gas expands on the hot side while it is heated at high pressure.

4-1 Displacement
The gas moves from the hot to the cold side at constant volume. Heat is stored in the regenerator. Pressure declines.



(a) Phases of the Stirling cycle.



(b) Theoretical pressure-volume curve.

(c) Actual pressure-volume curve.

Figure 16. - The Stirling cycle.

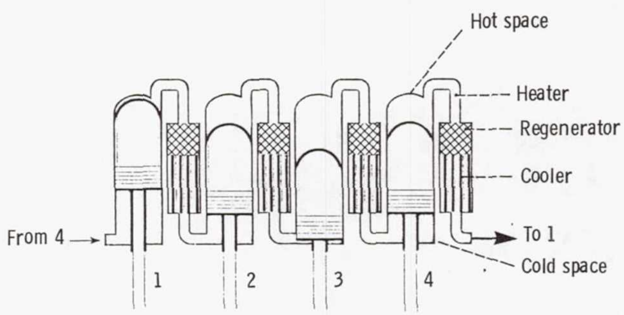


Figure 17. - The double-acting principle.

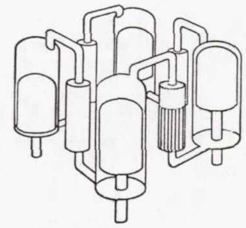


Figure 18. - Square arrangement of cylinders in double-acting Stirling engine.

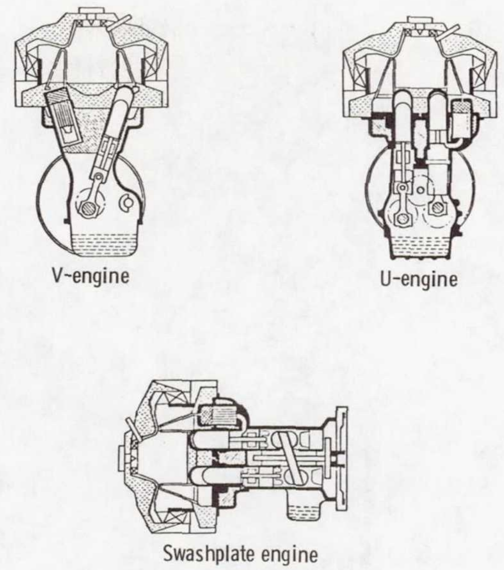


Figure 19. - Stirling engine drive configurations.

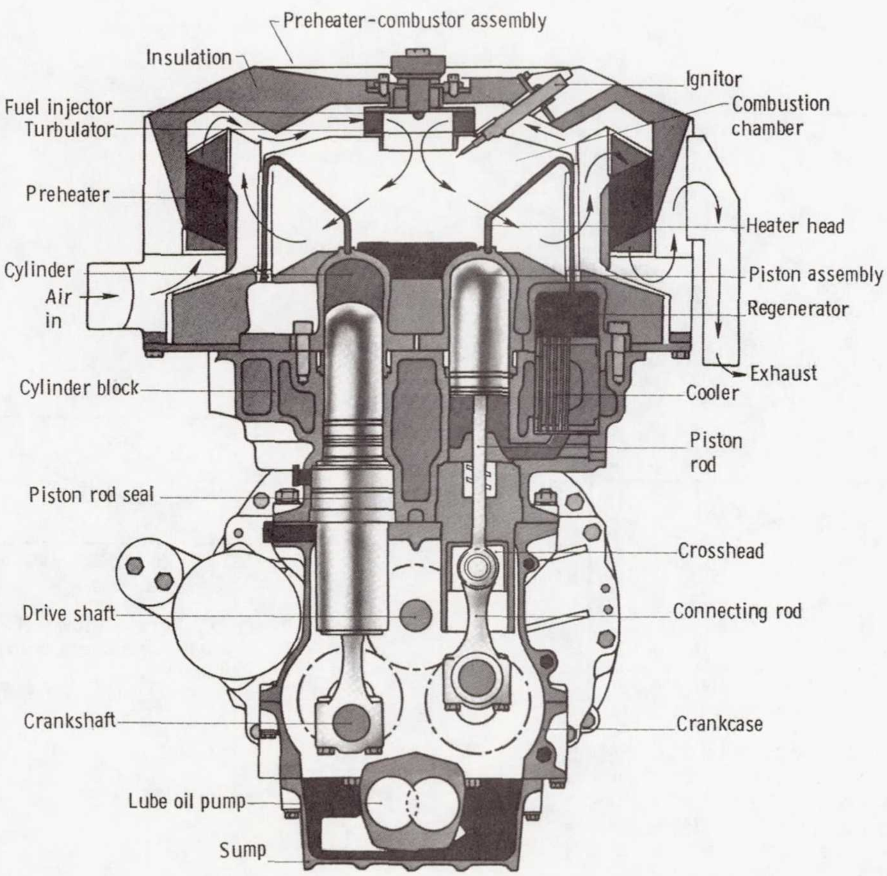


Figure 20. - United Stirling engine (typical of the 4-95 (P40) and 4-275 (P75) engines).

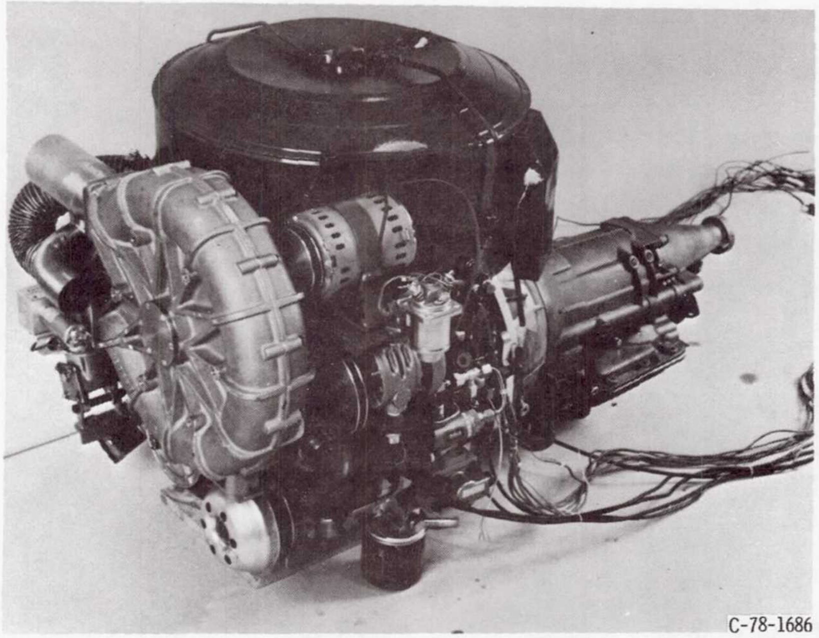


Figure 21. - United Stirling P-40 equipped for test installation in passenger car.

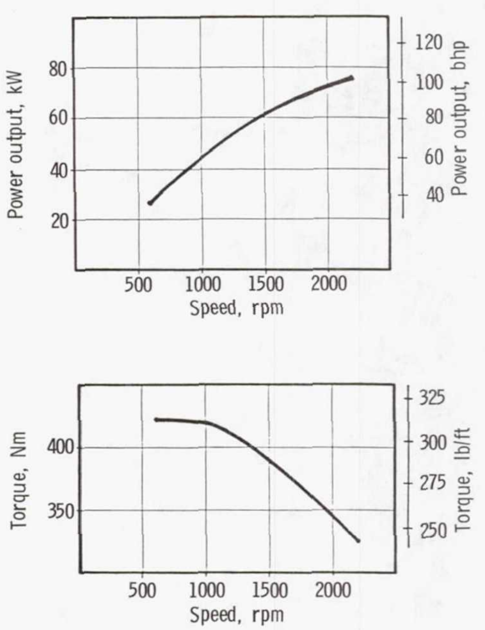


Figure 22. - United Stirling 4-275 engine power and torque vs. speed. Maximum power output, 75 kW at 2200 rpm; maximum torque, 420 Nm at 600 to 1000 rpm; torque rise, 25 percent; speed operating range, 600 to 2200 rpm.

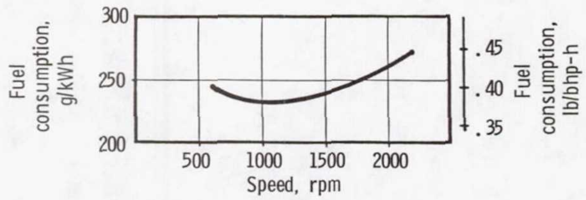
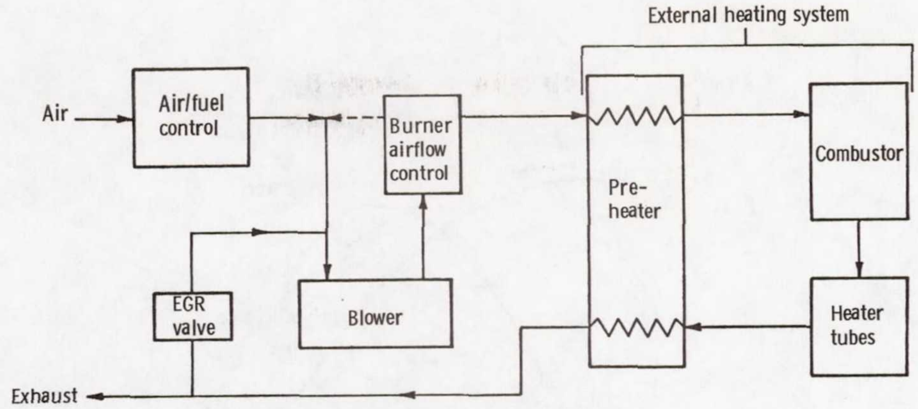
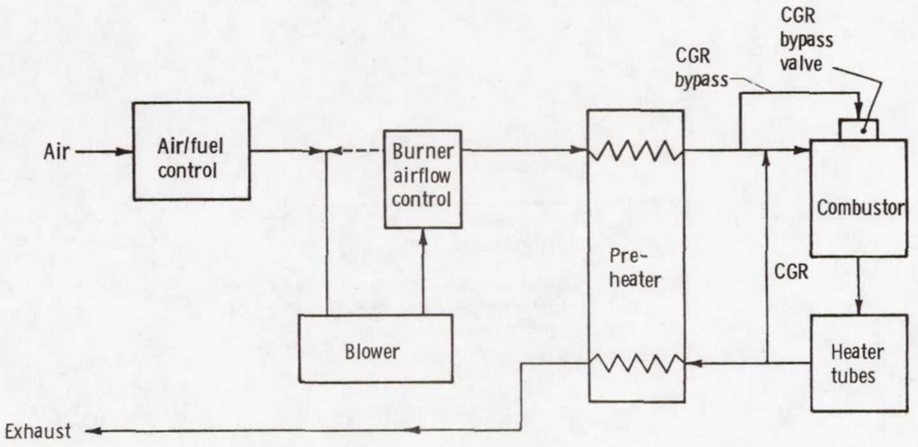


Figure 23. - United Stirling 4-275 engine full-load fuel consumption vs. speed.



(a) EGR schematic.



(b) CGR schematic.

Figure 24. - Stirling engine NO_X emissions control systems.

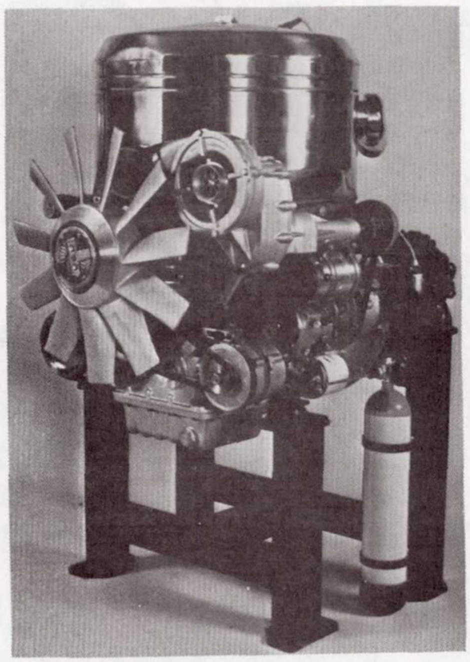


Figure 25. - United Stirling 4-275 engine.

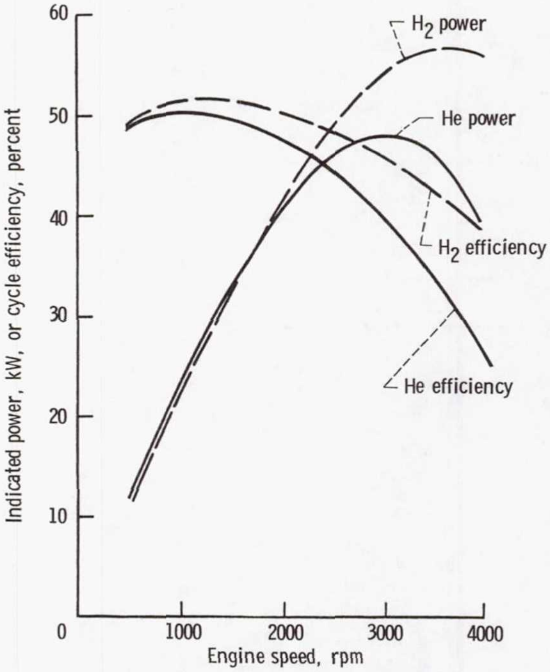


Figure 26. - Comparison of H_2 and He optimized Stirling engines. Cylinder temperature, 704° C; heater tube temperature, 724° C; cooler temperature, 57° C; pressure, 100 bar.

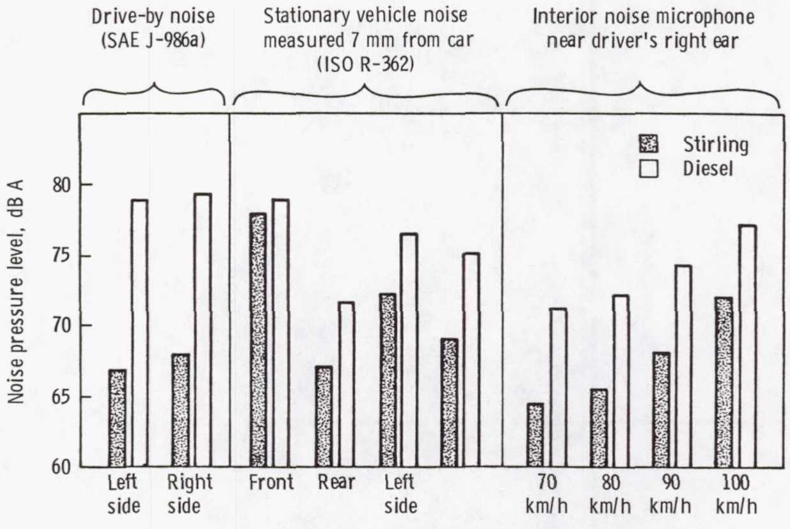


Figure 27. - Comparison of Stirling and diesel noise in an Opel Rekord automobile.

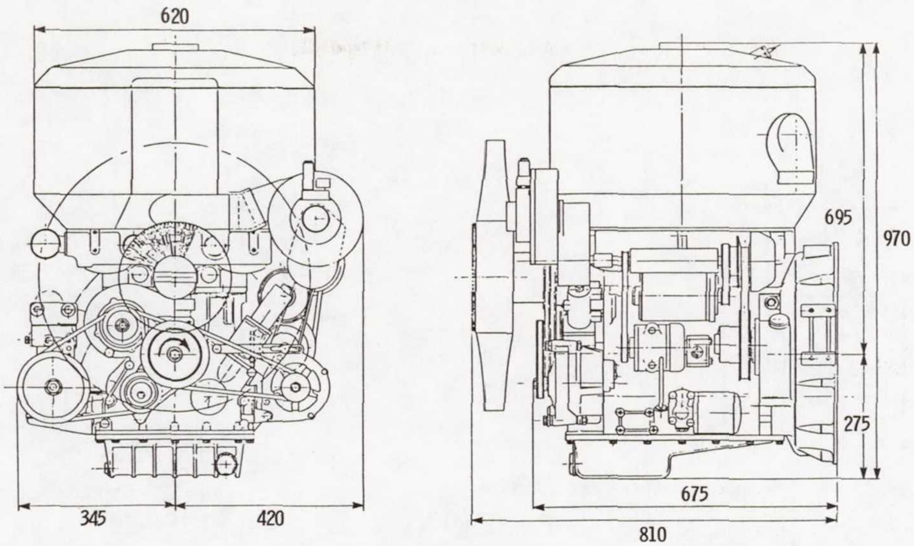


Figure 28. - United Stirling 4-275 engine overall dimensions; dry weight, 350 to 400 kg, depending on equipment; weight-power ratio, 4.7 to 5.3 kg/kW (7.7 to 8.8 lb/bhp); volume-power ratio, 8.01 liters/kW (0.213 ft^3/hp). (All dimensions are in centimeters.)

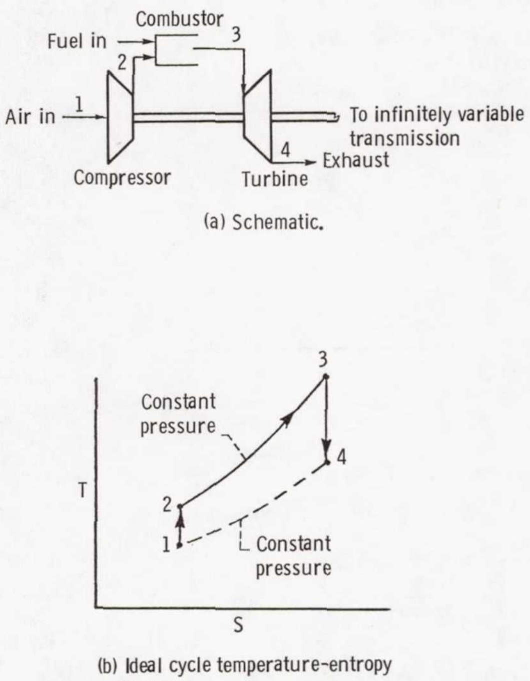


Figure 29. - Simple open Brayton cycle.

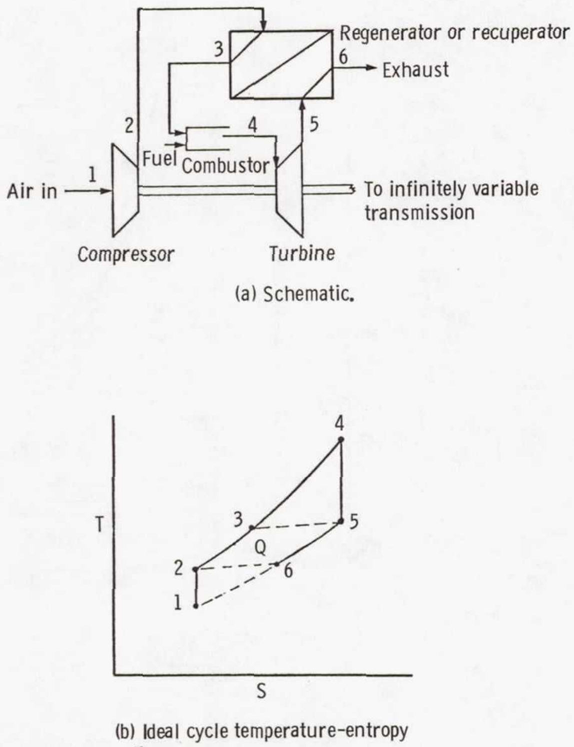


Figure 30. - Regenerated open Brayton cycle.

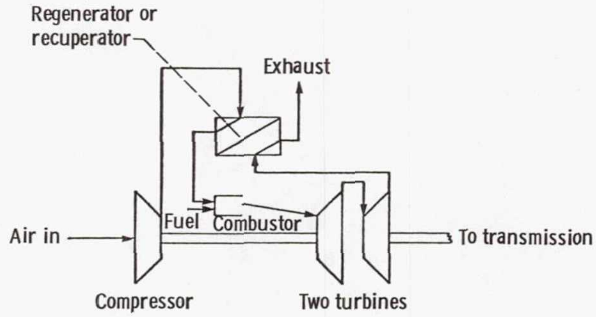


Figure 31. - Diagram of a two-shaft, heat-recovery-cycle gas turbine engine.

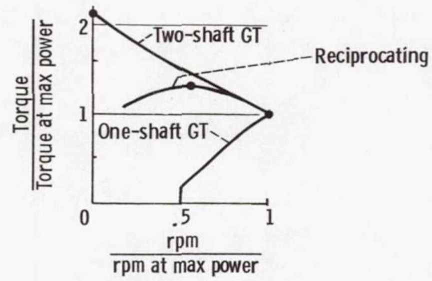


Figure 32. - Engine torque-speed characteristics.

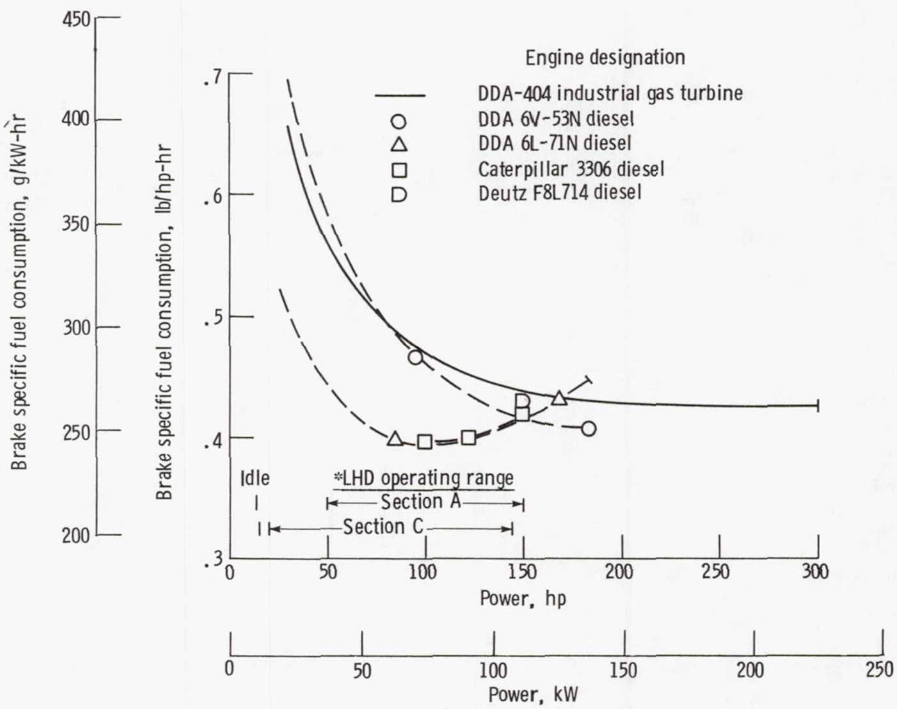


Figure 33. - Fuel economy, industrial gas turbine vs. naturally aspirated diesels. (*Refers to duty cycles for mine sections described in (1).)

(a) Surfaces exposed to compressor discharge air temperature
(b) Combustor dome
(c) Exhaust duct not shown

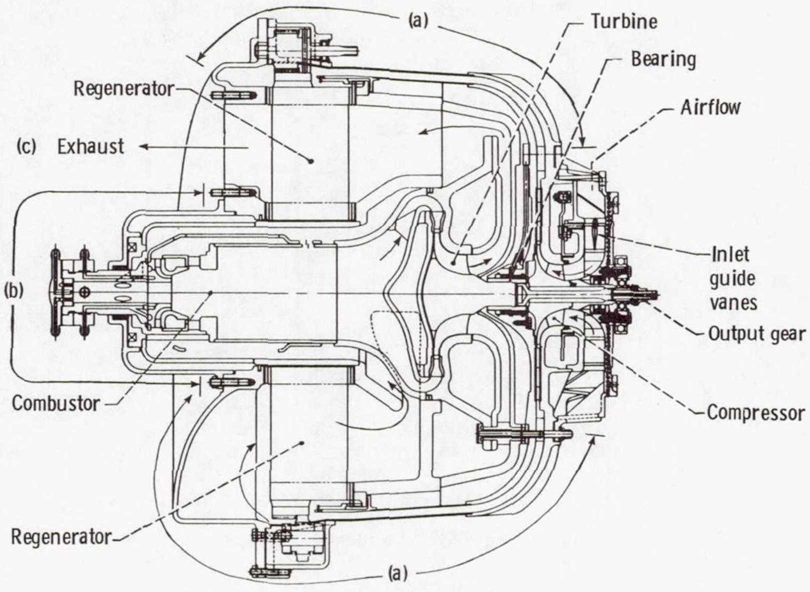


Figure 34. - AGT-101 single-shaft engine.

External surfaces exposed to
(a) Compressor discharge air temperature
(b) Combustor inlet air temperature
(c) Power turbine exit gas temperature
(See fig. 36)

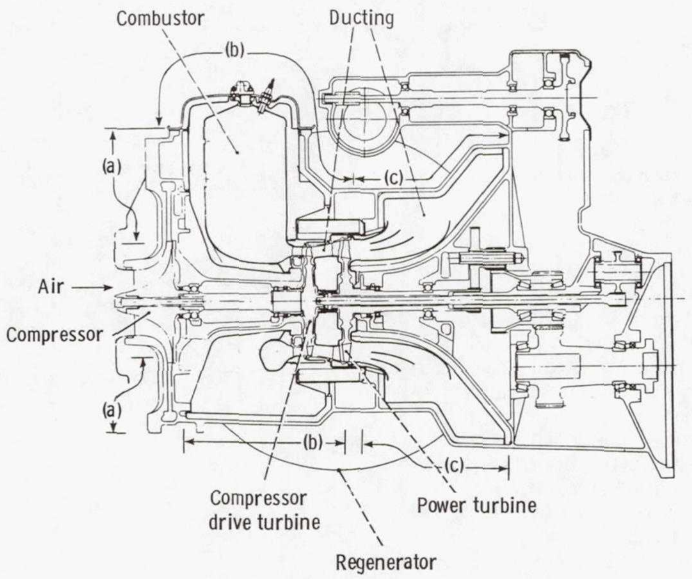


Figure 35. - IGT two-shaft engine.

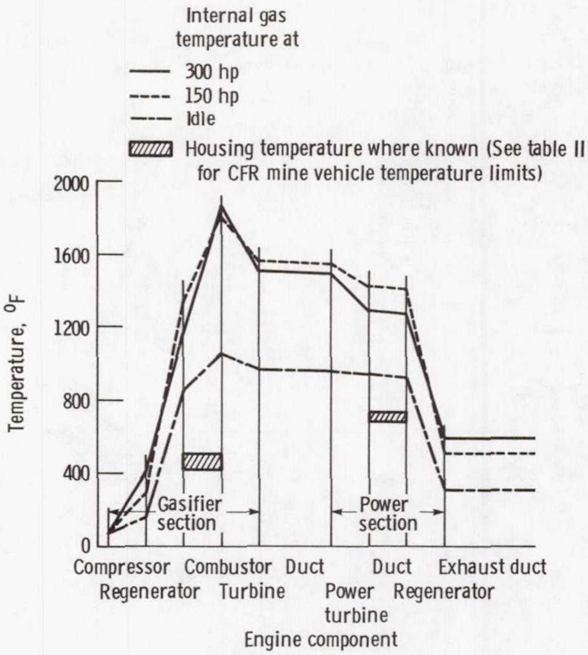


Figure 36. - IGT gas turbine temperatures.

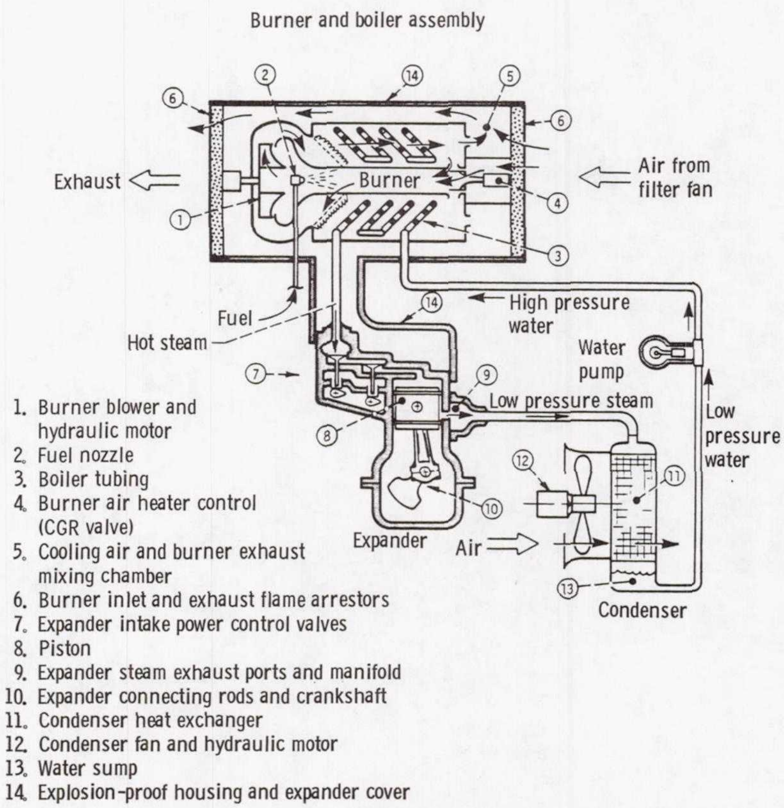


Figure 37. - Schematic of mining steam engine without control functions.

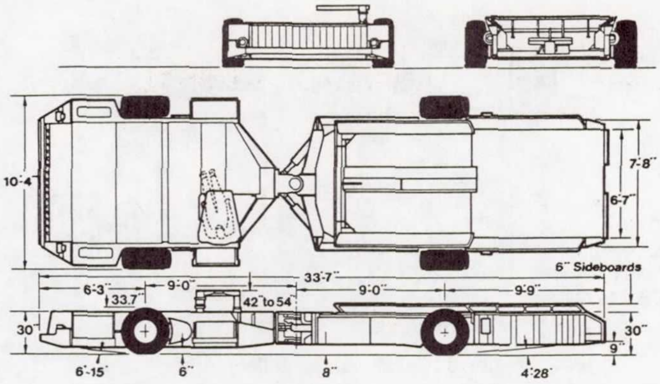


Figure 38. - Steam-powered RAMCAR general layout.

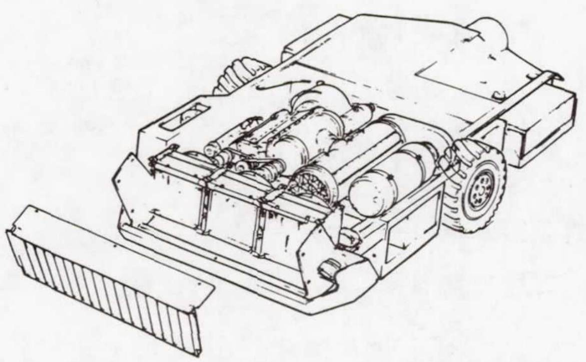


Figure 39. - Artist sketch showing grill removed and bumper dropped for engine removal.

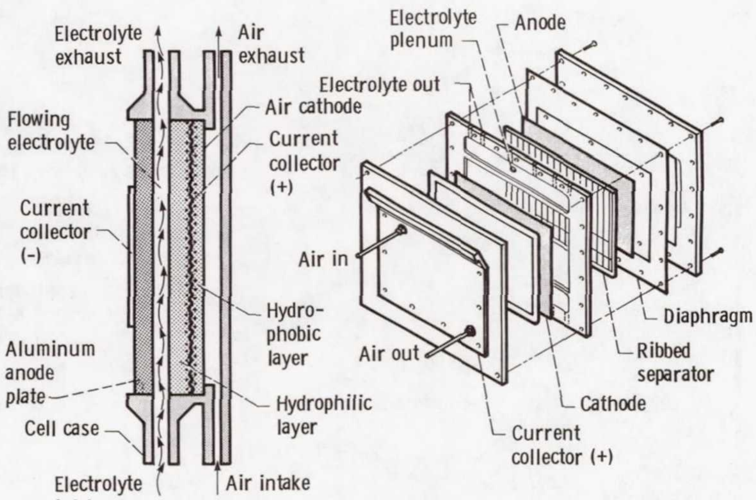


Figure 40. - Aluminum-air cell.

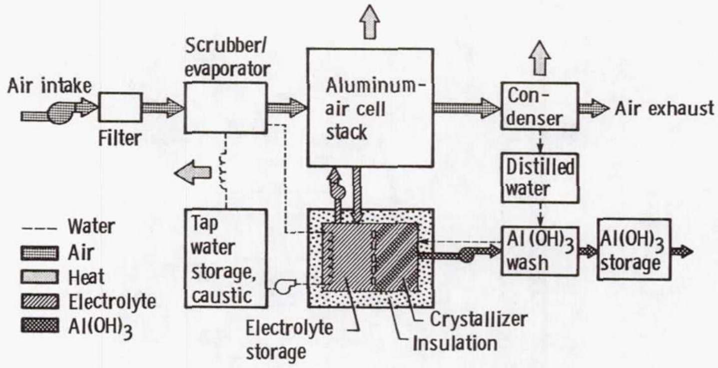


Figure 41. - Aluminum-air battery system.

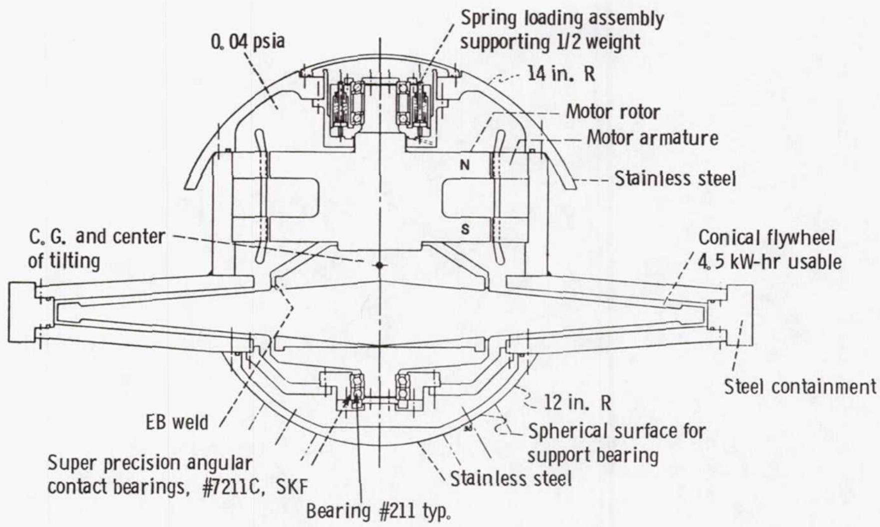


Figure 42. - Flywheel capsule (4.5 kW-hr).

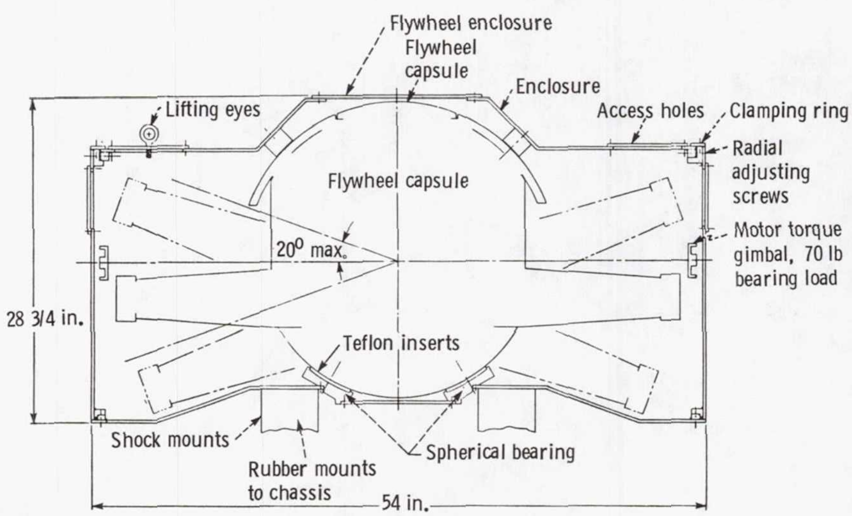


Figure 43. - Flywheel package (4.5 kW-hr).

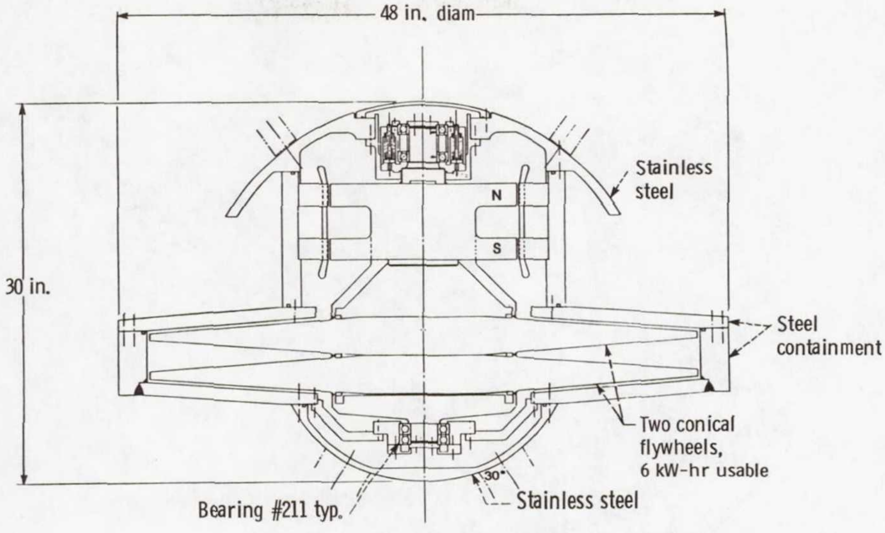


Figure 44. - Flywheel capsule (6 kW-hr).

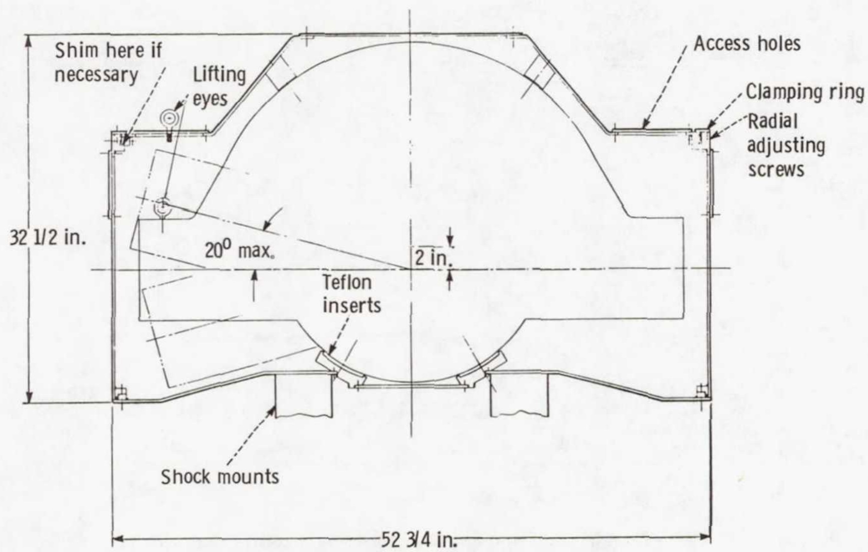


Figure 45. - Flywheel package (6 kW-hr).

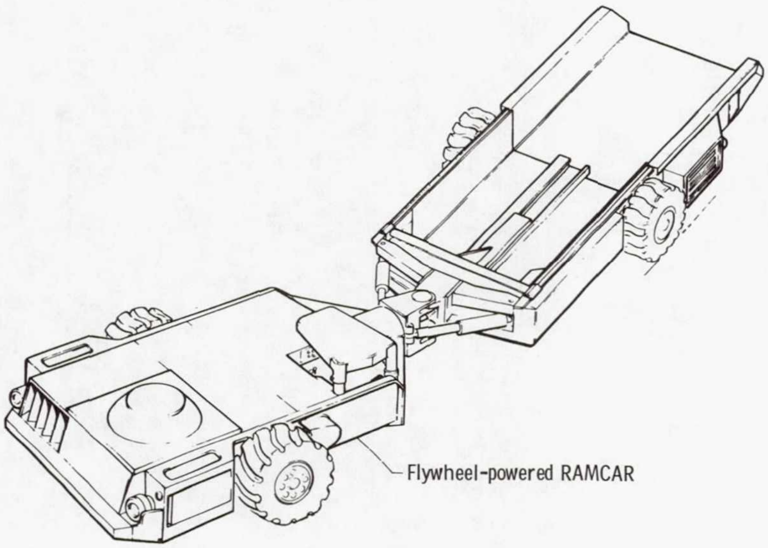
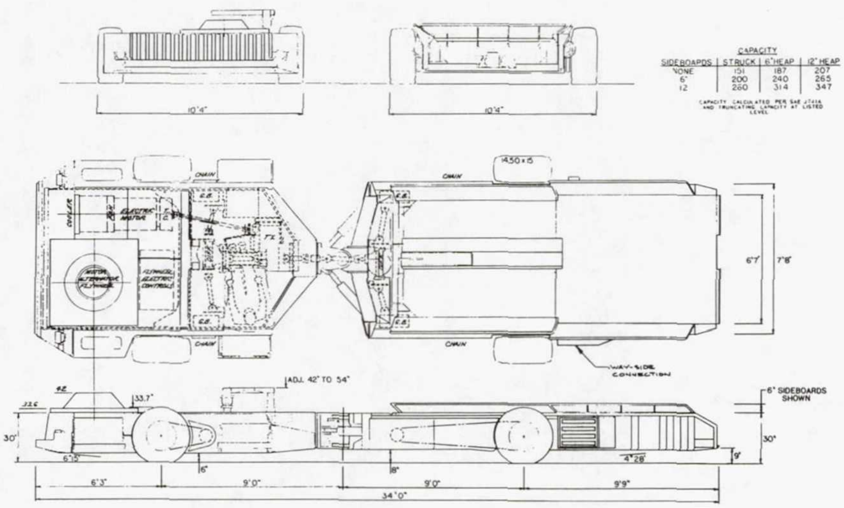


Figure 46. - Artist sketch; flywheel-powered RAMCAR.



	CAPACITY		
SIDEBOARDS	STRUCK	6" HEAP	12" HEAP
NONE	151	187	207
6"	200	240	265
12	260	314	347

CAPACITY CALCULATED PER SAE J741A AND TRUNCATING CAPACITY AT LISTED LEVEL

Figure 47. - Overall vehicle configuration for flywheel-powered Ramcar.

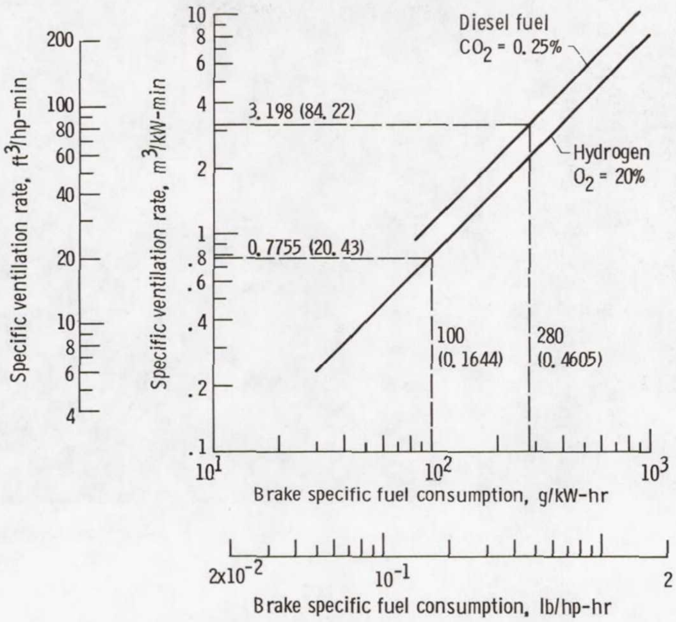


Figure 48. - Comparison of specific ventilation rate (SVR) for engines operating with hydrogen and no. 2 diesel fuels vs. brake specific fuel consumption (BSFC).

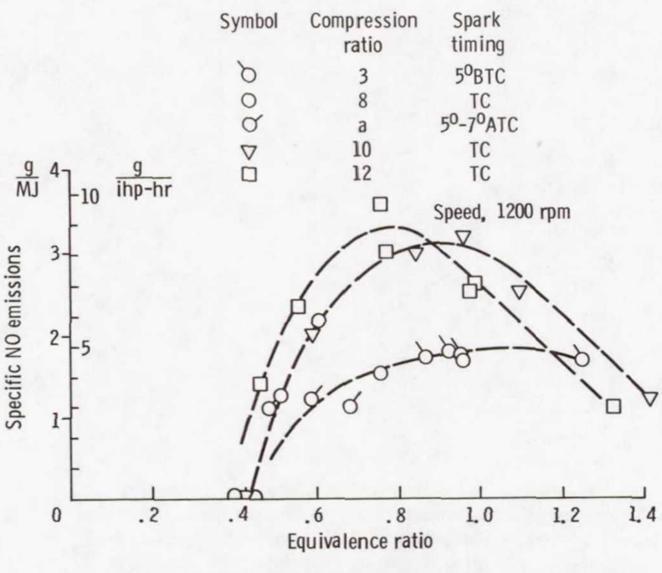


Figure 49. - Specific NO emissions as a function of equivalence ratio, for various compression ratios. Engine speed, 1200 rpm; spark timing as indicated.

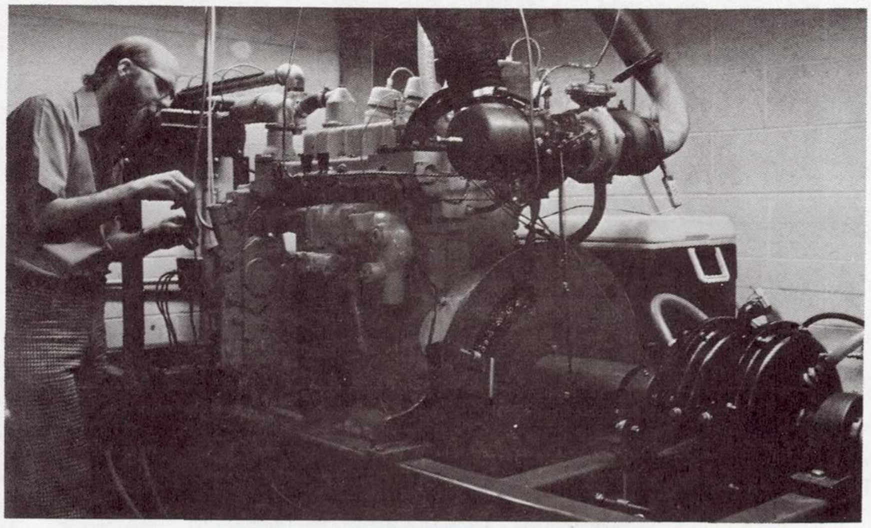


Figure 50. - Caterpillar engine modified for hydrogen operation on test at Denver Research Institute.

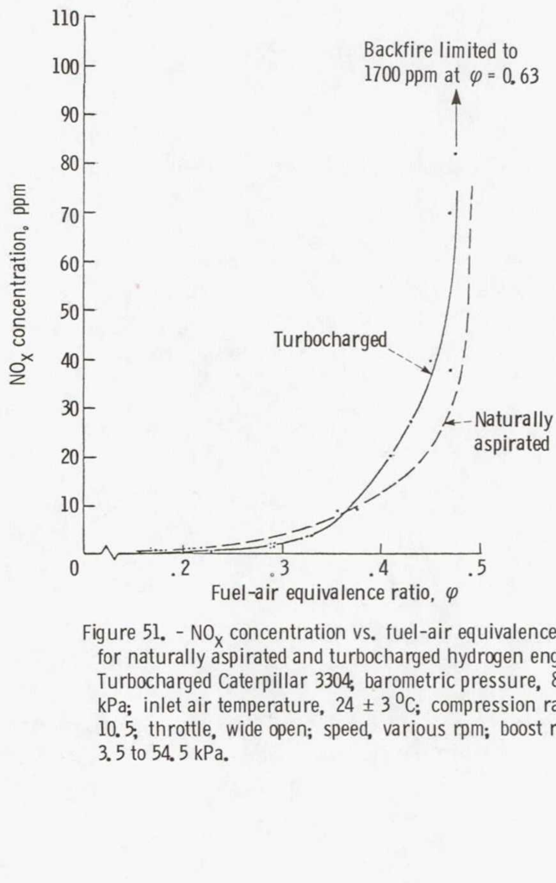


Figure 51. - NO_x concentration vs. fuel-air equivalence ratio for naturally aspirated and turbocharged hydrogen engines. Turbocharged Caterpillar 3304; barometric pressure, 83.3 kPa; inlet air temperature, 24 ± 3 °C; compression ratio, 10.5; throttle, wide open; speed, various rpm; boost range, 3.5 to 54.5 kPa.

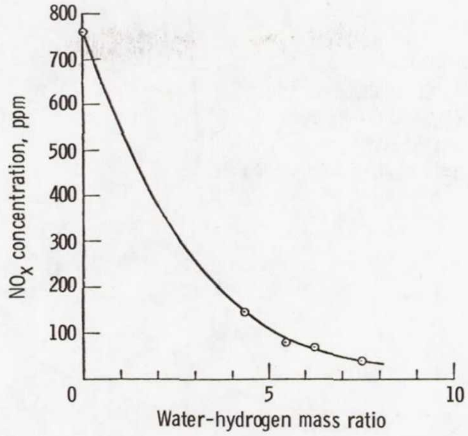


Figure 52. - Effect of water injection on a hydrogen bus engine. Spark, 14^0 BTC; compression ratio, 12; equivalence ratio, 0.60; engine speed, 3000 rpm; barometric pressure, 25.3 in. Hg; inlet air temperature, 30 ^{0}C.

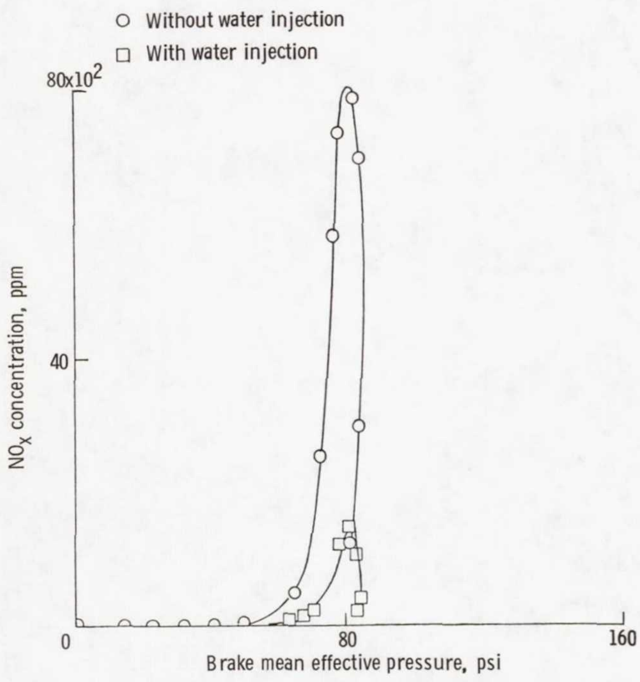


Figure 53. - Comparison of NO_x emissions with and without water injection.

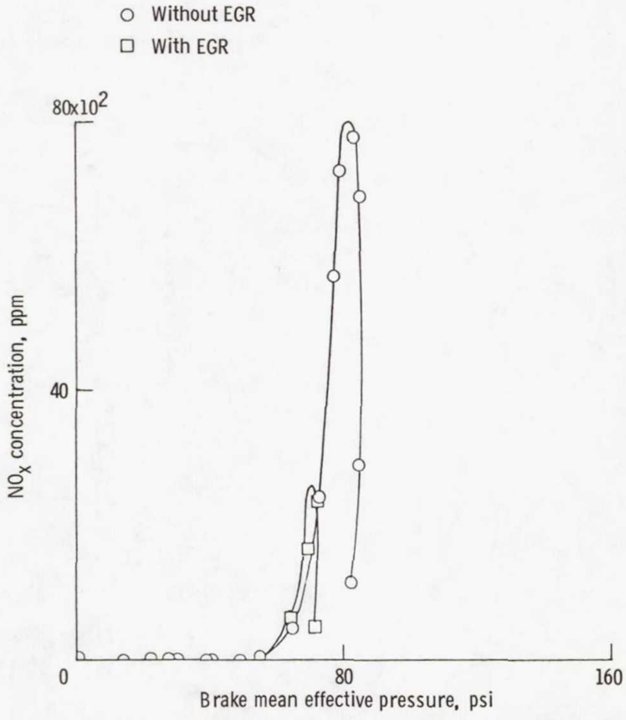


Figure 54. - Comparison of NO_x emissions with and without exhaust gas recirculation.

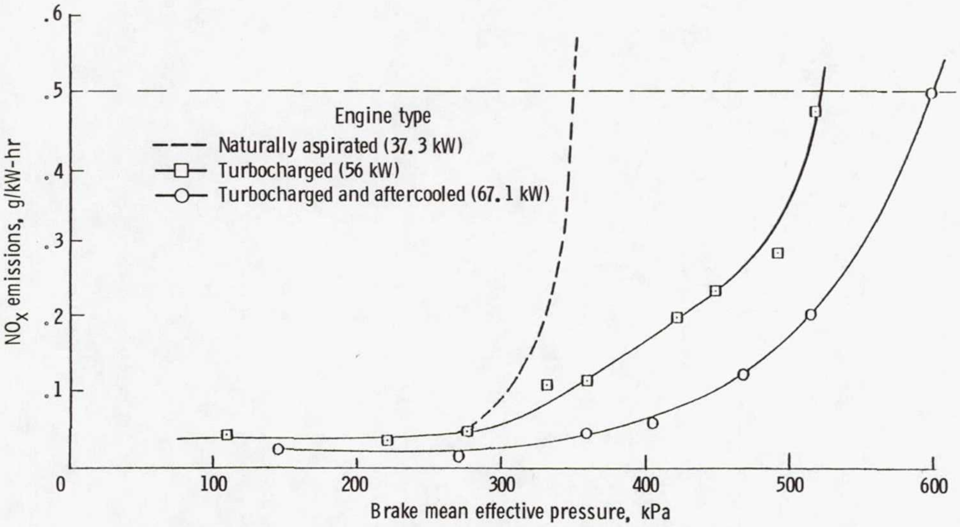


Figure 55. - Brake specific NO_x emissions vs. brake mean effective pressure for naturally aspirated, turbocharged, and turbocharged-aftercooled hydrogen engines. Turbocharged Caterpillar 3304; barometric pressure, 83.3 kPa; inlet air temperature, 24 ± 3 °C; compression ratio, 10.5; throttle, wide open; speed, 1800 rpm.

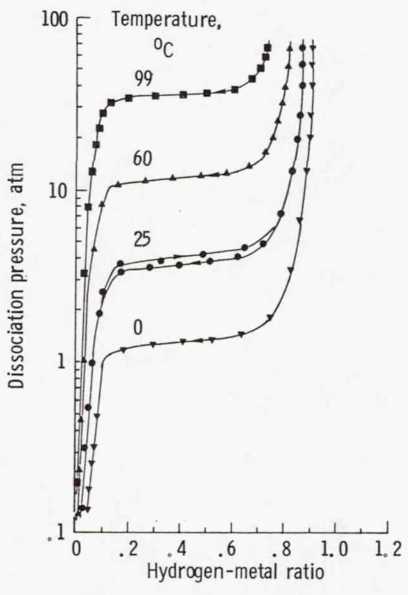


Figure 56. - Various isotherms for $MNi_{4.5}Al_{0.5}$ annealed 4 hr at 1125° C.

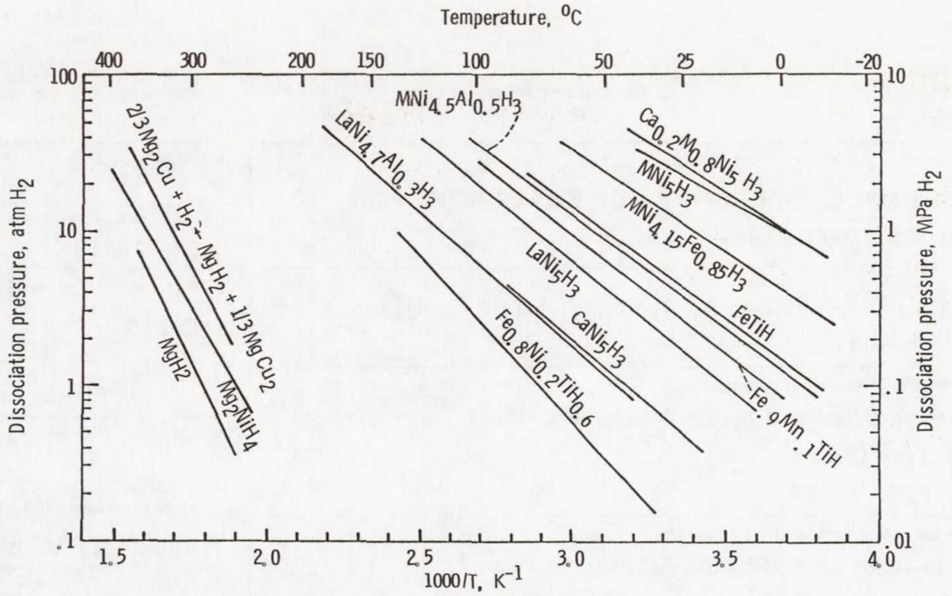


Figure 57. - Van't Hoff plots (desorption) for various hydrides.

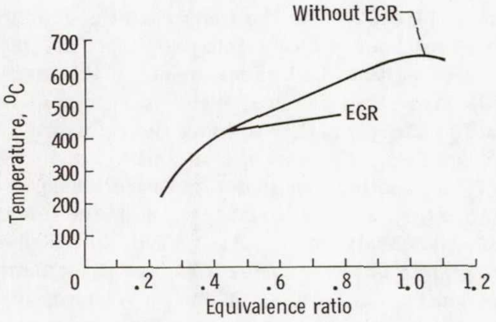


Figure 58. - Exhaust gas temperature for hydrogen-fueled engine. Engine speed, 1800 rpm; inlet air temperature, ~24 °C.

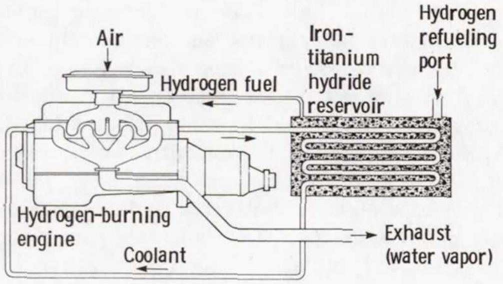


Figure 59. - Hydrogen storage heated by engine coolant.

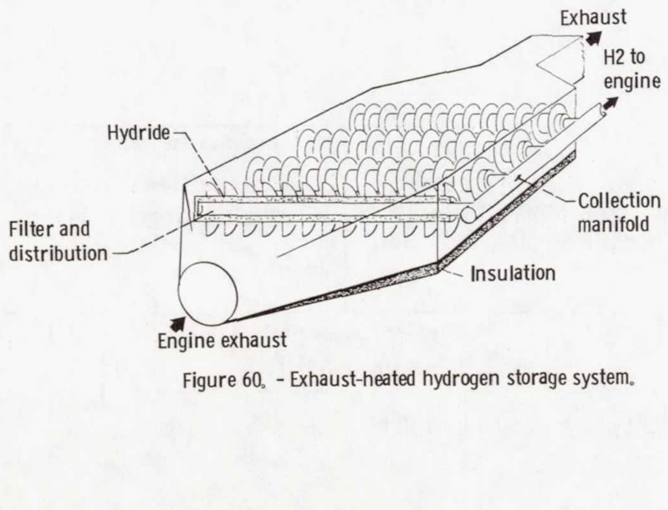


Figure 60. - Exhaust-heated hydrogen storage system.

1. Report No. NASA TM-82695	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle ASSESSMENT OF ALTERNATIVE POWER SOURCES FOR MOBILE MINING MACHINERY		5. Report Date
		6. Performing Organization Code 778-18-12
7. Author(s) James E. Cairelli, William A. Tomazic, David G. Evans, and John L. Klann		8. Performing Organization Report No. E-978
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		10. Work Unit No.
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Memorandum
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The NASA Lewis Research Center, under Interagency Agreement J0100026 with the Department of Interior, Bureau of Mines, has performed an assessment of alternative power sources for mining applications, primarily mobile underground equipment. This report presents the results of that assessment. Each candidate alternative power source was assessed in terms of the following requirements, which were established as a first step in the assessment: (1) ability to achieve the duty cycle, (2) ability to meet Government regulations (MSHA certification), (3) availability (production readiness), (4) market availability, and (5) packaging capability. An initial screening reduced a variety of possible candidates to the following, which were evaluated in more detail: (1) improved diesel, (2) Stirling, (3) gas turbine, (4) Rankine (steam), (5) advanced electric (batteries), (6) mechanical energy storage (flywheel), and (7) use of hydrogen evolved from metal hydrides. The candidate power sources were divided into two categories - heat engines and energy storage systems - since the basic constraints are different for each. Heat engines are basically limited by emissions; energy storage systems are limited by energy storage density. Each alternative power source is described briefly, including its current development status, specific problem areas, and possible future improvements. Each candidate is then evaluated against the requirements initially established. Research and development efforts for each candidate power source are discussed and evaluated in terms of potential. Recommendations are made for each power source in terms of possible near-term or future application to mining use and the specific problem areas that must be addressed prior to that application.

17. Key Words (Suggested by Author(s)) Heat engines; Energy storage; Stirling; Diesel; Gas turbine; Steam engine; Emissions; Underground mines; Hydrogen fuel; Hydrides; Batteries; Flywheel		18. Distribution Statement Unclassified - unlimited STAR Category 44	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price*

* For sale by the National Technical Information Service, Springfield, Virginia 22161