SAND2007-3849P

Evaluation of Lightning Coupling into the Sago Mine

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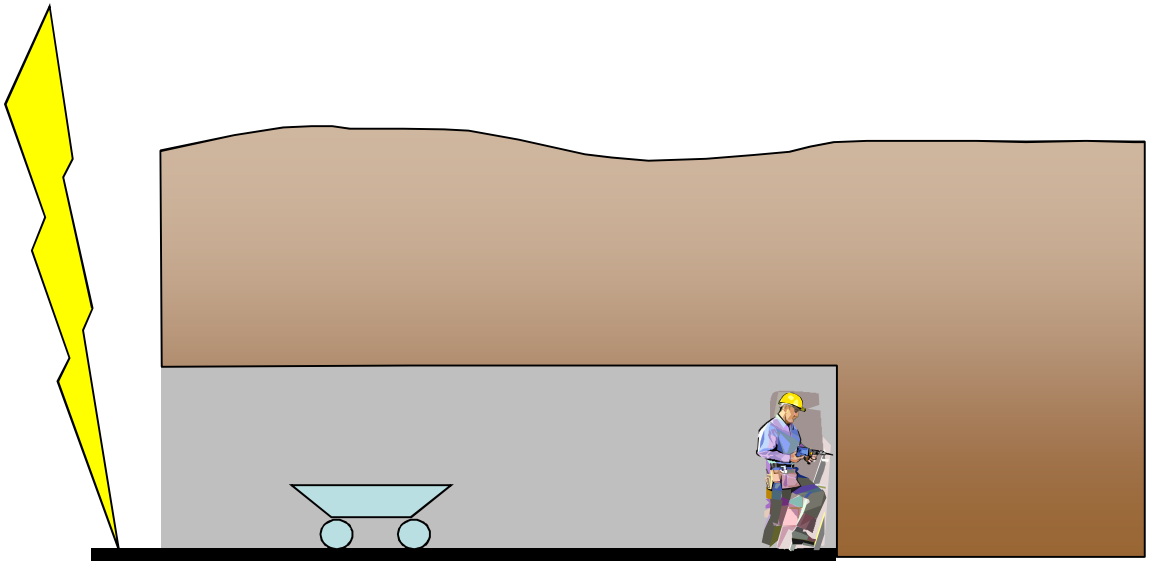
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia's role was to determine if lightning was a plausible cause

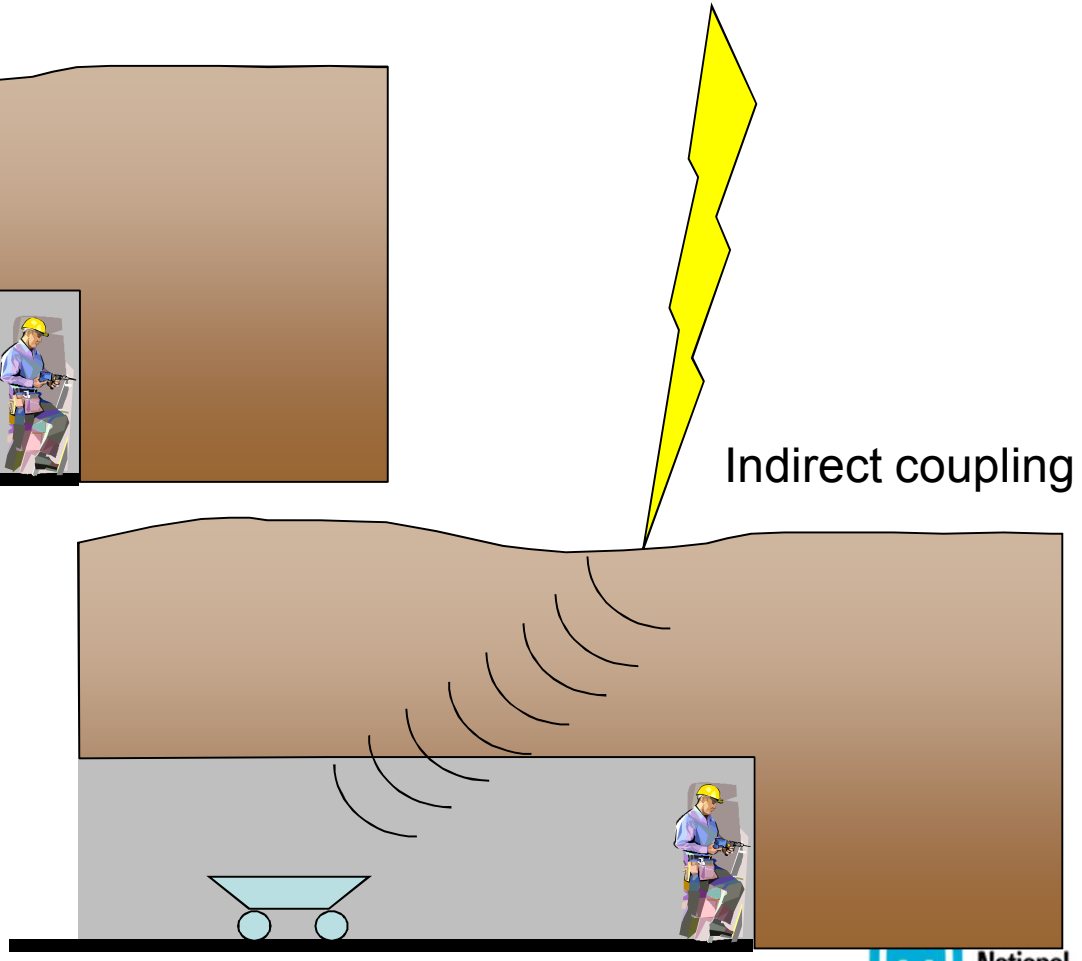
Could lightning have created an electrical arc in the sealed area at Sago?

Photo 1. An upward, ground-to-cloud lightning flash in Rapid City, SD, on 26 March 2004. [Photo © 2004 by Tom Warner]

Lightning can propagate by direct attachment or electromagnetic (indirect) coupling



Direct attachment

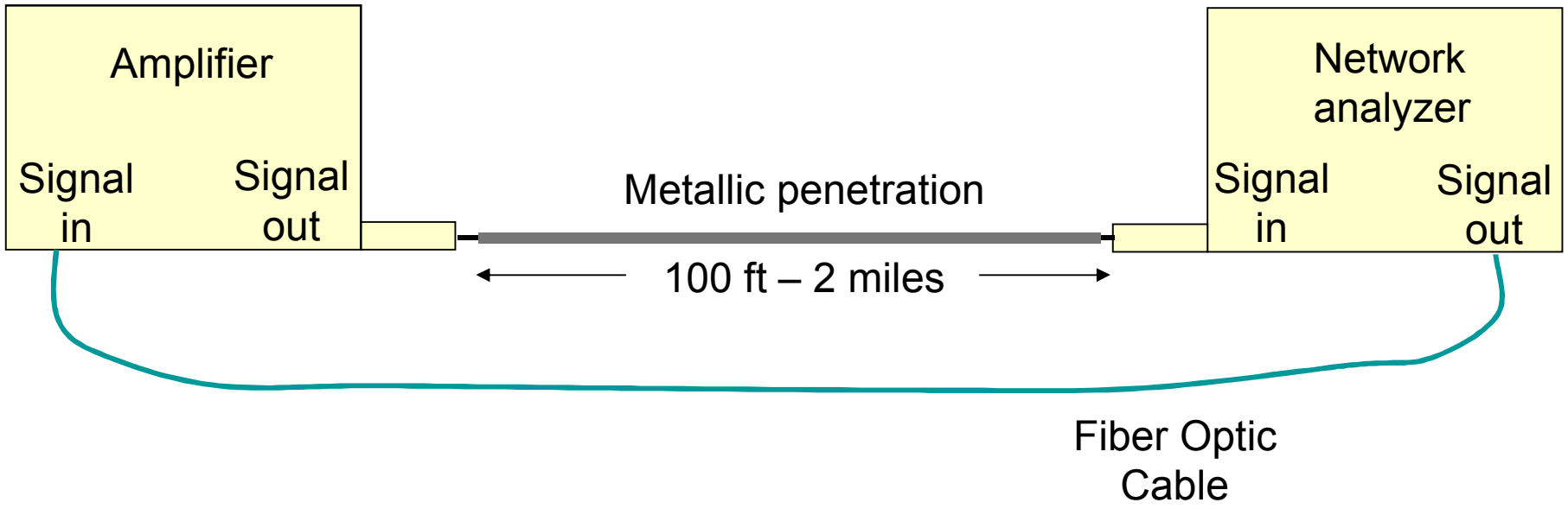


Indirect coupling

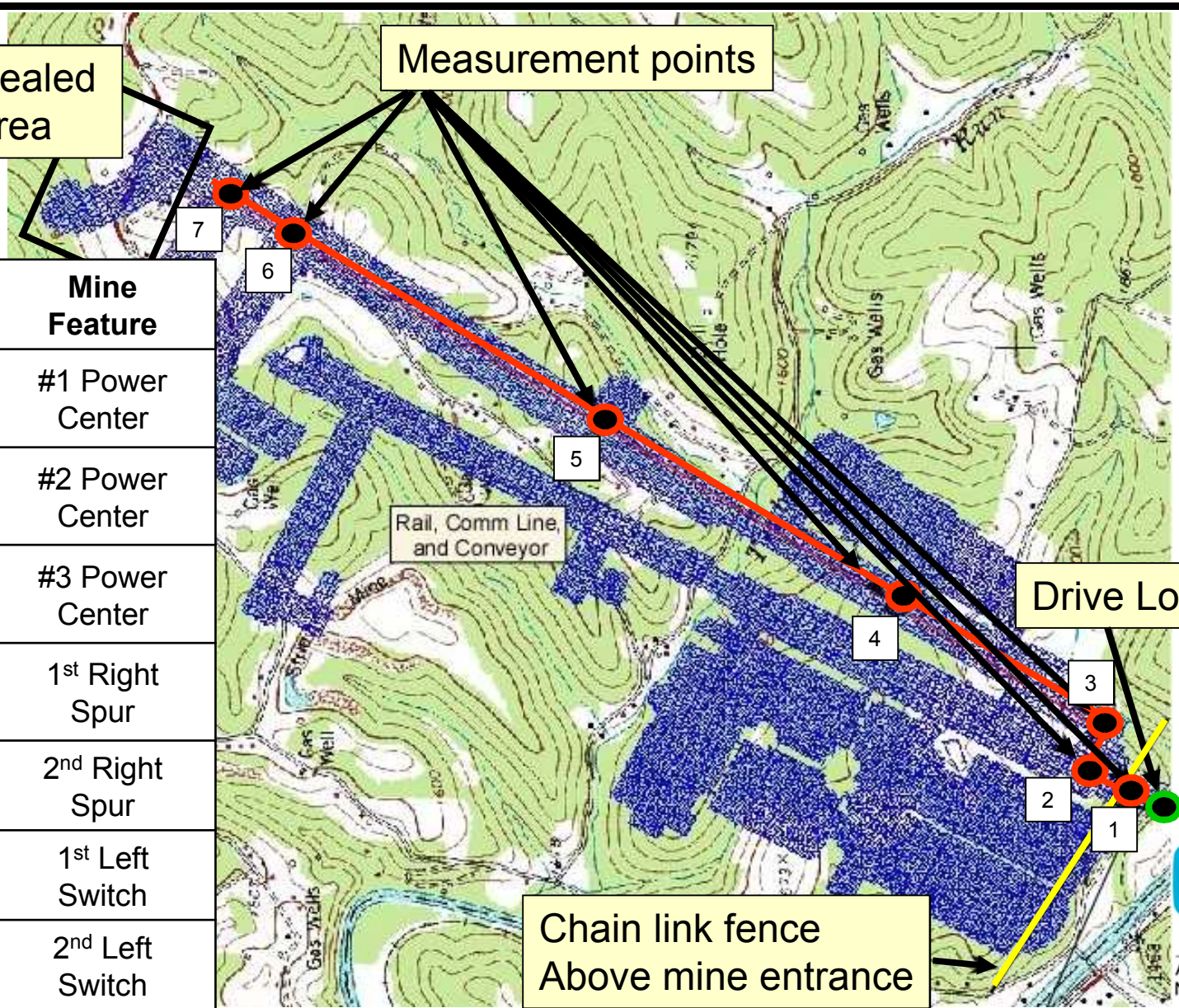
Direct-attachment lightning effects on mine penetrations were determined

- Measured transfer functions of direct coupling paths
  - Rails
  - Conveyor
  - Power shield
  - Trolley communication line
- Applied a mathematical representation of a lightning stroke to the transfer function
  - to calculate realistic voltages and currents on conductors inside the mine
  - Assumed worst-case scenario of lightning attachment at the mine entrance

Direct-drive measurement technique



Direct-drive measurement locations



Location	Mine Feature
1	#1 Power Center
2	#2 Power Center
3	#3 Power Center
4	1st Right Spur
5	2nd Right Spur
6	1st Left Switch
7	2nd Left Switch

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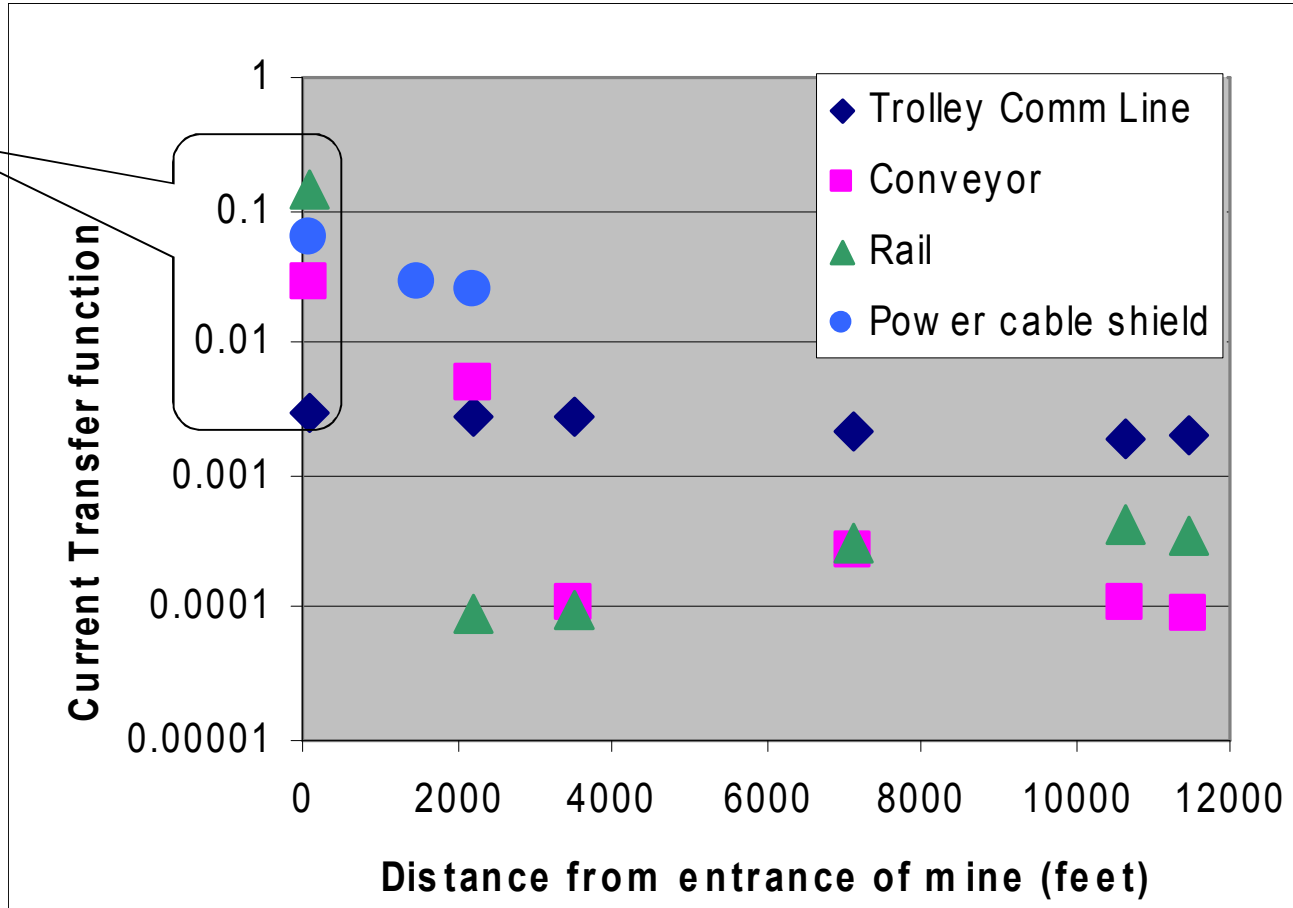
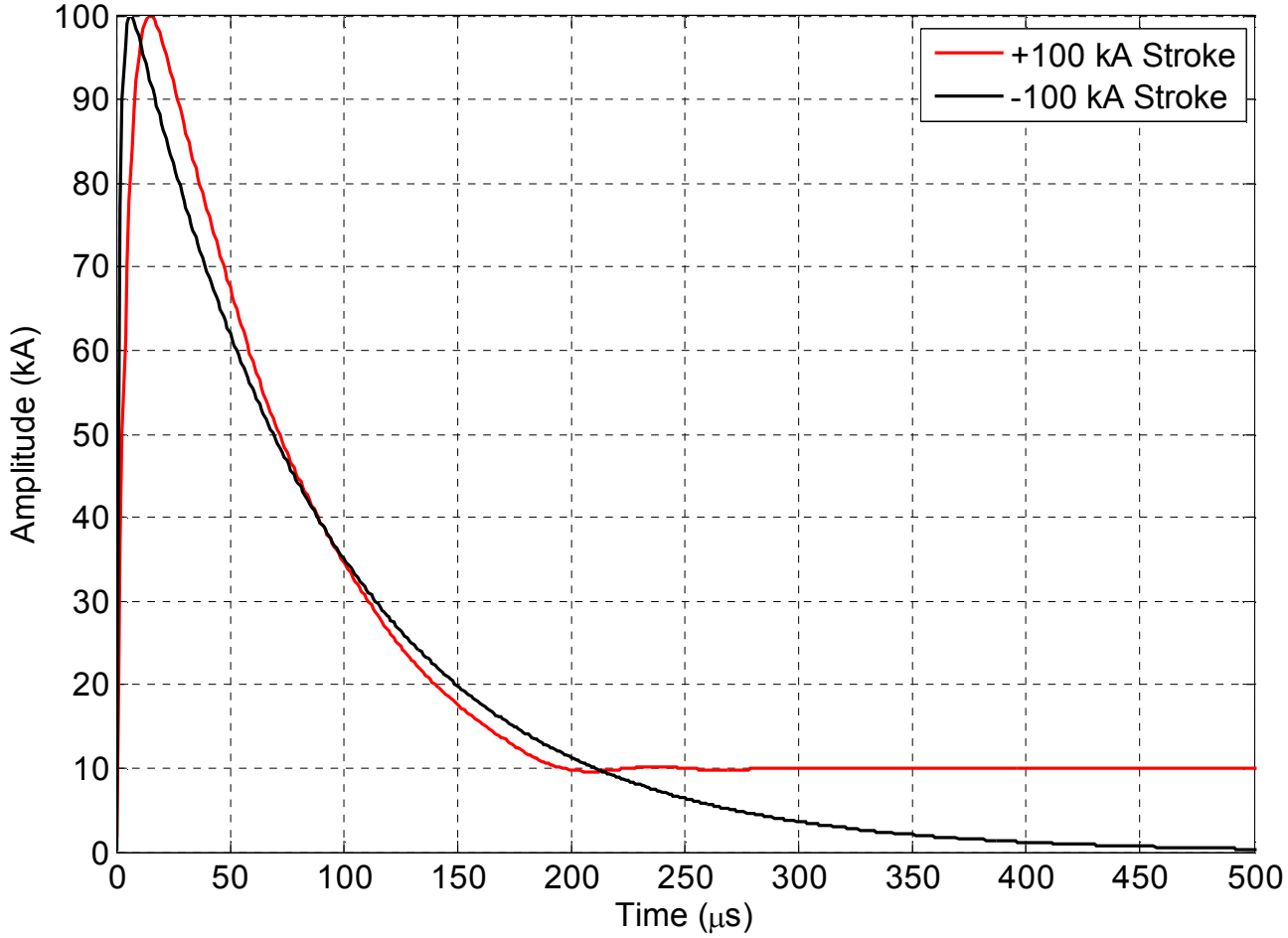
Direct-drive transfer functions

$$\text{Transfer function} = \frac{\text{Output current (A)}}{\text{Input current (A)}} \text{ or } \frac{\text{Output voltage (V)}}{\text{Input voltage (V)}}$$

Results at Power Center #1, 100 ft into mine



Mathematical representation of lightning stroke



References for lightning waveforms:

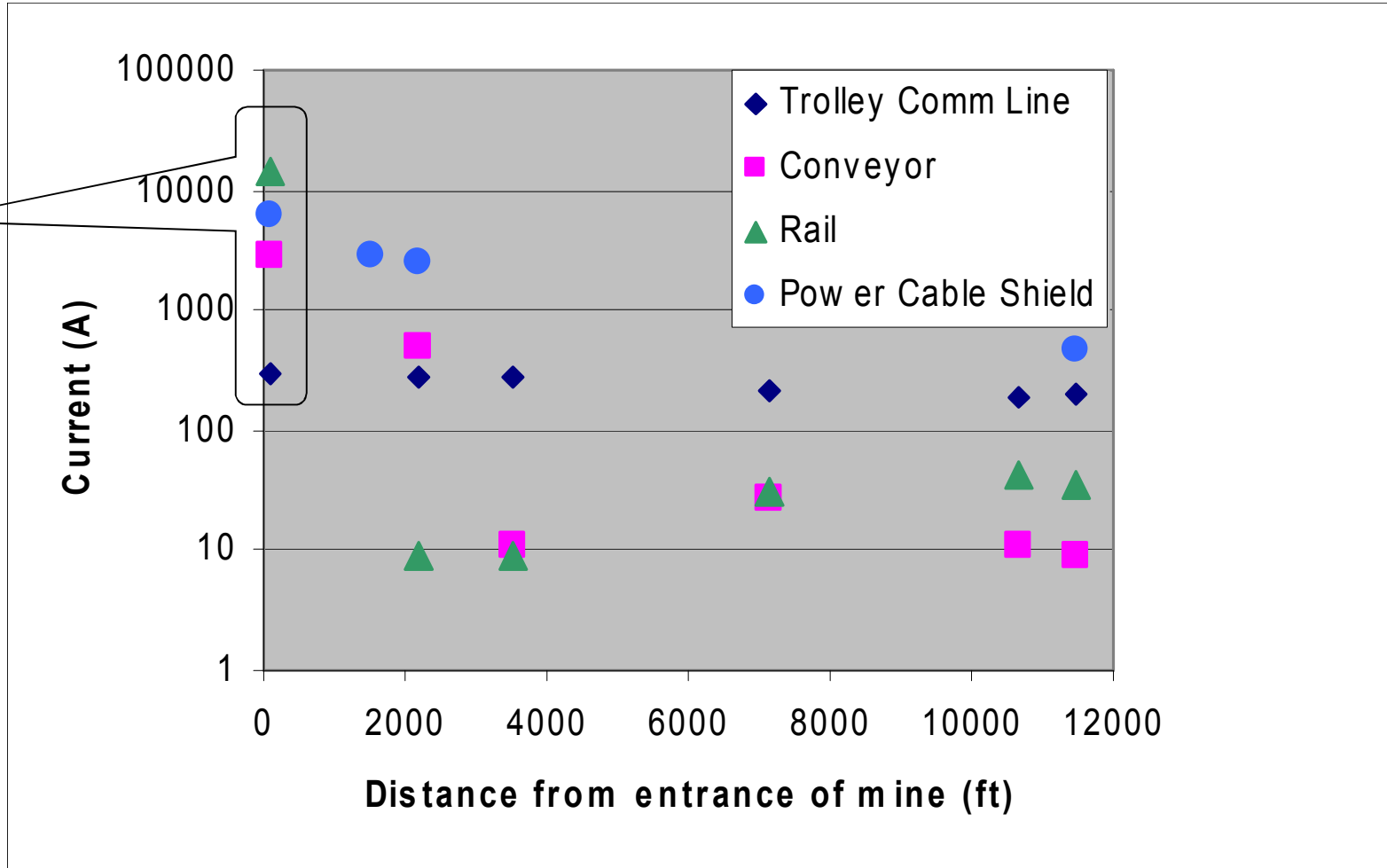
Cianos, N., and Pierce, E. T., *A Ground-Lightning Environment for Engineering Usage*, Technical Report 1, SRI Project 1834, August 1972.

Rakov, Vladimir A., and Martin A. Uman, *Lightning*, Lightning Physics and Effects, Cambridge University Press, New York, NY, 2003.

Direct-drive results given lightning attachment at the mine entrance

Results = Transfer function x Mathematical Representation of Lightning Strike

Results at Power Center #1, 100 ft into mine



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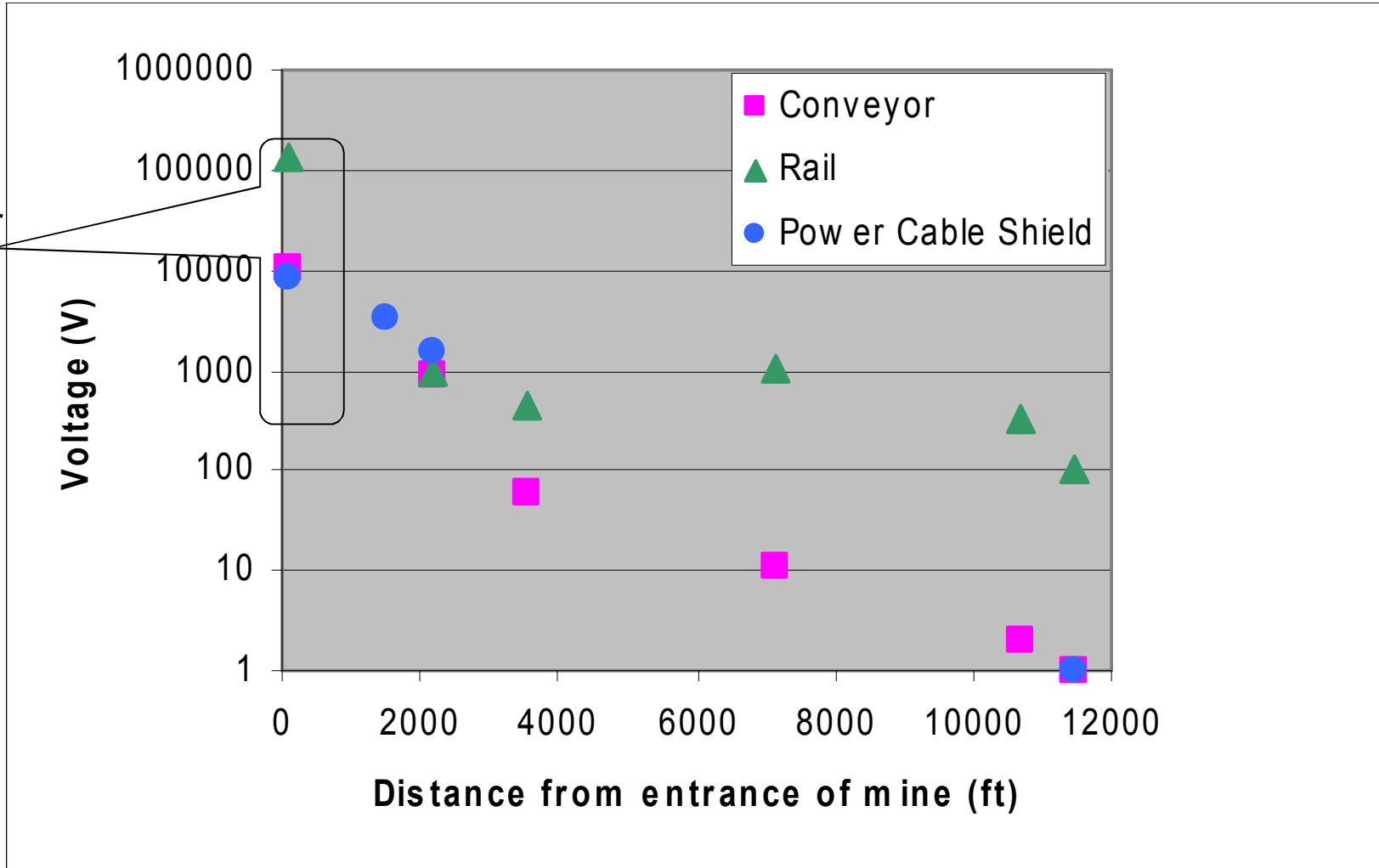
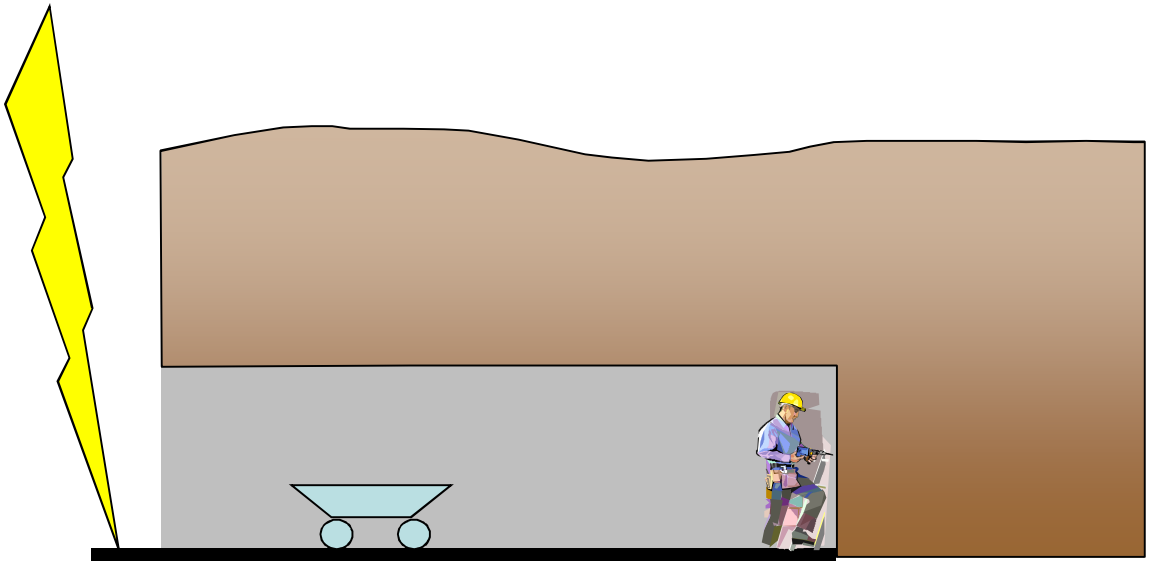
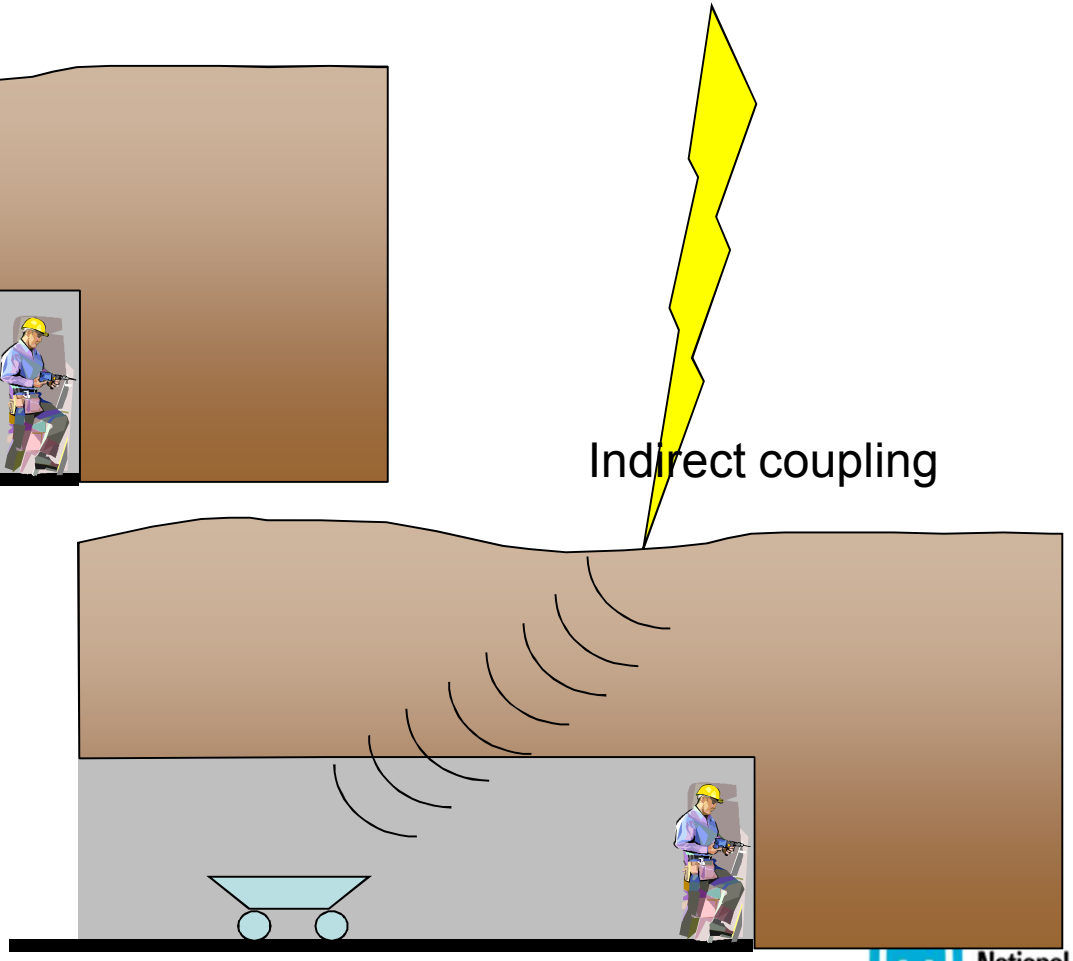


Lightning can propagate by direct attachment or electromagnetic (indirect) coupling



Direct attachment

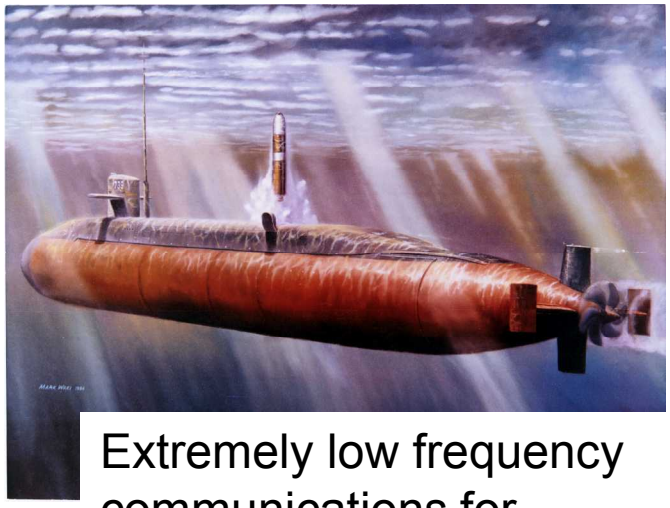
Indirect coupling



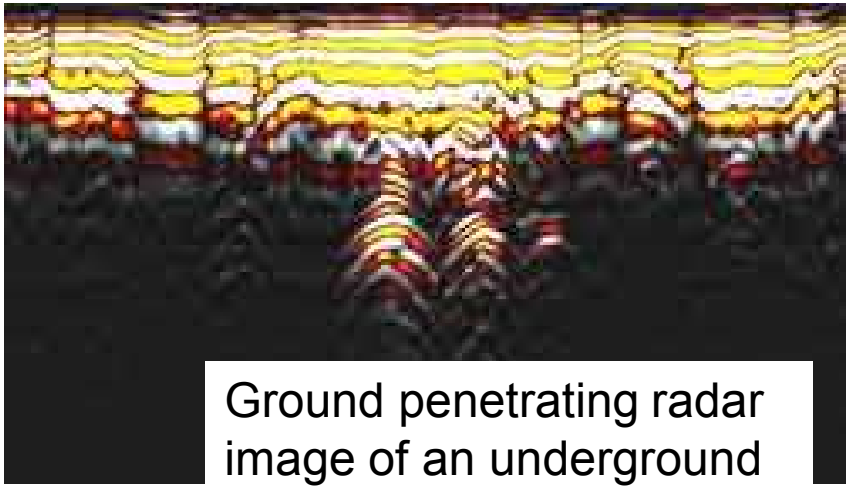
Common examples of electromagnetic propagation

Radiation from power lines

communications



Extremely low frequency communications for submerged submarines



Ground penetrating radar image of an underground cavern

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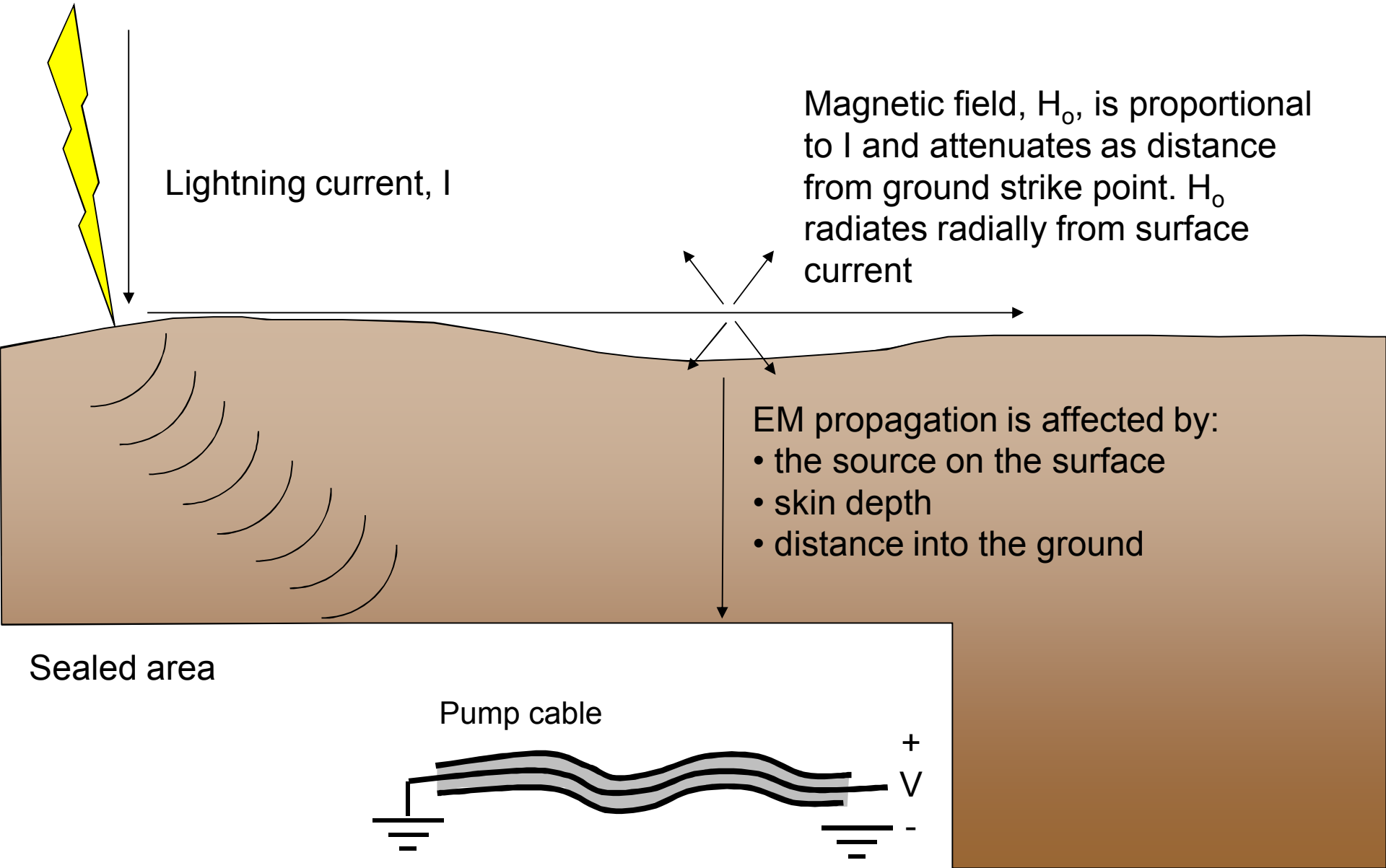
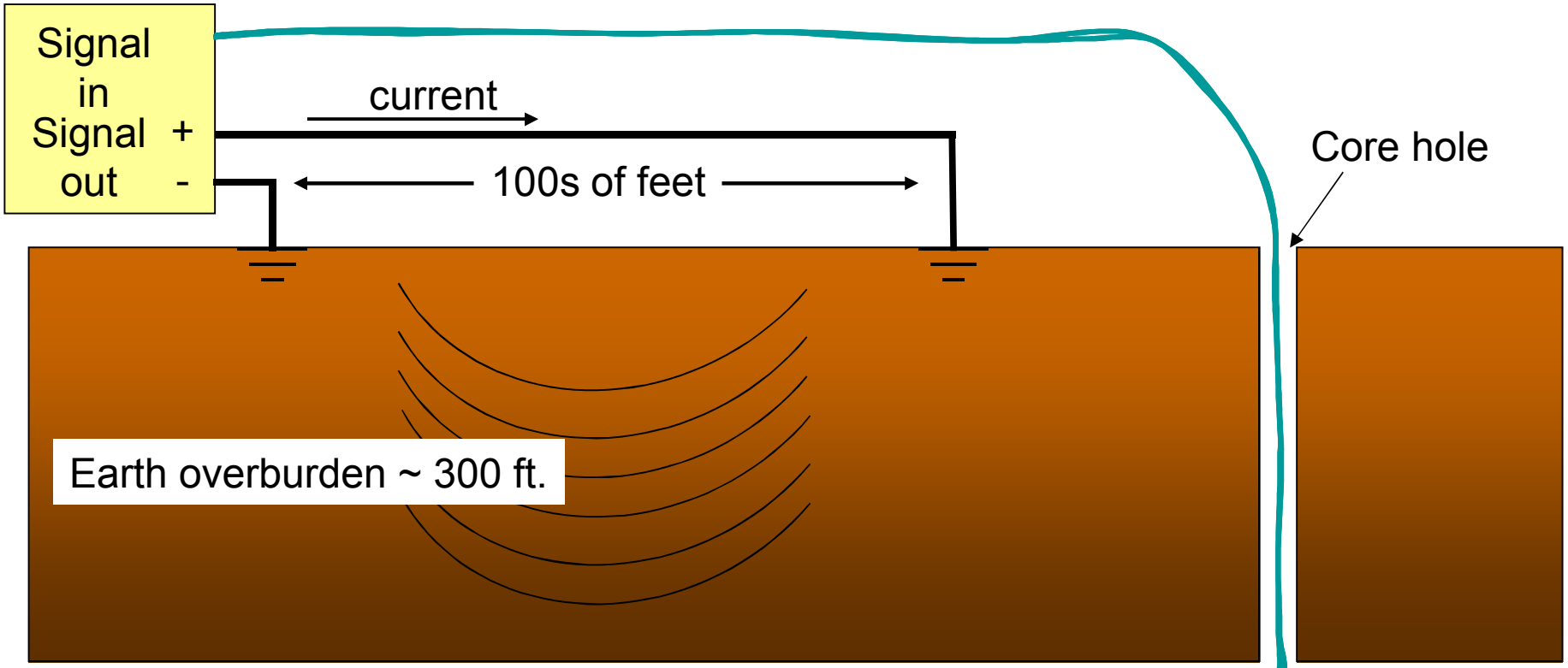
Lightning energy penetrates the earth through electromagnetic waves

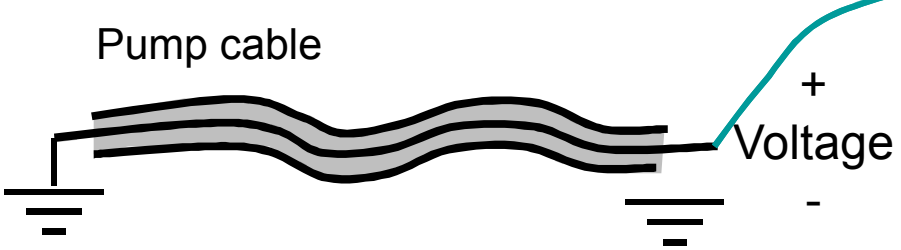


Indirect coupling of lightning effects in the sealed area were determined

- Measured transfer functions of indirect coupling paths
  - Electric field mapping in sealed area
  - Voltage measurements on pump cable in sealed area
- Applied a mathematical representation of a lightning stroke to the transfer functions
  - to calculate realistic electric fields in the sealed area and voltage on pump cable
  - Used recorded lightning strokes and related cases
- Compared measured results with a simplified analytical model of electromagnetic propagation through the earth

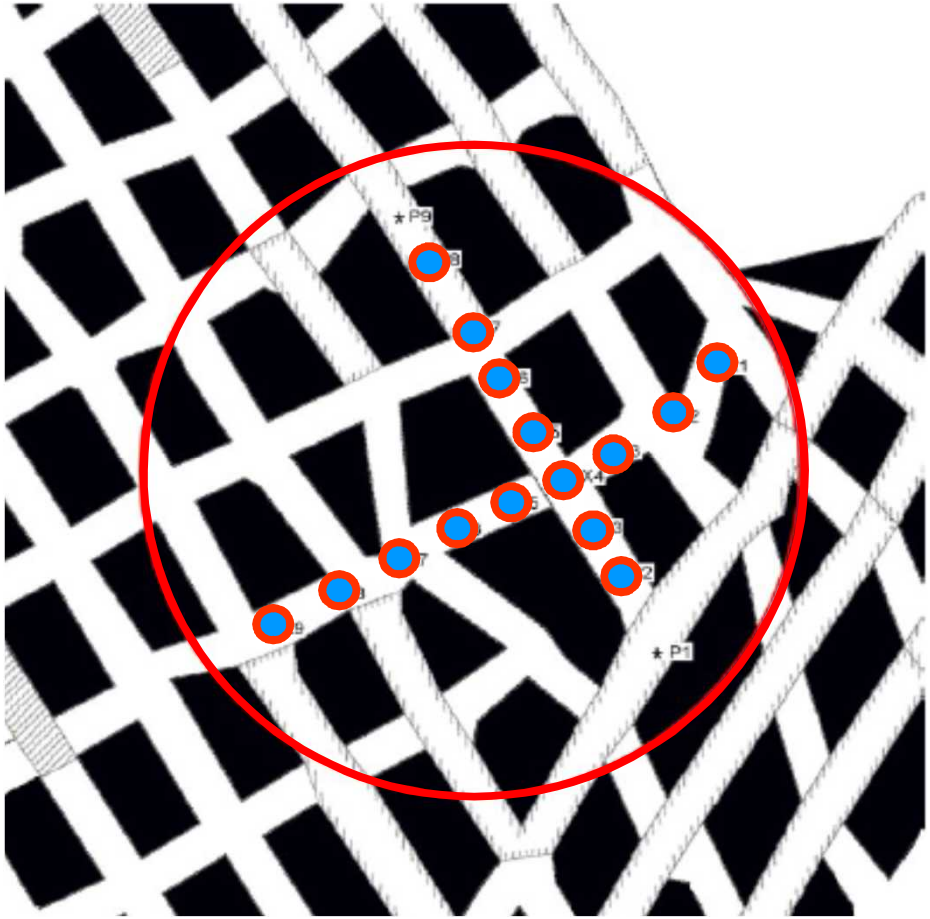
Indirect-drive measurement technique





Electric field

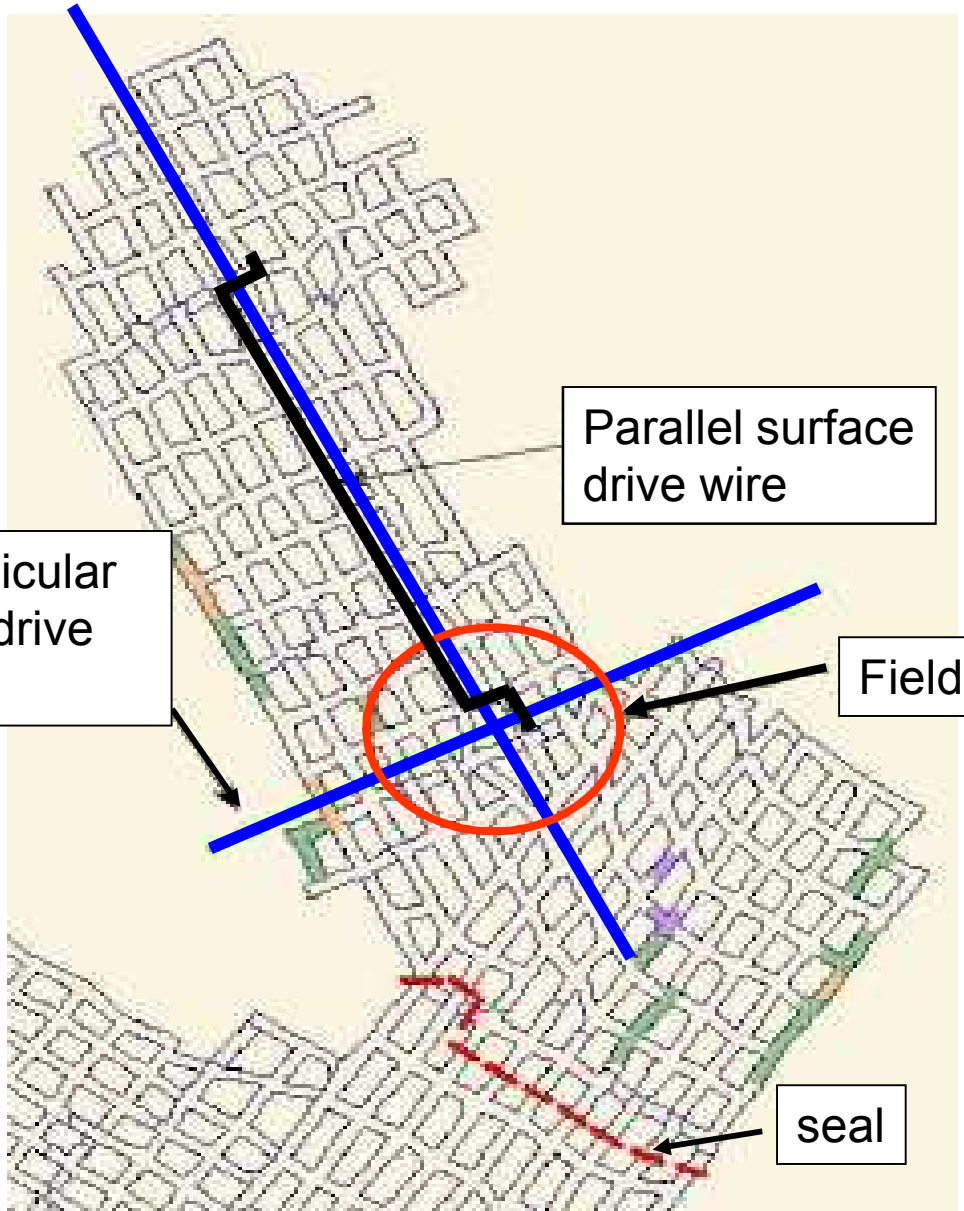
Indirect-drive electric field measurement locations



Measurement locations in sealed area

Custom antenna used in sealed area was developed to evaluate DOE facilities

Pump cable and surface drive orientation



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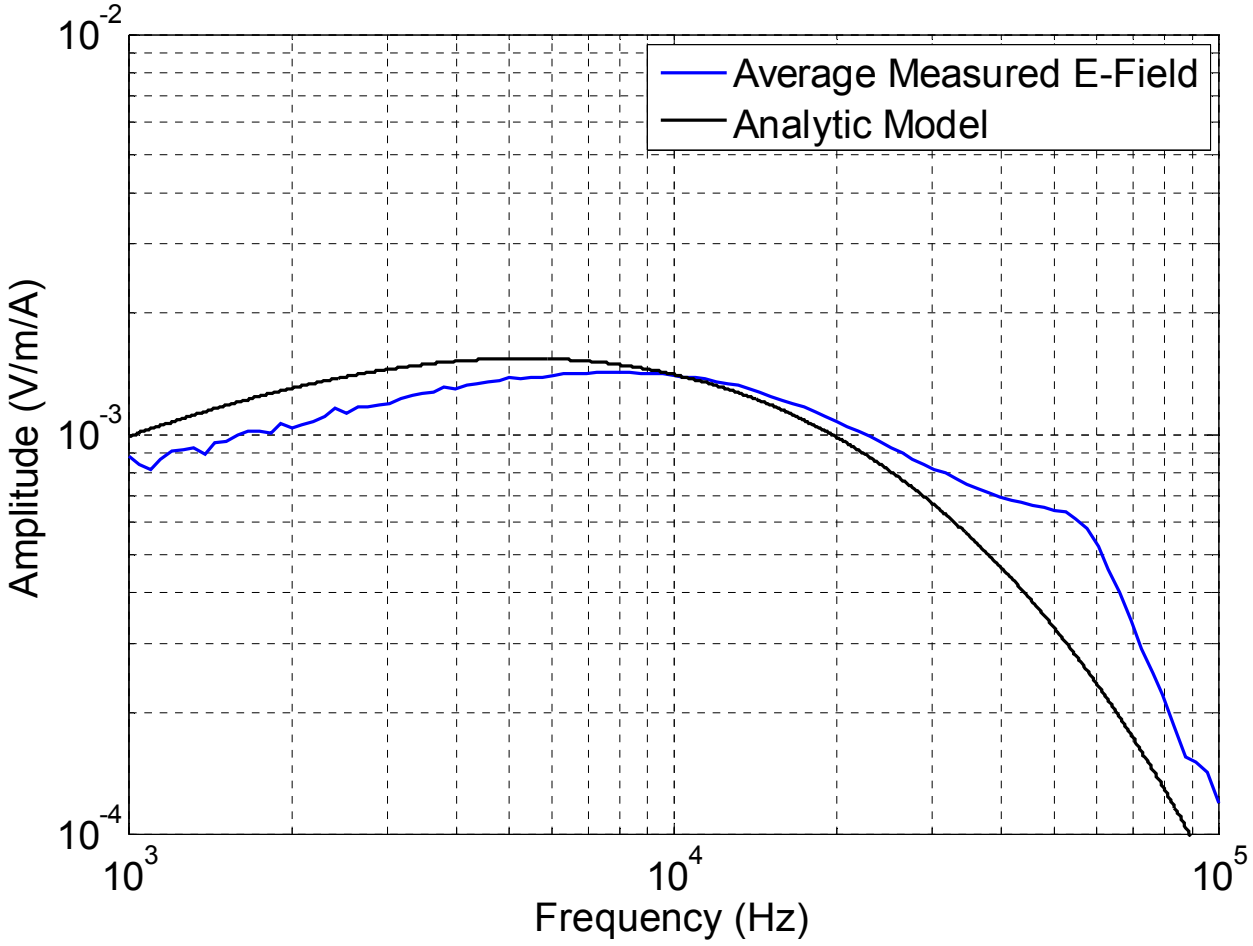
Indirect-drive electric field measurements agree with analytical model

$$\text{Electric field transfer function} = \frac{\text{Electric field in sealed area (V/m)}}{\text{Input (surface) current (A)}}$$



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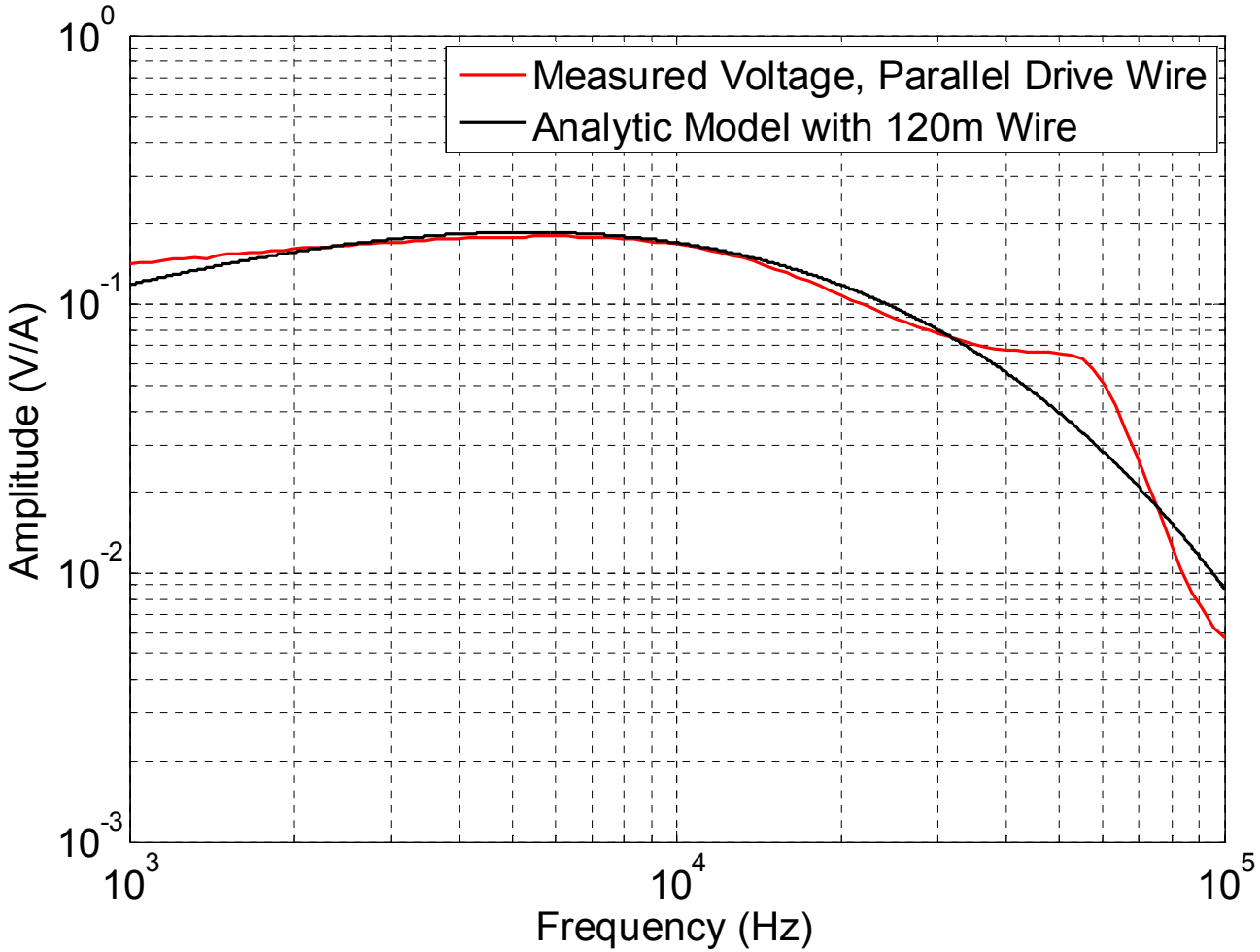
Indirect-drive voltage measurements agree with analytical model

$$\text{Voltage transfer function} = \frac{\text{Voltage on pump cable in sealed area (V)}}{\text{Input (surface) current (A)}}$$



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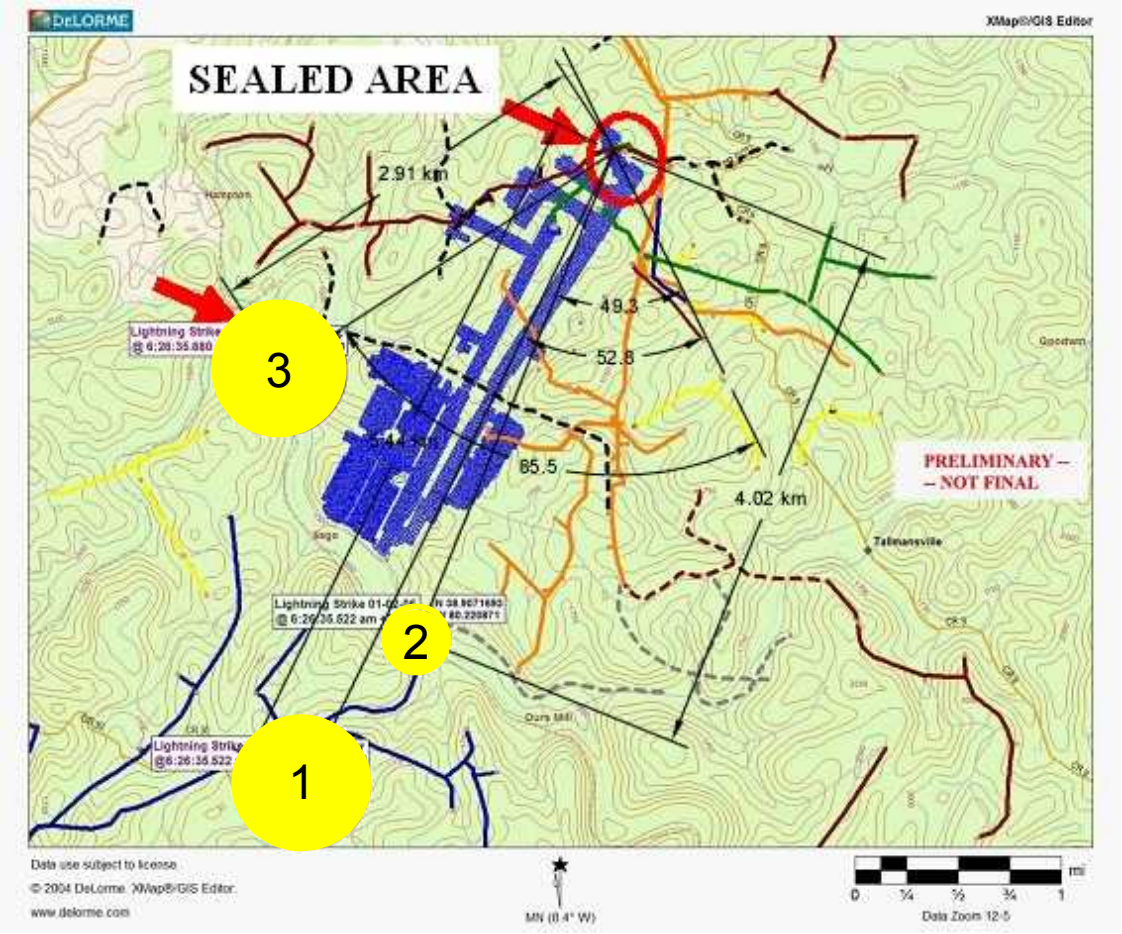
Next, voltage on the pump cable is calculated given lightning strokes in the area

- Use recorded lightning strokes, assuming vertical cloud-to-ground geometry
- Use a recorded lightning stroke, assuming horizontal geometry of lightning arc channel
- Assume a vertical cloud-to-ground lightning stroke close to sealed area

Data record of lightning activity in the area



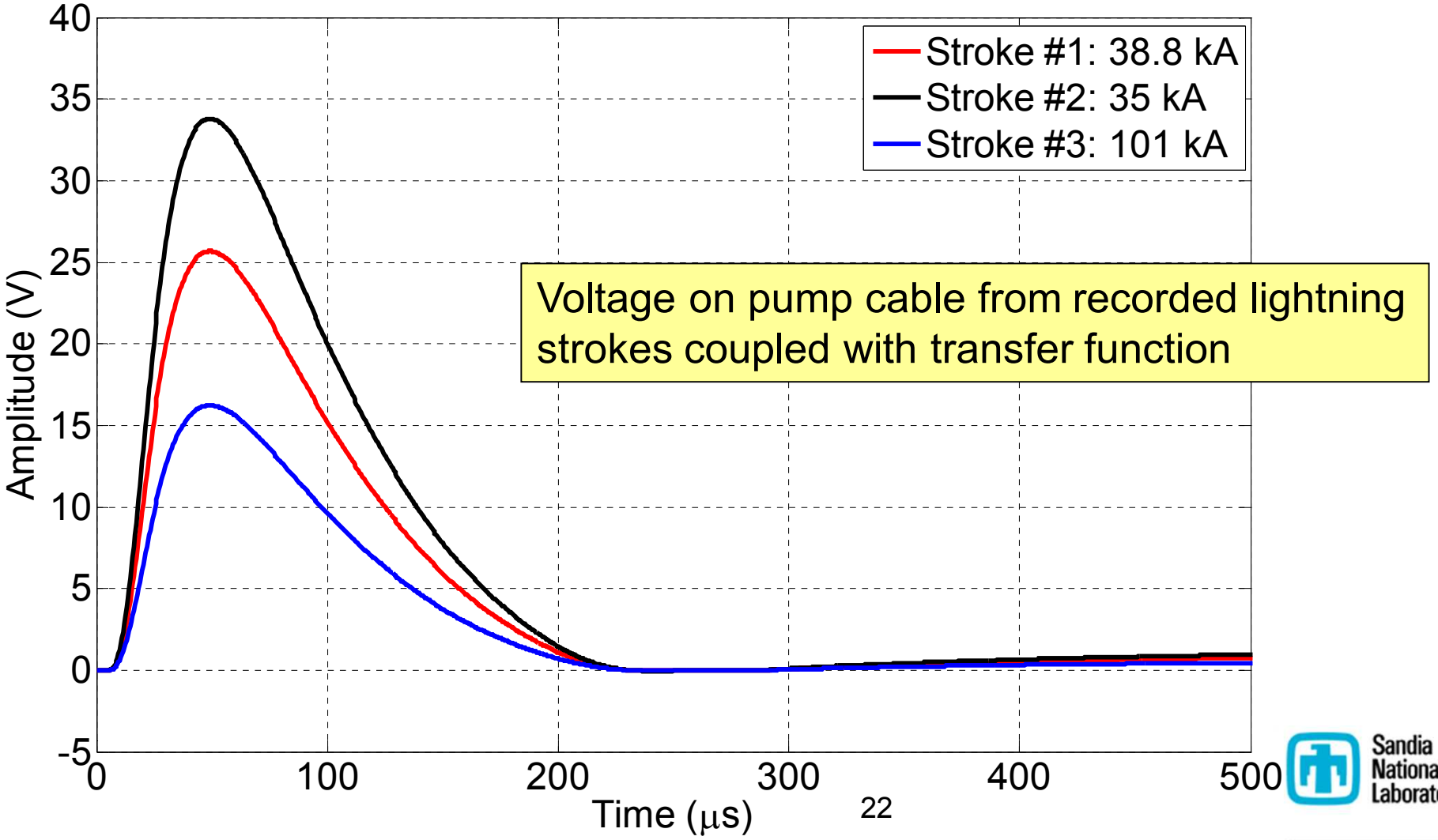
Lightning Strokes detected @ 6:26:35 am on Jan 2, 2006 around Sago:

Stroke 1: +38.8 kA (NLDN)*
Stroke 2: +35 kA (USPLN)*
Stroke 3: +101 kA (NLDN)

* Independent analysis indicates that Stroke 1 and Stroke 2 represent one stroke

NLDN = National Lightning Detection Network
USPLN = United States Precision Lightning Network

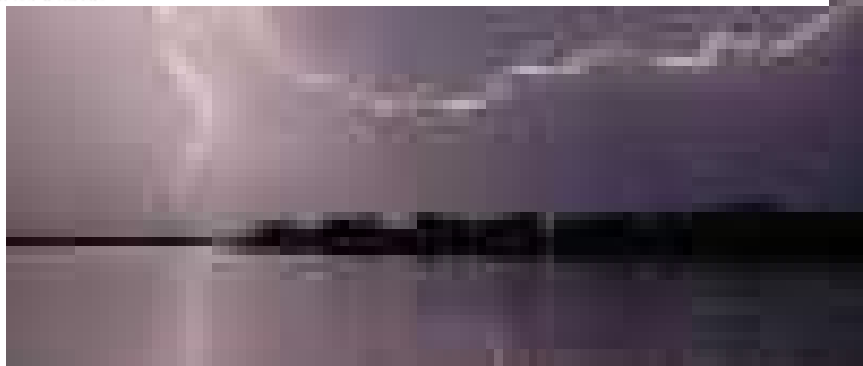
Vertical cloud-to-ground lightning stroke data does not support high-voltage arcing on the pump cable



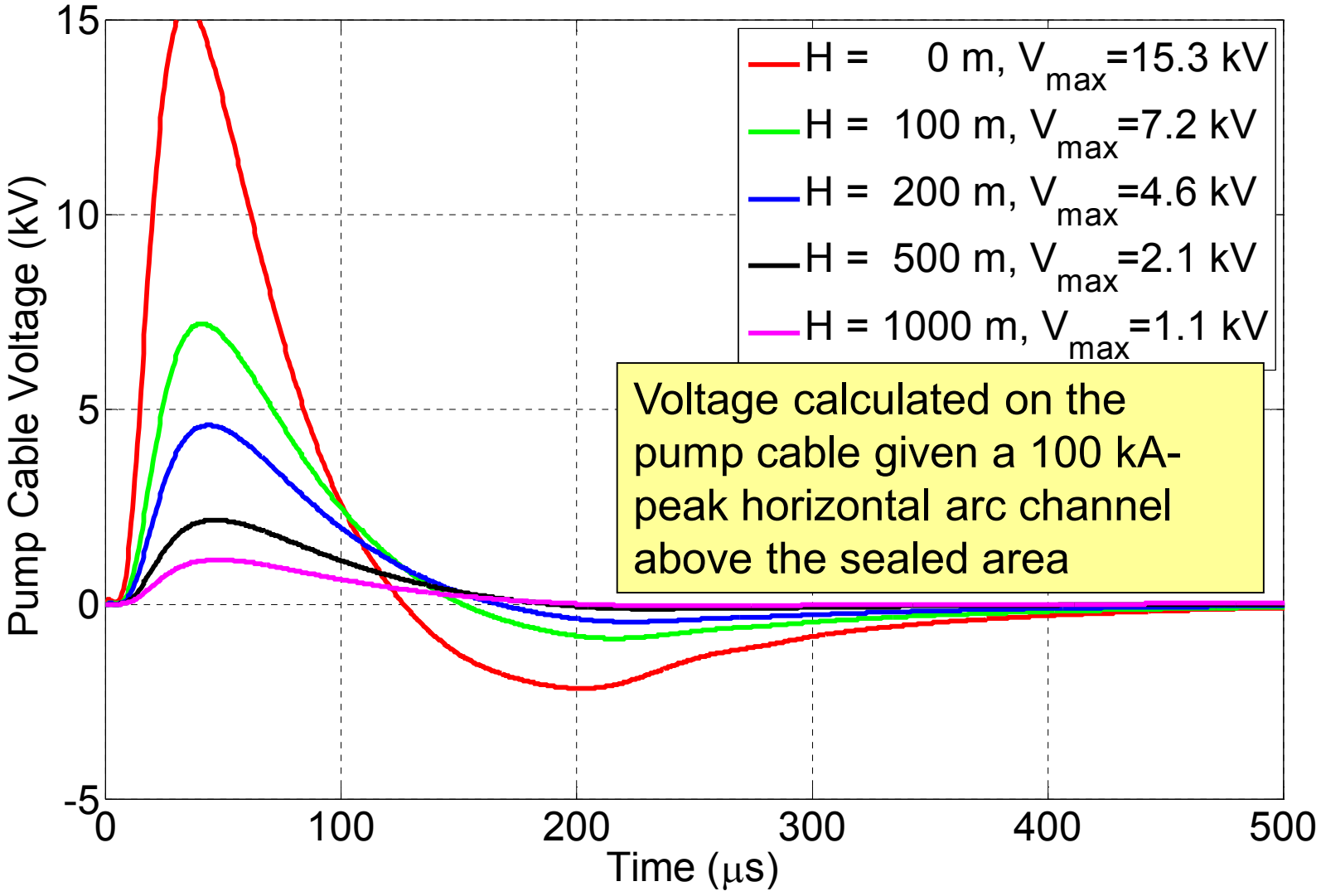
The lightning detection network data is limited

- In general, the lightning detection networks detect approximately 80 – 90% of cloud-to-ground flashes and approximately 50 - 70% of individual strokes within a flash.
- Presence of horizontal arc portions of lightning strokes are not resolved by the lightning detection network sensors.
- Positive, upward-going lightning initiated from tall structures are generally not detected by the sensors. Communication towers are within a mile of the sealed area.

Photo 1. An upward, ground-to-cloud lightning flash in Rapid City, SD, on 26 March 2004. [Photo © 2004 by Tom Warner]



Case 1: Horizontal arc channel above the sealed area does support high voltage arcing on the pump cable



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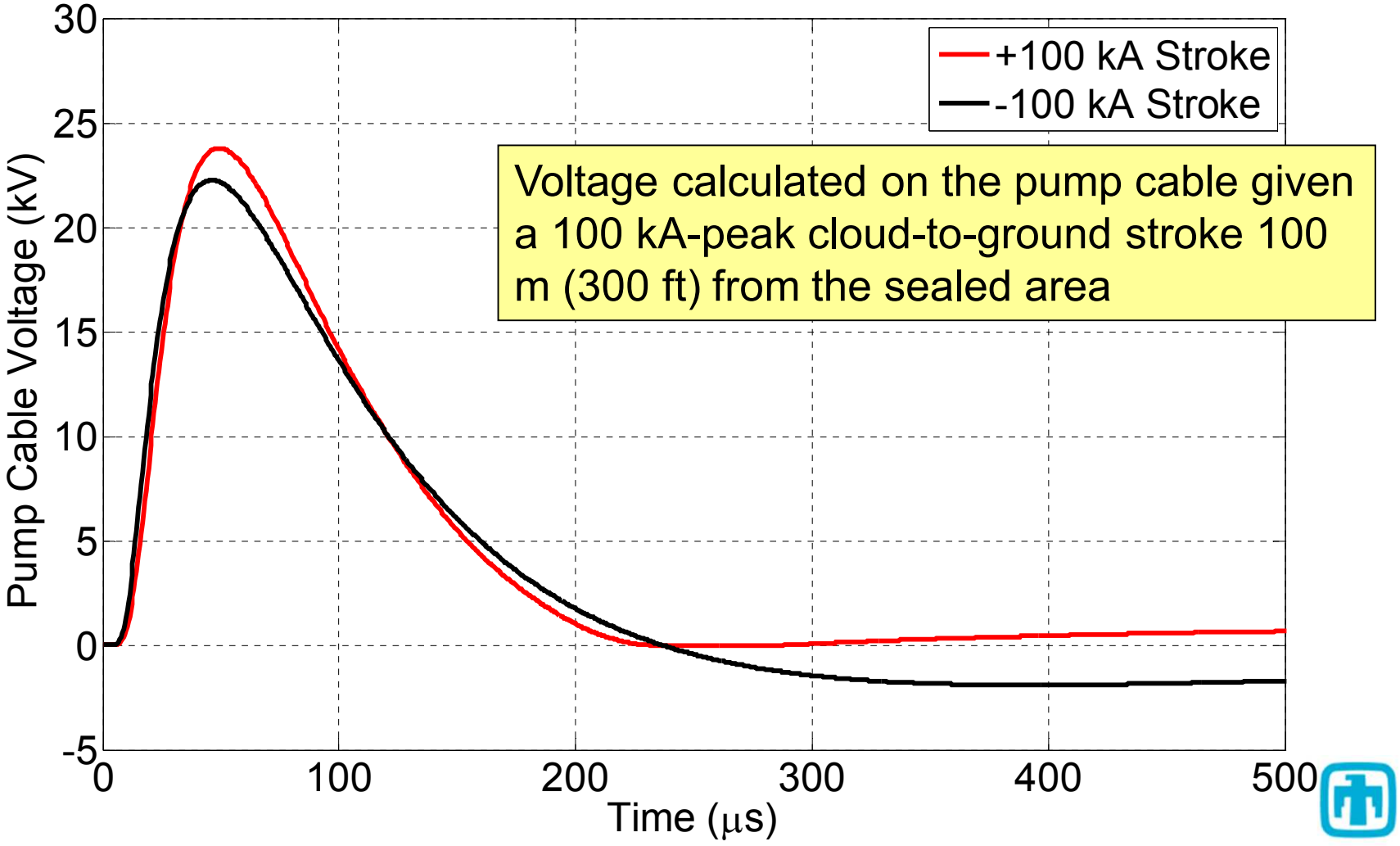
Case 2: Undetected lightning stroke close to the sealed area does support high voltage arcing on the pump cable



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Could lightning have created an electrical arc in the sealed area at Sago?

- From measured direct drive paths --- ***No***
- From 2 recorded lightning strokes (assuming vertical cloud-to-ground geometry) --- ***No***
- From recorded lightning stroke (assuming horizontal arc channel over the sealed area) --- ***Yes***
- From undetected cloud-to-ground lightning stroke close to the sealed area --- ***Yes***

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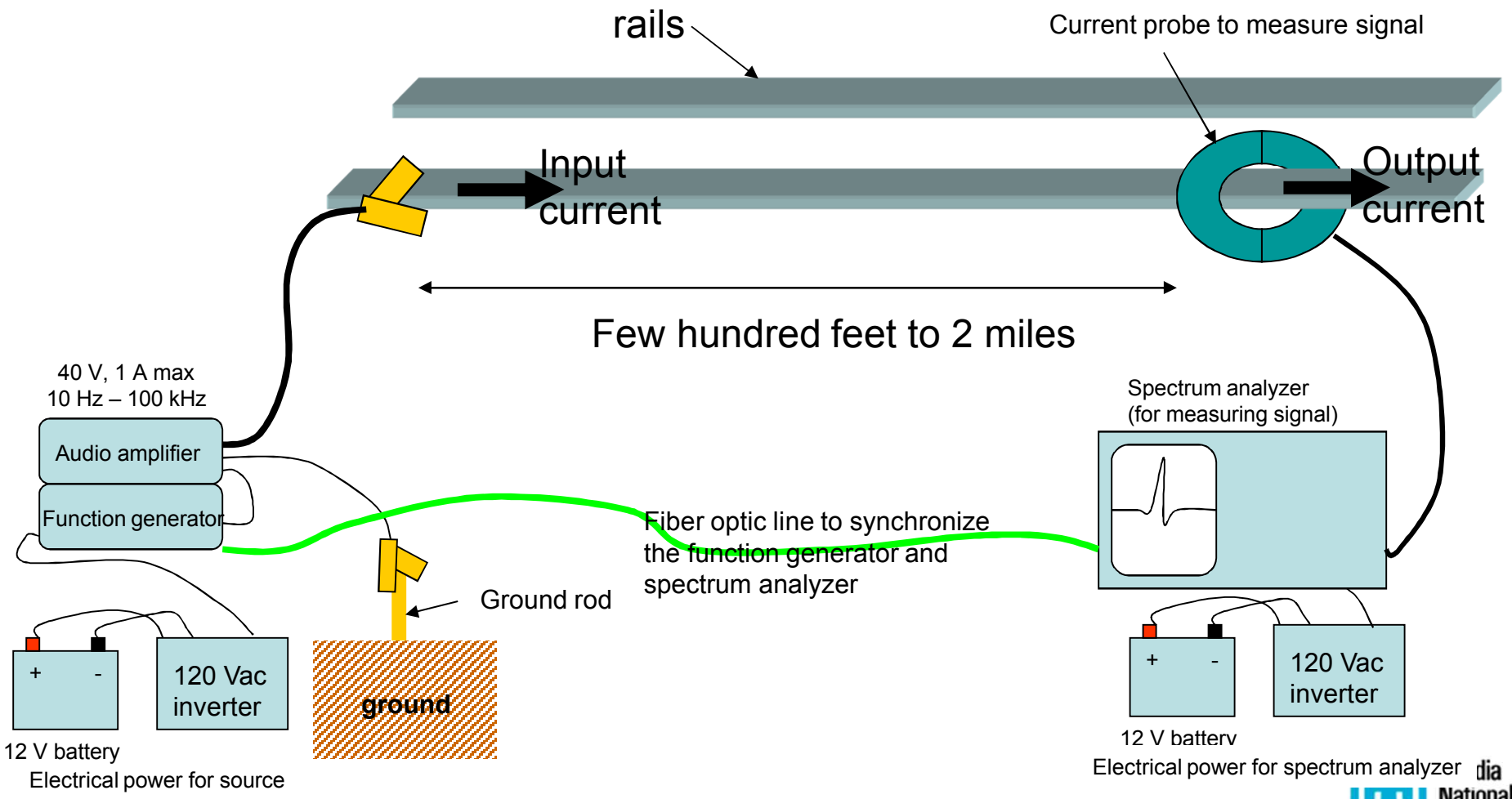
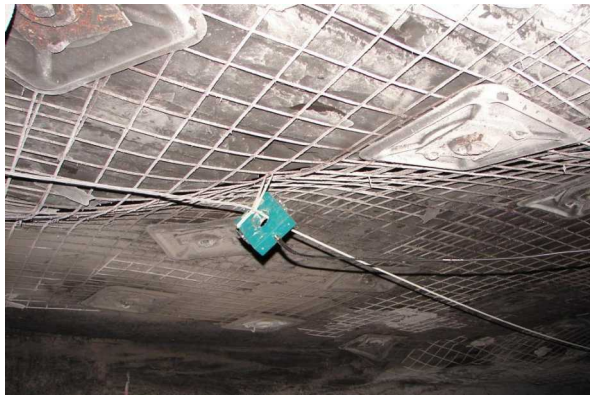
Observation: It is possible that lightning coupling through the measured direct-drive paths could cause electrical shocks to personnel, even miles back into the mine

Backup slides

Direct-drive measurement setup





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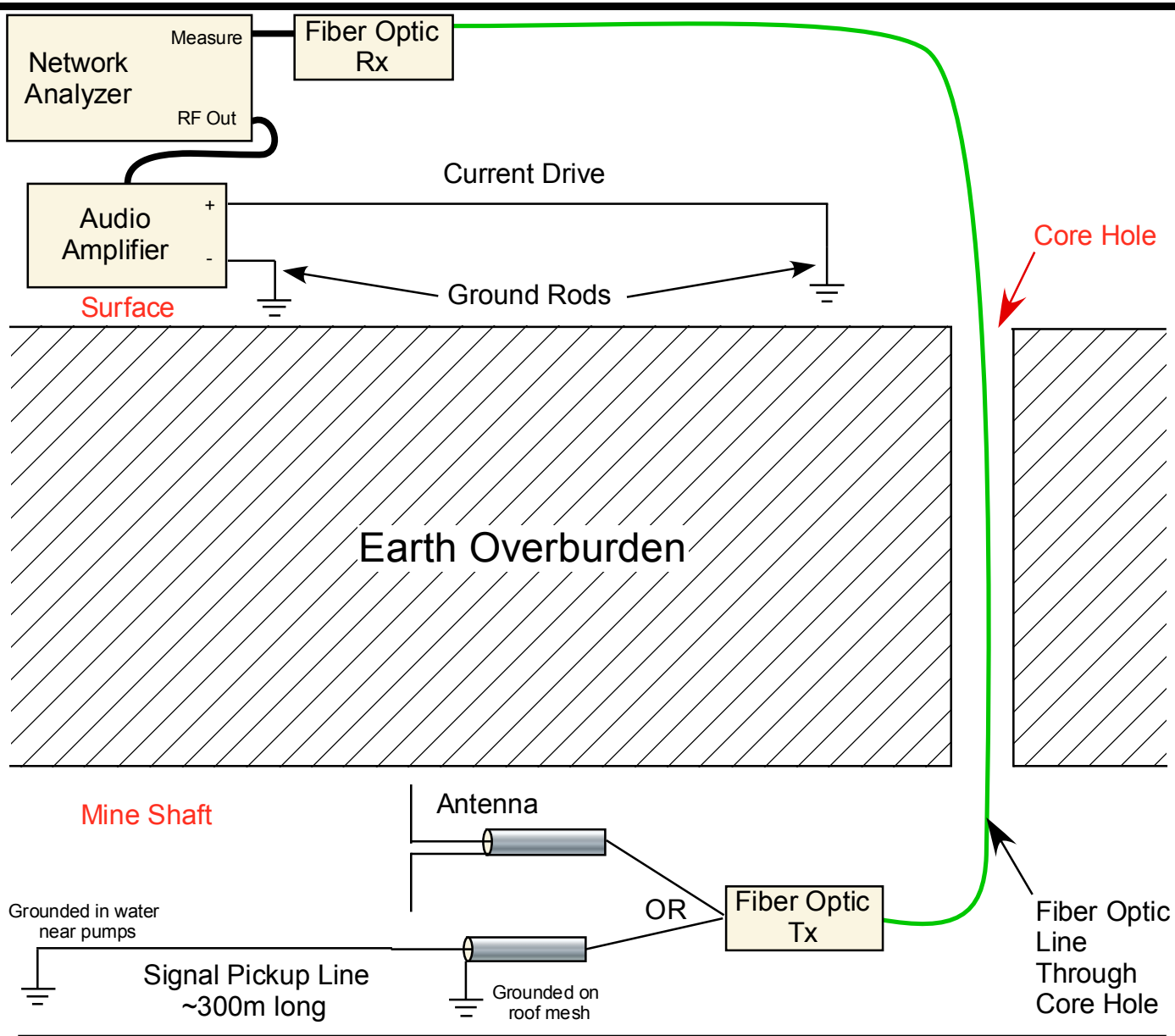

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1976 Bureau of Mines report – "EM Detection System for Detecting and Locating Trapped Miners"

TABLE 1. - Mines where EM location systems have been tested

Mine	Mine type	Location	Overburden, feet
Bureau of Mines Safety Research.	Coal.....	Bruceton, Pa.....	80
Rainbow No. 7.....	...do.....	Rock Springs, Wyo...	140
Latrobe Construction.....	Limestone...	Latrobe, Pa.....	325
Inexco No. 1.....	Fluorspar...	Jamestown, Colo.....	350
Camp No. 2.....	Coal.....	Morganfield, Ky.....	375
U.S. Tunnel.....	Hardrock tunnel.	Idaho Springs, Colo.	390
Copper Queen.....	Copper.....	Bisbee, Ariz.....	400
Guyan No. 1.....	Coal.....	Amherstdale, W. Va..	400
Robena No. 1.....	...do.....	Waynesburg, Pa.....	400
Putnam.....	...do.....	Elmwood, W. Va.....	460
Somerset.....	...do.....	Somerset, Colo.....	500
Robena No. 4.....	...do.....	Waynesburg, Pa.....	990
Geneva.....	...do.....	Dragerton, Utah.....	1,500
Grace.....	Iron.....	Morgantown, Pa.....	2,400
Galena.....	Lead, zinc..	Wallace, Idaho.....	4,300

These results were obtained under mock-emergency conditions. That is, the transmitter is deployed at an unknown point, and the surface personnel do not require any "hints" to perform the location. No fine tuning, no conversation between trapped miners and rescuers, and no additional adjustments are required.

SUMMARY AND CONCLUSIONS

An EM system has been built and tested that permits the detection and location of trapped miners. The hardware required is compact, sturdy, and in general practical for use in mines. Successful field tests of the system have been conducted at a wide variety of mines.