DESIGN CONSIDERATIONS FOR MICRO NUCLEAR REACTORS TO SUPPLY POWER TO OFF-GRID MINES

B. Gihm[1], G. Cooper[1], D. Morettin[1], P. De Koning[1], M. Carreau[2] and J. Sarvinis[1]
[1] Hatch Ltd., Mississauga, Ontario, Canada
(E-mail of corresponding author: bgihm@hatch.ca)
2 Hatch Ltd., Montreal, Quebec, Canada

Abstract

Nuclear technology vendors have been proposing to develop small scale nuclear reactors to supply power and heat to remote industrial operations such as a mining site. Based on extensive experience in integrating different power generation technologies with captive mining power systems, Hatch examined the technical requirements of small scale nuclear reactor application in remote mine power generation.

Mining power systems have unique characteristics and challenges that set them apart from utility grid connected power systems. Key examples of such unique characteristics are:

- A small number of large motor loads such as hoists, pumps, shovels, pumps and crushers represent a large fraction of the peak load. These equipment may cause significant load fluctuations and put the power systems under high stress.
- There is no organic demand growth (i.e., the load growth occurs as a step increase)
- The extreme environmental conditions and remoteness of the sites introduce a set of operational challenges and require specialized planning.

This paper presents real remote mine operation data to demonstrate the load profile of remote mining sites. The operation characteristics and performance requirements of diesel reciprocating engines are discussed, which have to be matched or exceeded by a small scale nuclear power plant if it is to be a viable technical alternative to diesel power. The power quality control options from wind power integration in isolated grids are discussed as a parallel can be drawn between wind and nuclear power application in remote mine power systems. Finally the authors provided a list of technical constraints and design considerations for very small modular reactor development.

1. Introduction

A review of the current small modular reactor (SMR) development proposals reveals that their intended applications generally fall under two categories. First, SMRs are proposed to reduce the financial risk of a new nuclear power plant project with lower initial capital requirements and shortened construction time. The examples of reactors that belong in this category are mPower™, NuScale™ and SMART. Second, very small reactors are proposed to supply electricity to remote off-grid power markets such as Northern Canadian communities and mining sites. The examples of reactors that belong in this category are Toshiba 4S, Gen4Module, StarCore, and Radix Power Systems.

The proponents of very small modular reactors (VSMRs) have identified that many of northern communities and remote industrial sites are dominantly served by fossil fuel generated heat and electricity, and the communities and corporations are exposed to fuel supply logistics challenges and high fuel cost. The proposed solution to lower power costs at remote locations is to replace the diesel reciprocating engines (gensets) with small nuclear reactors. Considering that electricity costs at remote locations often exceed $1.00/kWh, VSMR seems to be a commercially viable technology at some sites.

The mining industry has been at the forefront of technology development and adaptation. For instance, the world's first AC power system installations was the 75 kW hydro power plant at King Gold Mine in Telluride, Colorado in 1891, built several years ahead of the Niagara Falls power station [1]. In the authors' opinion, remote mining sites consuming 10 to 100 MW of electricity are the most probably first adapters of VSMR technology, rather than remote communities; i.e., most remote communities only require 1~2 MW of peak power [2] which can be adequately provided with renewable power sources and energy storage devices.

In examining a few VSMR concepts, the authors noticed the lack of end-user requirements and system integration discussions for VSMRs; it seems that the technology vendors are simply assuming that VSMRs will supply power to a grid as a base-load generator with some load following capability. In a captive power system, the supply and load must be actively managed from the entire system perspective. Mining equipment typically consists of very large reactive components and the power systems are exposed to large load swings; thus, the flexibility and ruggedness of the power supplies are very important. Redundant generating capacity is also required to ensure uninterrupted power during forced outages of generating equipment and to allow for maintenance activities. The vendors need to approach VSMR design as a part of the power system design project, with adequate considerations for the mining micro-grid characteristics and behaviours.

Hatch offers unique expertise in the design of captive power systems for remote mining operations employing reciprocating engine, steam turbine, and combustion turbine driven generators. As remote mines have adapted renewable power technology to offset diesel power generation in recent years, Hatch has been developing renewable power integration strategies including developing a proprietary smart grid controller technology. The authors expect that VSMRs will encounter a unique set of system integration challenges in remote mining applications which must be identified and addressed during the early technology development period.

In this paper, the authors will discuss the typical mine power system characteristics and requirements and recommend technical considerations for small nuclear power systems in remote mining applications.

2. Brief Description of Mining Operation

At remote mining locations, minerals with high commercial value such as gold, diamond, nickel and iron ores are typically mined (e.g., Baffinland Iron Mines, Northern Baffin Island, Nunavut). Since the minerals have transported to the market or other refinery facilities, and the associated transportation cost is generally high, the mined ores are processed to increase the mineral concentration (i.e. gold concentration in ore is typically 2~5 ppm). After ores are extracted from the ground, they are typically crushed, milled and/or processed by floatation processes. In some cases, minerals are smelted on site to final product to further decrease the transportation burden; however, smelting requires significant energy, and it is only performed when a low cost source of electricity is available at site.

2.1 Load Changes

The load cycle in a captive mine power system differs noticeably from that in a typical residential and commercial grid system. In a residential/commercial grid, the load is slowly varying and it is often cyclical throughout a day and the total average load is a function of changes in population and societal economic condition; i.e., electricity demand generally follows diurnal human activity cycle, and there is ‘natural’ load growth or decrease.

In a mining power system, the long term load changes follow the staged mine development schedule. Mine sites are developed and expanded in repeated stages in which all loads are installed and brought online within a short time period. Frequently, a mine has several different excavation sites over a broad area that spans tens of kilometres, which are supported by high voltage transmission lines or with separate power plants. There is no ‘natural’ load change following a completion of a development stage, and the load is generally flat throughout the day since mines are in operation 24 hours a day. Similarly, the seasonal load changes are minimal.

2.2 Load Types

The mine loads consist of operation support components (e.g., residential quarters and office buildings) and pit and processing operations components (e.g., excavation and ore processing equipment). The former consists of relatively smaller loads in comparison to the later which includes large machines that consume significant power relative to the overall power system capacity. Excavation and ore processing typically include following equipment:

- Drilling machines, hoists, conveyor belts and shovels
- Ventilation, heating and cooling
- Crushers, mills, cyclones, dryers
- Various pumps
- Smelters

Many of these operational loads are motor loads which draw several times more power at the start up, and require a significant portion of reactive power. Table 1 shows large block loads greater than 200 horse power (hp) and their key characteristics at a northern Canadian mine site (site name withheld for commercial reasons) consuming an average power of 11.5 MW. As it can be seen in the table, some loads represent a large fraction of the total load (i.e. rod mill consuming 14% of the total load) and a few equipment draw large inrush current at machine start-ups (i.e. vacuum pump drawing 4161 kVA).

Description	HP	Starter Type[1]	Volts	FLA[2]	LRA[3]	Inrush Current	Starting kVA
Primary Jaw Crusher	400	FVNR	4160	52.1	7.6	395.96	2853.02
Secondary Cone Crusher	400	FVNR	4160	52.1	7.6	395.96	2853.02
Lump Floats Cone Crusher	400	FVNR	4160	52.1	7.6	395.96	2853.02
Lump Floats Cone Crusher Dust Collector Fan	450	FVNR	4160	57.2	7.6	434.72	3132.30
DMS Cyclone Feed Pump	250	VSD	600	222.61	N/A	445.22	462.69
Rod Mill	1750	VSD	4160	251.54	N/A	503.08	3624.86
Secondary Desliming Cyclone Feed Pump	400	VSD	600	352.05	N/A	704.1	731.72
Spiral Tailings Pump	250	VSD	600	222.61	N/A	445.22	462.69
Vacuum Pump	600	FVNR	4160	76.0	7.6	577.6	4161.80
Reclaim Water Pump	450	FVNR	4160	57.2	7.6	434.72	3132.30
Process Water Pump	350	VSD	600	303.86	N/A	607.72	631.56
Process Water Flush Pump	300	FVNR	4160	38.4	7.1	272.64	1964.46
Fire Water Electric Pump	400	FVNR	4160	52.1	7.6	395.96	2853.02

Table 1 Large block load electrical characteristics

3. Power System Behaviour at a Remote Mine

The electrical load profiles presented in this section (Figure 1 to Figure 10) is the actual operational data from a remote mine in Canada, covering one year period starting from June 1, 2013. The site name and locations are withheld to protect commercial interests of the operator.

The remote mining site in consideration is located in Northern Canada in a semi-desert arctic region of permafrost. The yearly mean temperature at the site is approximately -10 ºC, and the minimum temperature at the site can be as low as -50 ºC. The mine properties are spread over an area spanning approximately 80 km in distance. Most activities are currently occurring at the main mine (mine #1) but the operation is expanding to include several satellite mines, including a few that already have been developed.

Currently, the site operation is mainly supported with fossil fuel generated heat and electricity with low level penetration of wind-generated electricity. The current peak electricity and heat demands at the mine are 23 MWe and 17 MWth, respectively. The electricity and heat demand is increasing due to new mines being developed, and the total electricity demand is projected to be over 70 MW when the site is fully developed.

[1] FVNR: Full Voltage Non-Reversing, VSD: Variable Speed Drive
[2] FLA: Full Load Amperes
[3] LRA: Locked Rotor Ampere

The main mine is currently supported with 6 EMD gensets (3.6 MW each) and 5 Caterpillar gensets (3 × 1.8 MW and 2 × 1.1 MW units), with the satellite mines supplied locally with additional Caterpillar gensets or via high voltage transmission line from the main site.

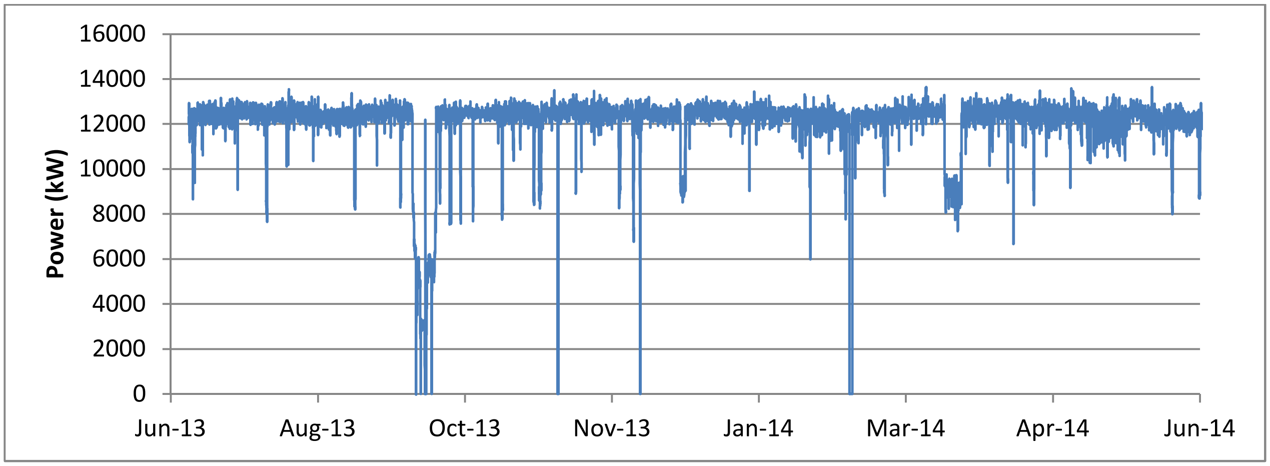

Figure 1 EMD power plant output at Mine #1

Figure 1 shows that the electrical load at Mine #1 is flat throughout the year with minimal seasonal variation. The total generation capacity of EMD plant is 21.6 MW (6 gensets × 3.6 MW). However the plant is operated with only 4 units operating at ~80% capacity, with 1 unit in hot standby and 1 unit in cold standby or undergoing maintenance. This configuration referred to as N+2 redundancy, and is typical at remote mining operations. In case of a genset unit failure, the other 3 units are able to operate at 110% capacity for up to 1 hour while the hot standby unit ramps up to full capacity.

The load profile shows several occasions when the load drops to zero. These are generally representative of intermittent mining process equipment outages, and seasonal maintenance closures. The captive power system must provide flexibility to accommodate these planned and unplanned load changes. Figure 2 shows an individual EMD generator power output in the same period.

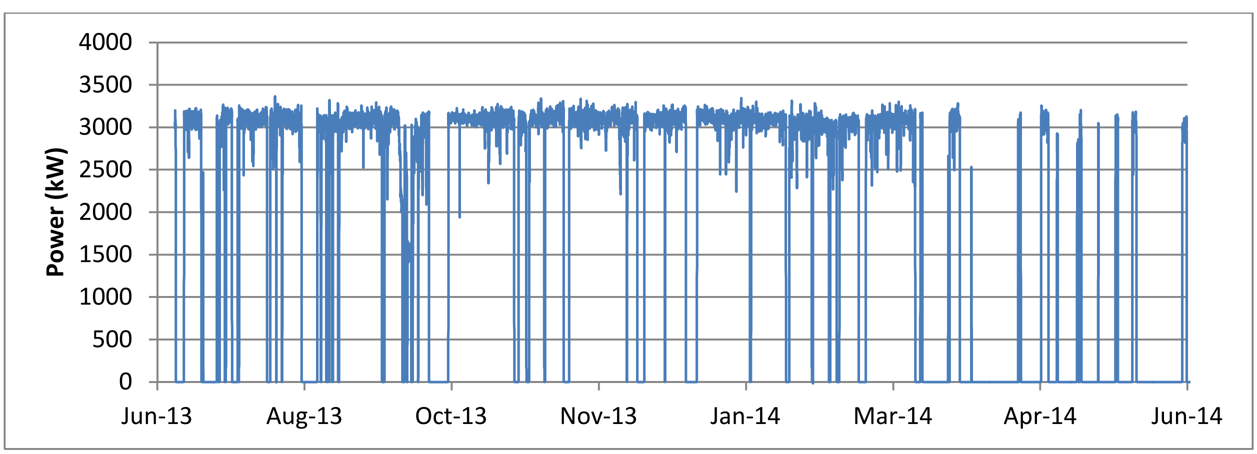

Figure 2 EMD plant generator #1 output

Figure 3 shows the EMD plant electricity output on March 1, 2014. As discussed in Section 2.1, cyclical daily load changes are not observed and the load is nearly flat throughout the day. However, approximately 10% load fluctuations within minutes are observed which can be attributed to a major electrical load starts and shutdowns.

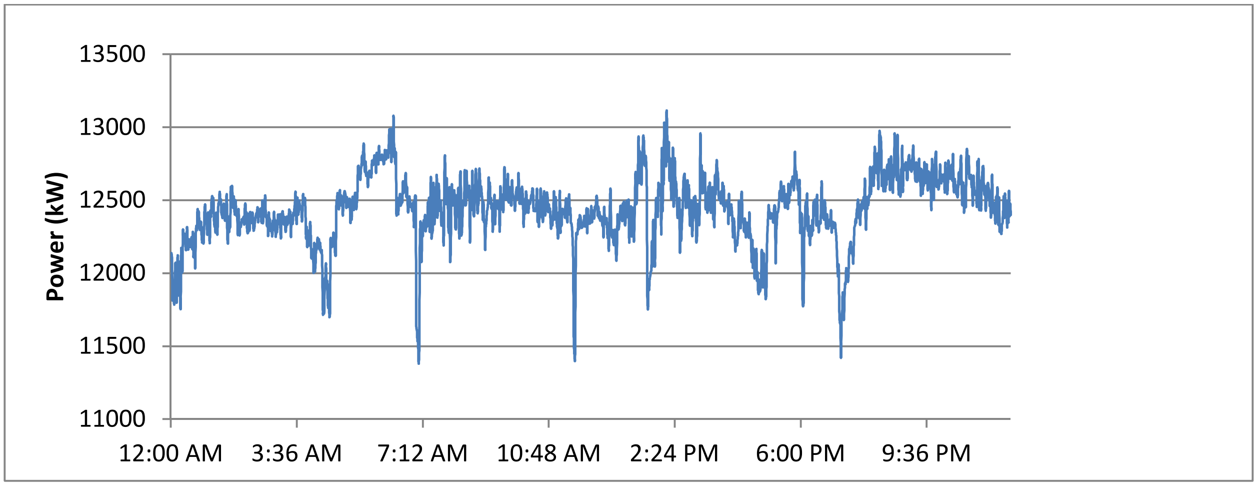

Figure 3 EMD plant electricity output fluctuations in a single day

Figure 4 shows the Caterpillar plant output at mine #1. The plant has 4+1 redundancy, and it is operating below 50% peak capacity most of the time.

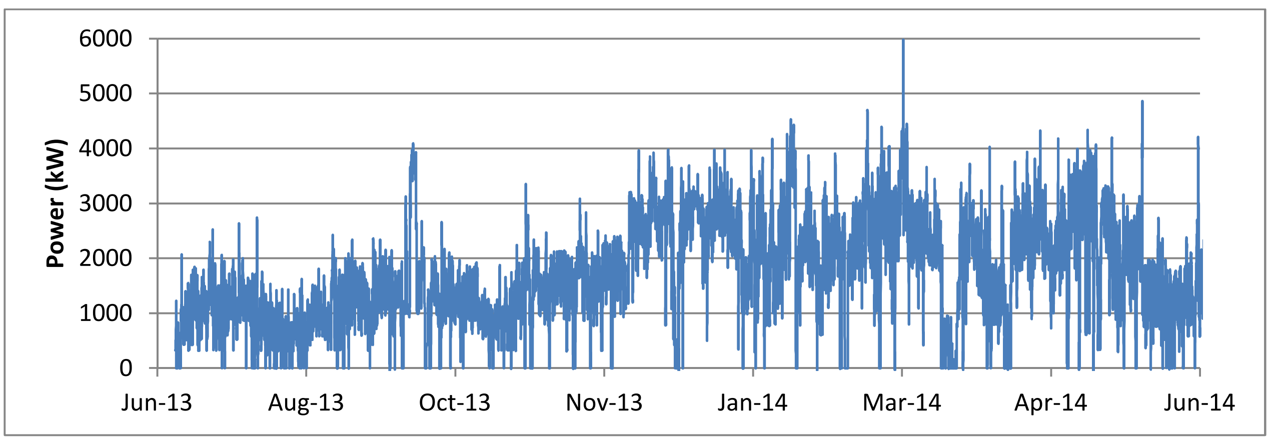

Figure 4 Caterpillar power plant output at Mine #1

Figure 5 and Figure 6 show the respective power output of the Caterpillar plant and its individual gensets on March 1, 2014. Although the total power output of the plant seems to be flat during the day, the individual genset response in Figure 6 reveals that the gensets are subject to rapidly varying load fluctuation, including 100% load loss.

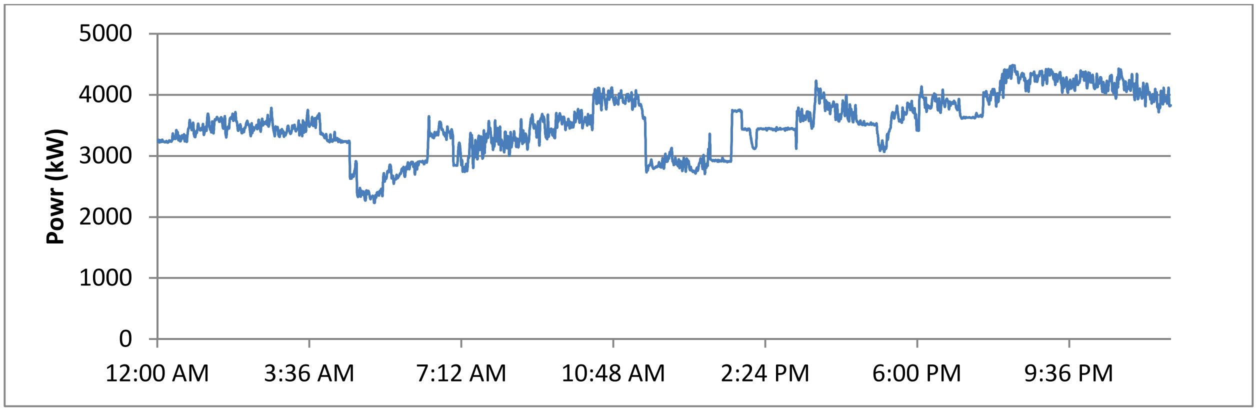

Figure 5 Caterpillar plant power output on March 1, 2014

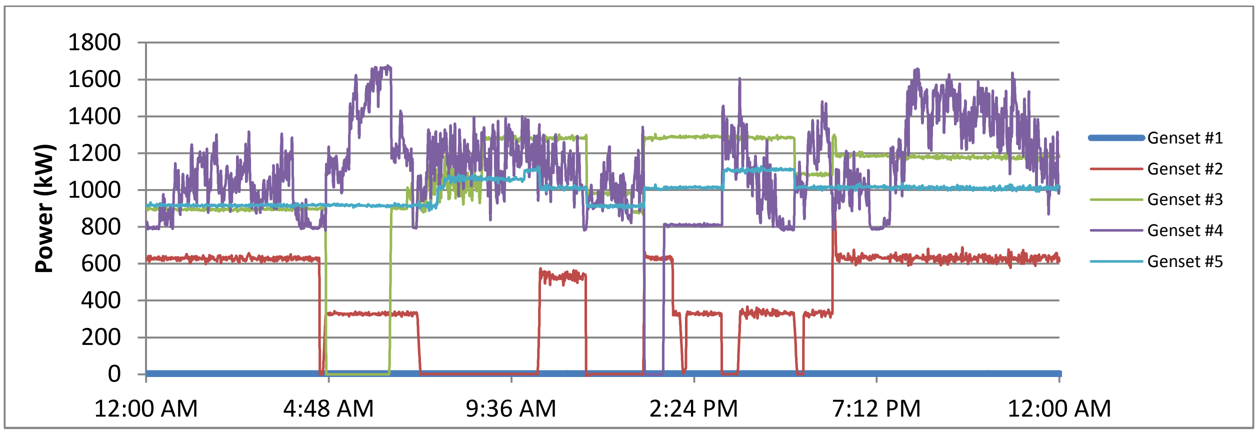

Figure 6 Caterpillar plant individual genset power output in a day

Figure 7, Figure 8, and Figure 9 show the generator responses at start-up mine locations (e.g. mine #2, #3, and #4). As systems and equipment are being installed and commissioned, the load fluctuations are more severe than those at a mature mine. In Figure 9, it can be observed that the generator is faced with ±100% load fluctuations due to motor start-ups and sudden load losses. Figure 10 shows that the generator faced a total load loss between 7:05 am and 7:17 am.

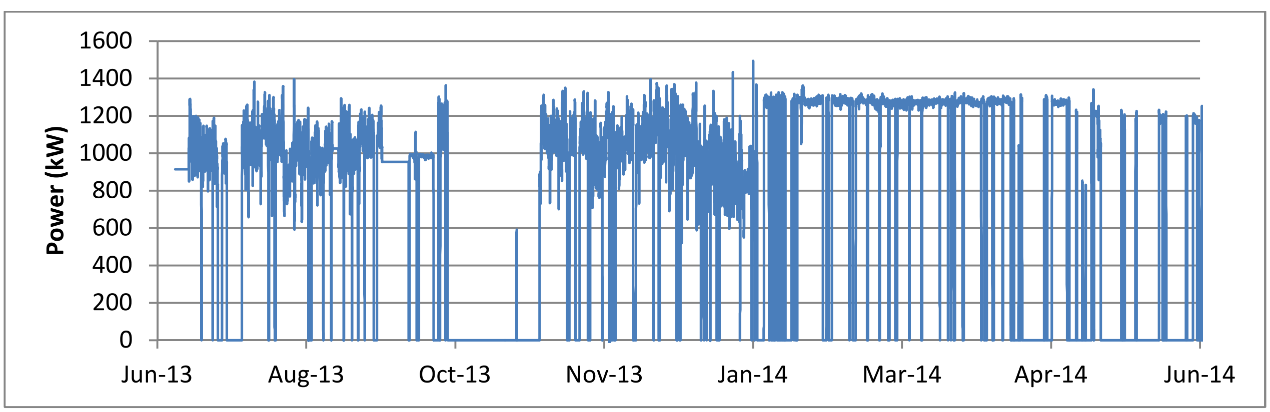

Figure 7 Load fluctuations at Mine #2

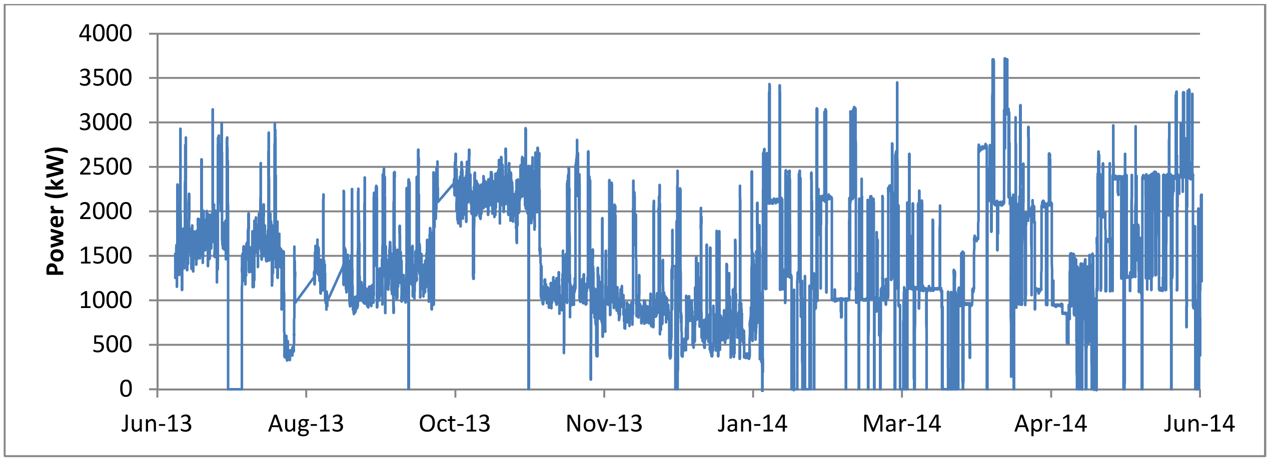

Figure 8 Load fluctuations at Mine #3

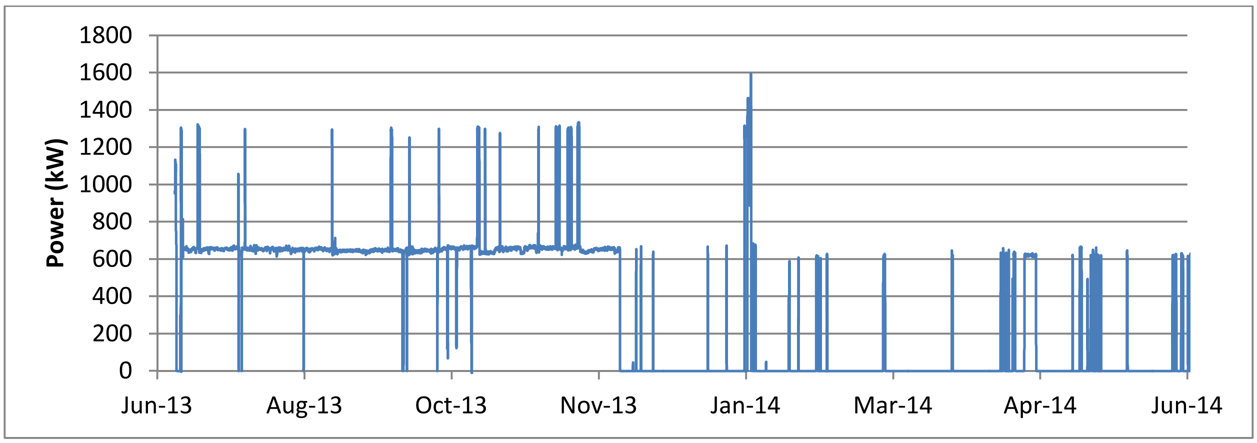

Figure 9 Load fluctuations at Mine #4

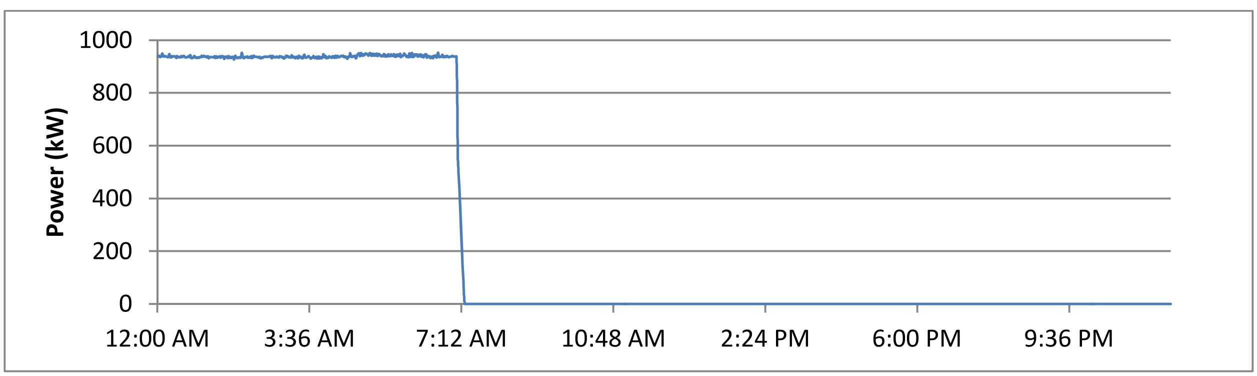

Figure 10 Complete load loss at Mine #3 on March 1, 2014

4. Wind/Diesel Integration in Remote Mine Power System

The rationale behind employing renewable electricity sources at mining sites is similar to the argument of using a small nuclear power in remote mining; i.e., they are price competitive with diesel-based power generation and eliminate fuel transportation challenges. Remote mines have been grappling with the power cost for many years, and several companies have started employing renewable power sources such as wind and solar photovolatics to reduce the power cost at mines. The examples of companies adapting renewable power are Rio Tinto's Diavik mine in Northwest Territories, Barrick's Veladero mine Argentina and Glencore Xstrata's Raglan mine in Quebec.

More complex control systems are required to integrate wind power in a grid because of the generation intermittency. If the wind power is integrated with a system with a slowly changing load such as residential and commercial grids, the technical difficulty mostly originates from the supply side (i.e., wind power generation is uncontrolled). In case of wind power integration with a remote mining power systems, the technical difficulties come from both supply and load sides. In addition to the generation intermittency, the load may fluctuate abruptly and destabilize the network if sufficient diesel driven spinning reserve is not maintained. Thus, the renewable power penetration has been limited in remote mining locations, and the mines still require the reciprocating engines to be able to provide 100% of the load. However, some engines can be shut off during the high wind power generation period to reduce the overall diesel fuel consumption, and engine hours accrual.

In high penetration systems, it is anticipated that the entire network has to be operated as an integrated power system. Advanced supervisory control systems and component monitoring become necessary. There are several different ways to support system power quality in wind power integration and some of them are listed in the following subsections. It is expected that several of these control options will be required to integrate small nuclear reactors in a mining power system.

4.1 Supply Side Options

- Controlled Dump Loads: Fast acting devices that help to balance the generation and load such as steam turbine bypass valves and condensers sized for high levels or steam bypass, and resistive load banks.
- Synchronous Condenser to provide reactive power and controls voltage.
- Power Storage: Flywheels or advanced power converters and small battery banks are used to assist in managing power flows for power smoothing.
- Active Power Control Devices to monitor grid condition and act to insure high power quality.
- Active Renewable Control to control power output of the renewable device. Power control or simply turning off some of the units.

4.2 Grid Side Options

- Load Dispatching: Active dispatchable of specific loads and making the distinction between critical and non-critical loads
  - Dispatchable loads such as resistance heaters.
  - Load shedding sequences where non-critical loads are turned off in a specified sequence until the systems stabalizes to minimize impact to operations.
  - Start up sequences where large loads are started sequentially and not concurrently to minimize total inrush current.

  - Protection of sensitive loads with emergency generators.
- Capacitors Banks: Installation of capacitors to smooth out rapid system fluctuations and partially correct systems power factor.
- Active Load Control: Replacing large inefficient loads with better or different devices, or soft start systems of large motors.

5. Designing of Small Nuclear Reactors for Remote Mines

Any vendor planning to develop a small nuclear reactor for a remote industrial application needs to remember that the reactors are intended to replace diesel powered reciprocating engines which are highly versatile and rugged machines. Thus, VSMR should be able to match or provide a similar level of operational performance of a reciprocating engine. The following system design considerations were produced based on diesel engine performance requirements at remote mine sites.

5.1 Constraints

- Redundancy: remote mines are located in an extreme climate where mid-winter power loss is a life-threatening crisis. A typical diesel power plant employs N+ 2 redundancies, typically in a 4+2 configuration. The units are normally operating at 80% capacity, such that 3 units operating at 110% generating capacity can provide for the full load after a generator trips while a hot-standby backup unit ramps up. Since nuclear reactors should not operate beyond the rated capacity, the 4 units should operate at 75% capacity normally if 3 (N-1) units operating at 100% capacity can support the full power load. If VSMR reactor is a similar size to the total load (i.e. 10 MW reactor supplying to 10 MW mine), then 100% backup diesel power in hot standby will be necessary.
- Cooling: it should be considered that many remote mines operate in desert-like environment and large water body is generally not available as a heat sink.
- Ambient temperature: mines operating in northern areas experience large annual temperature variations. If a VSMR plans to use air cooling, then the large temperature fluctuation needs to be considered.
- Insulation and heating: at mines operating in the Arctic region, system components are at potential risk of freezing. A vendor needs to ensure that the system can be adequately heated or located inside of a heated building, and a frozen component does not cause safety issues.
- Modularization: the transportation challenge and lack of local skilled labour demands that maximum extent of modularization is employed in the system design. It is preferable that the majority of the components are shipped to sites completed pre-assembled.
- Auxiliary power supply: mine power quality can degrade severely or be completely lost following a generator trip, especially if VSMR becomes a major power supply in the system. A vendor should not expect that an external power source is available to operate safety related equipment.
- Lack of skilled labour: it is very difficult to staff a power plant at remote mining sites. High level of design simplification, autonomous operation, passive and inherent safety features need to be incorporated to reduce operator requirement.

- Parts: there will not be a local supply of parts. The maintenance crew and parts will have to be flown in and that could mean that a reactor is unavailable for weeks.

5.2 Other Design Considerations

- Sizing: a typical remote mine consumes 4 to 30 MW. Considering the redundancy requirement, a reactor producing more than 10 MW of electricity would be too large for most sites. It is probable that 3~5 MW is an optimal output power size.
- Expandability: the power system needs to expand following a mine expansion. A vendor should consider how additional units can be added to a central nuclear power plant from which power is distributed to satellite mine sites via high voltage transmission lines. Alternatively, additional nuclear power plants can be installed at satellite mine expansion sites. There will be a design implication on operating room locations and design, as well as on reactor control methods.
- Reactor lifetime: a typical mine lifetime is 7 – 20 years, which is significantly shorter than 40-60 years which is the conventional reactor design lifetime. The reactor needs to be either transportable such that it can be relocated to a new mine site once a mines resource is depleted, or the design lifetime should be reduced to avoid an over-design.
- Deep load following: as exhibited in this paper, mining power load can fluctuate rapidly. In addition to deep load following capability to accommodate sudden change of 25% of the peak load and 100% turbine bypass capability is recommended. A vendor should examine how to integrate load flattening devices such as flywheels and synchronous condensers with a VSMR.
- High mechanical inertia: the generator needs to be designed with sufficient rotating inertia to accommodate large motor loads start-ups.
- Fast start-up: the typical time for a reciprocating engine to start-up, warm up, synchronize and connect to the power system is about 2 minutes from a hot standby. Since it is unlikely that a nuclear power reactor can ramp up from 0% to 100% power in 2 minutes, a supplementary technology such as battery storage should be utilized.

6. Conclusion

Small nuclear reactors have a strong economic potential to replace diesel reciprocating engines in remote mining power systems. In order to replace diesel generators at mines, it is necessary that the alternative technology delivers an equivalent level of operational performance. The vendors need to consider that the reactors will be exposed to harsh operating conditions and they are subject to highly demanding performance requirements, in comparison to those deployed in residential grids.

The authors believe that the traditional reactor design approach may not be sufficient. In order to design a successful VSMR for remote mine power systems, the design scope needs to encompass the entire grid design and operation. Historical lessons are available from the past Hatch experiences in integrating wind power and diesel engines in a captive mine power systems: with increasing penetration, the entire network has to be operated as an integrated power system. Several technology options can be deployed on the supply side and on the grid side to assure the power quality in mining operation, which may include smart grid controller systems, load dispatching devices and energy storage systems. The authors believe that an early consideration of system integration technologies that can supplement small nuclear reactors in captive power systems will improve the adaptability of the technology in mining industry.

7. References

[1] IEEE Global History Network, "Milestones:Ames Hydroelectric Generating Plant, 1891", IEEE., Retrieved August 18, 2014. http://www.ieeeghn.org/wiki/index.php/Milestones:Ames_Hydroelectric_Generating_Plant,_1891

[2] Natural Resources Canada, “Status of Remote/Off-Grid Communities in Canada”, August 2011.