Report on the
Underground Mine Feeder Cable

Soudan Underground Laboratory

Prepared for
University of Minnesota School of IT Physics & Astronomy
QCPS # 0000094163 dated 01/30/2009

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Project Description

Introduction

The Minnesota Department of Natural Resources (DNR) operates the Soudan Underground Mine State Park that is the site for the University of Minnesota Soudan Underground Laboratory.

This report compiles the results of an engineering analysis of the electrical 2/0 copper cable feeder that was installed in 1983. The cable is joined to become a loop that routes in the mine shaft to level 27, and this circuit includes two oil switches providing redundant feed to level 22 pumps. The feeder extends down 2,341 feet via a mine shaft to the 27th level. Concern has been expressed about cable capacity and other factors that may indicate replacement in the foreseeable future, including the following concerns:

- Increasing supplied loads
- Laboratory loads
- Cable feeder age
- Current and projected loads by the U of M laboratory for this coming April 2009
- Voltage drop exceeding the suggested 3% limit of the National Electrical Code Fine Print Note for Feeders as monitored by site electrician over the past years
- Additional pumping loads
- Simultaneous operation of more dewatering pumps than was typical this past spring (2008) – the dewatering pumps are believed to be required only during high spring runoff and only once during a ten-year interval

Local Conditions

The power system includes a 43.8kV to 2.52kV, 1500kVA step down delta - delta transformer, a line-up of switchgear including fused load break switches for the feeder in question and other loads. The feeder in question has a splice at the electrical room converting to two cables, each installed down the mine shaft splicing in junction boxes at different levels of the mine, connecting to oil switches for redundancy functions, and tying together at the 27th level of the mine. The loop is kept open, but is designed to provide redundant feeds to mine elevations in case a cable failure occurs. The visible cable has a corrugated armor, orange jacket, ground, and no neutral. Normal temperature in the mine is 50 degrees Fahrenheit year around. A portion of the cable loop from the electrical equipment room to the mine shaft runs in rigid metal conduit through a 2-foot by 2-foot buried tunnel.

The installed cable from the provided data is a 5kv cable consisting of (3) # 2/0 AWG 19 strand copper conductors with semi conducting tape and 0.110" thick mineral filled chemically cross linked polyethylene (XLPE) insulation (black vulkene). The cable has color-coded hash marks (white, red, blue) identifying the individual conductors. The conductors are cabled together with a #6 AWG copper ground wire and non-hydroscopic fillers. Wrapping the cable is a .010"thick rubber tape, a JWJ finish with 33 ends of #8 wire armor, with wire bands every 25 feet and non-sticking white powder overall.

Standards Applied

Variables involved when determining suitability of a cable include:

1) Short circuit withstand capacity

2) Continuous current carrying capacity of the conductor size

3) Correction factors for ambient temperatures

4) Correction factors applicable to the method of installation

5) Voltage drop in the cable for the length used

Two approaches are predominantly used to determine cable ampere capacity, 1) values from tables of the National Electrical Code (NFPA70) when applicable and 2) values with extrapolations from IEEE Standard S-135 which are typically used by the electric power industry. For the cable in question, requirements and values of the National Electrical Code (NEC) – NFPA 70 2008 – as adopted by the MN legislature will be used. Other specific physical parameters used for cable calculations will be gleaned from the book Power Cable Manual printed by the Southwire Company and cable manufacturer's data as accumulated in cable library of ETAP software by Operation Technology, Inc of Irvine, CA.

Voltage Drop in cable is calculated from alternating current resistance (R) and effective reactance (X) of NEC Chapter 9 Table 9 using the following formulas.

The formula below is used to determine the receiving voltage:

$$Vr = Vs - (IR \cos \Phi + (\sqrt{-1})IX \sin \Phi) \times \sqrt{[Vs2 - (IX \cos \Phi - IR \sin \Phi)\ 2]}$$

Where: Vr = receiving voltage

Vs = source voltage

ΔV = Voltage drop

I = Full load current

R = line resistance for three phase conductor

X = line reactance for three phase conductor

Φ = angle whose cosine is the load power factor

L = approximate length of cable in meters

Next, the % voltage drop is determined by applying this formula:

$$\% \text{ voltage drop} = (\Delta V/Vs)*100 \quad \text{where:} \quad \Delta V = Vs - Vr$$

Calculation of Cable Short Circuit Withstand Capability

The short circuit withstand capability of 2/0 copper cable (reaching a conductor temperature of 250 degrees C as the limit for XLPE cable) when protected by power fusing (conservatively using a two cycle clearing time) is 50 kA. The Soudan mine 1500kVA service transformer with 6.5% impedance at 2300 volts could supply a fault to 10kA (with contributing nearby motors). Therefore, the 2/0 cable has the thermal capacity to withstand fault conditions available at the Soudan mine.

Calculations of Cable's Capacity for Projected Loads

Referencing NEC Table 310.71, ampacity for applications of 2/0 cable at 2300 volts and 90 degrees C. is 215 amperes. This is based on an ambient air temperature of 40 degrees C (104 degrees F) that would be appropriate for the outdoor portions of the cable if exposed to sun light in the summer.

Referencing NEC Table 310.77, ampacity for applications of 2/0 cable at 2300 volts installed in underground duct banks of a single duct and three ducts is 220 and 185 amperes respectively. Using ETAP software applying the Neher-McGrath method suggested by NEC, two ducts of 2/0 copper 3 conductor cables in this arrangement have a capacity of 194 amperes each.

Appendix A indicates a cable load of 168.3 amps and a voltage sag of [100.64% (of 2.4kV at the service bus) - 97.89% (at the 22 level 2 bus) =] 2.75% at the "22 Level 2". This calculation is made with oil switches directing power flow to the 22 level 2 pumps from the cable loop that extends first to 27 level and back up to 22 level. This longer length of feeder cable to 22 level 2 is the worst case condition for voltage sag.

Calculations of Cable's Capacity for Spare Capacity (if any)

Appendix B with additional cable loading (26 amps or 100kVA, the maximum cable capacity) shows a voltage sag of [100.35% (at the service bus) – 96.75% (at the 22 level 2 bus) =] 3.60% at the "22 Level 2". Also, the voltage result at 460 volt motor control centers (MCC) of 93.65% and 99.00%. The 93.65% voltage is below the minimum acceptable 95% voltage (or 5% sag) on 460volt MCC buses and would require adjustment of the transformer's primary voltage adjustment taps.

Narrative on Voltage Requirements

The NEC fine print notes (Branch circuits - 210.19(A) FPN No. 4; Feeders – 215.2(A)(3) FPN No. 2; and Conductors - 310.15(A)(1) FPN No. 1) that make reference to a limit of 3% voltage drop on conductors say:

FPN No. 4: Conductors for branch circuits as defined in Article 100, sized to prevent a voltage drop exceeding 3 percent at the farthest outlet of power, heating, and lighting loads, or combinations of such loads, and where the maximum total voltage drop on both feeders and branch circuits to the farthest outlet does not exceed 5 percent, provide reasonable efficiency of operation. See FPN No. 2 of 215.2(A)(3) for voltage drop on feeder conductors.

FPN No. 2: Conductors for feeders as defined in Article 100, sized to prevent a voltage drop exceeding 3 percent at the farthest outlet of power, heating, and lighting loads, or combinations of such loads, and where the maximum total voltage drop on both feeders and branch circuits to the farthest outlet does not exceed 5 percent, will provide reasonable efficiency of operation.

FPN No. 1: Ampacities provided by this section do not take voltage drop into consideration. See 210.19(A), FPN No. 4, for branch circuits and 215.2(A), FPN No. 2, for feeders.

NEC introduction section information on FPNs says:

90.5 Mandatory Rules, Permissive Rules, and Explanatory Material.

(C) Explanatory Material. Explanatory material, such as references to other standards, references to related sections of this Code, or information related to a Code rule, is included in this Code in the form of fine print notes (FPNs). Fine print notes are informational only and are not enforceable as requirements of this Code.

Additionally:

NEC ARTICLE 215 Feeders

215.2 Minimum Rating and Size

(B) Feeders over 600 Volts.

3) Supervised Installations. For supervised installations, feeder conductor sizing shall be permitted to be determined by qualified persons under engineering supervision.

From an engineering standpoint, the FPN phrase suggesting “reasonable efficiency” of operation’ is the goal. Standards of equipment (motors, ballasted lighting fixtures, appliances) specify that design voltages comply with ANSI C84.1. The standard specified design voltages are 115 for the nominal 120 volt circuit, 460 for the nominal 480 volt circuit, 2300 for the nominal 2400 volt circuit, and 4000 for the nominal 4160 volt circuit. Operating within 5% of these ANSI design voltages (not the nominal voltages) will meet the “reasonable efficiency” requirement.

An Estimate of the Cable's Life Expectancy

Most common failures of solid-dielectric cable are attributed to water trees (cross section views of cable degradation appear as multiple branching trees growing into the insulating materials). Cable insulation forms trees in two different ways; electrical trees form with high electrical stress and water trees form by small discrete voids, develop slowly over years and are accelerated by moisture, contaminants, high temperatures and voltage stress. Predictions of cable failures are calculated using data derived from reported failure rates per 100 miles per year of installed use. The XPLE (vulkene type) insulation has reported failure rates of 0.5 to 3.0 to 8.5 for 1 year, 10 years and 15 years of installed use respectively (Data from CEA 117 D 295, 1987).

Recommendation of Cable Replacement Time

The increasing failure rate over time is of concern for the cable. A simple calculation using 10 failures per hundred miles per year for the installed approximate one mile length installed gives yields one expected failure within the next 10 years.

The use of the cable for powering the underground mine as a public facility open for regular tours recommends that the cable be replaced at 30 years of use, i.e. in the year 2013.

The redundant feed arrangement for only pumps on level 12 suggests a missed opportunity to redundantly feed all levels of the mine with the cable loop. Full redundancy (requiring additional switches) would offer feeding the mine levels from either leg of the cable, adding flexibility to electric services in the mine. This redundancy would offer:

1) reliability
2) replacement of each leg of the cable on different schedules 15-20 year apart to average down the installation cost
3) minimal disruption time caused by cable failures or when replacing both legs simultaneously

Conclusion

The 2/0 three conductor cable feeding the Soudan mine is capable of feeding the current and known projected loadings. This cable can be loaded an additional 26 amperes (to the NEC allowed cable limit of 194 amperes) or an additional 100kVA with no out-of-standard voltage sags. Also, transformer tap adjustments for voltage adjustment are usually available if needed.

Barr Engineering Company recommends replacement of this XPLE insulated cable at 30 years of use or in the year 2013.

Professional Engineering Stamp

I hereby certify that this report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the laws of the State of Minnesota.

Peter L. Emmons

February 10, 2009 License # 14154

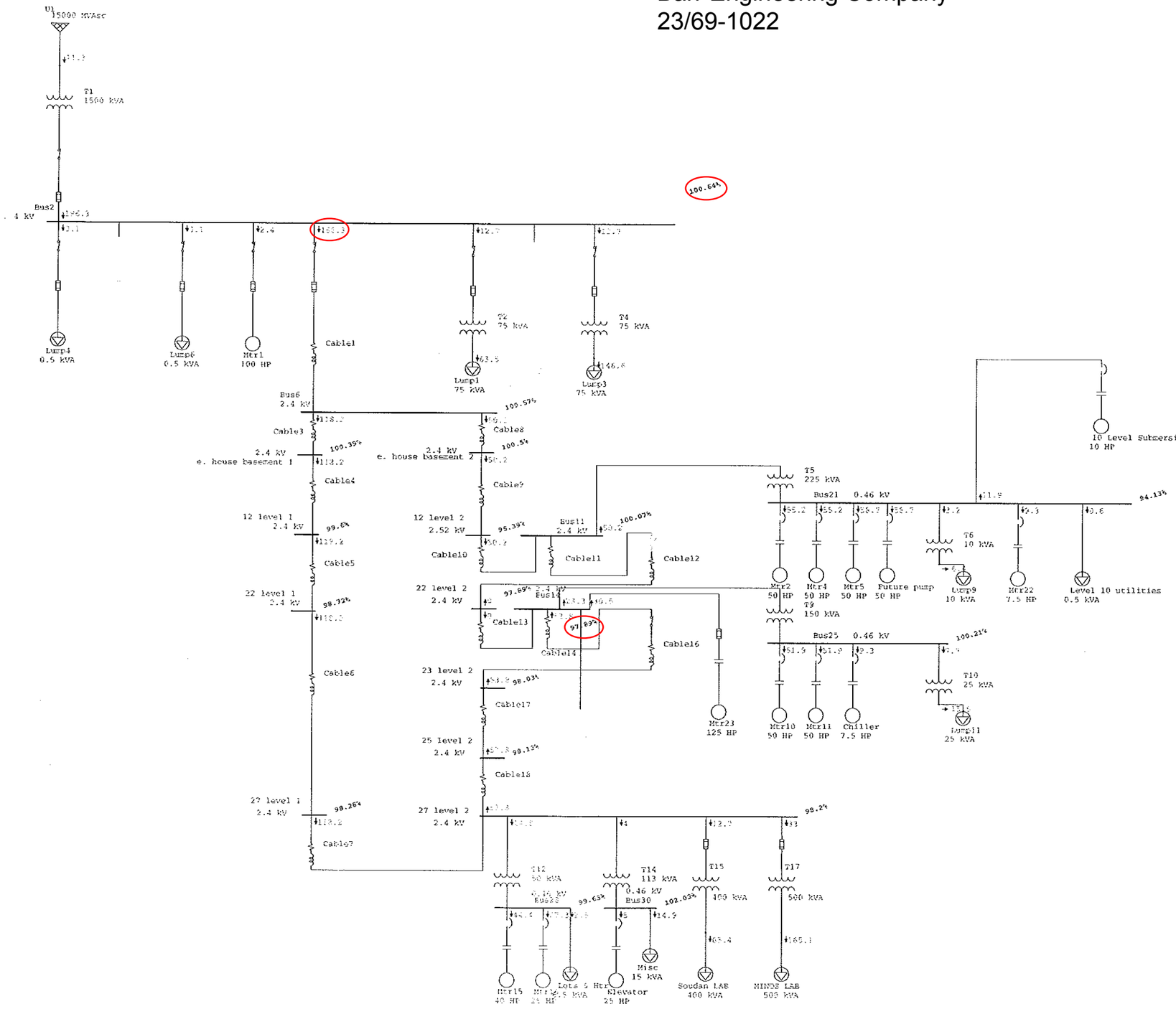
Appendices

Appendix A:

Single line representation of cable with projected loads and bus voltage percentage

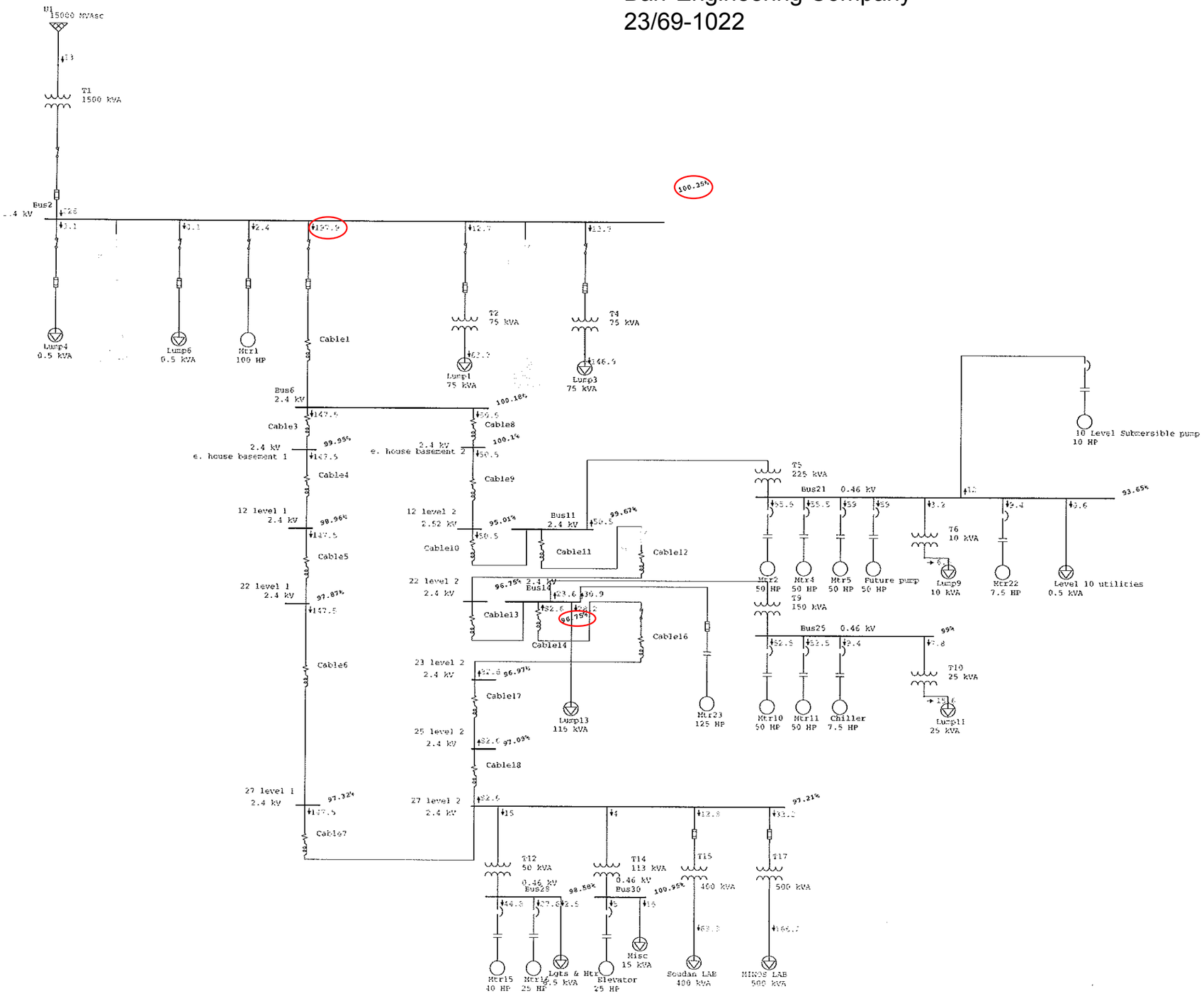
One-Line Diagram - OLV1 (Load Flow Analysis)

Appendix A
Barr Engineering Company
23/69-1022



Appendix B:

Single line representation of cable with cable spare capacity loads and bus voltage percentage

One-Line Diagram - OLV1 (Load Flow Analysis)

Appendix B
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