BEFORE THE
PUBLIC SERVICE COMMISSION OF WISCONSIN

In the Matter of the Application of American Transmission Company, As an Electric Utility, to Construct a New 345 kV Transmission Line from the Rockdale Substation to the West Middleton Substation, Dane County, Wisconsin

Docket No. 137-CE-147

DIRECT TESTIMONY OF DR. CHRISTOPHER L. DeMARCO

Q. Please state your name and business address.

A. Christopher L. DeMarco, 1415 Engineering Drive, Madison, Wisconsin.

Q. By whom are you employed and in what capacity?

A. I am employed by the University of Wisconsin-Madison, as a Professor and faculty member in the Department of Electrical and Computer Engineering.

Q. Please describe your educational background.

A. I received my Ph.D. and Masters of Science degrees from the Department of Electrical Engineering and Computer Sciences at the University of California, in Berkeley, California, in 1985 and 1982 respectively. I received my Bachelor of Science degree in Electrical Engineering and Computer Science from the Massachusetts Institute of Technology, Cambridge, Massachusetts, graduating with Phi Beta Kappa honors in 1980.

Q. Please describe your professional experience.

A. Upon completion of my graduate studies, I joined the Department of Electrical and Computer Engineering at the University of Wisconsin as an Assistant Professor in January 1985, with subsequent promotions to Associate Professor in 1990, and to Full Professor in 1995. I served as Department Chair in Electrical and Computer Engineering 2002-2005, and have held sabbatical appointments as a Visiting Associate Professor at MIT, and as a Visiting Professor at Northeastern University.

I have served as a consultant in a number of circumstances involving electric transmission systems. I am presently serving as a consultant advising the Bonneville Power Administration (BPA) in the area of power system voltage stability, under a contract entitled "Response-Based Voltage Stability Controls: Industry Expert Panel Services." I also have served as a consultant to Christensen Associates, Madison, Wisconsin, to evaluate electric generation resource valuation and risk, as influenced by transmission network constraints and ancillary service requirements.

A copy of my curriculum vitae is provided as Exhibit 851.

Q. What are your particular areas of specialization within the field of Electrical and Computer Engineering?

A. My teaching and research have focused primarily on analysis and control of electric power systems, with general control system design and instrumentation being a related interest. I am teaching a Ph.D./M.S. level course "ECE 731–Advanced Power Systems Analysis," focused on transients and protection in transmission systems and generators, and an undergraduate course "ECE 230 – Circuit Analysis" for the Spring 2009 semester. My research has spanned a range of areas in power systems, and as demonstrated in my work with the Bonneville Power Administration, voltage stability has been a long-standing focus. In recognition of my work regarding voltage stability, I was co-recipient of the 2005 Power Engineering Society Working Group Recognition Award for the working group report entitled: "Voltage Stability Assessment: Concepts, Practices and Tools."

Q. On behalf of what organization are you providing testimony in this proceeding?

A. I am providing testimony on behalf of the Coalition for Underground Alternative.

Q. What is the purpose of your testimony in this proceeding?

A. The purpose of my testimony in this proceeding includes (a) to evaluate the power systems analysis contained in ATC's filings regarding the Rockdale-West Middleton project; (b) to analyze the connection between transmission system needs described by ATC and the possible solutions to those transmission system needs, including whether ATC's proposed 345 kV transmission line represents the optimal solution to those transmission system needs; (c) to evaluate the voltage stability concerns assert by ATC and to describe best practices in solving such voltage stability problems; (d) to provide information regarding the placement of transmission lines underground, including 345 kV transmission lines; and (e) to evaluate whether the placing of the proposed transmission line underground creates any power system problems on ATC's transmission system.

Q. Please summarize the conclusions you have reached in this proceeding.

A. I describe in detail my conclusions and the reasons for those conclusions in this testimony. In summary I have concluded the following:

(a) ATC's proposed 345 kV Rockdale-West Middleton transmission line is substantially oversized relative to its predicted peak power carrying needs. The maximum power in megawatts to be carried by ATC's proposed 345 kV Rockdale-West Middleton transmission line is considerably smaller than the norm for transmission lines at this voltage level. The oversizing of ATC's proposed transmission line relative to its predicted future peak power carrying needs is most pronounced in the design ATC proposed and studied for an underground transmission line. ATC's underground transmission line design specified as a power handling capability more than three times greater than the predicted future power requirements and three times greater than what other surrounding equipment on the transmission grid could possibly handle. ATC did not conduct sufficiently thorough transmission system studies, particularly in regard to lower voltage alternatives to the 345 kV transmission line and options for underground placement.

(b) ATC's proposed 345 kV transmission line is not the optimal solution to the voltage stability concerns identified in ATC's transmission studies. ATC’s study methods fall far short of best practices in the industry regarding the solutions to the identified voltage stability concerns.

(c) Extensive information exists demonstrating an increasing trend to place transmission lines underground, including 345 kV transmission lines. There are millions of feet of 345 kV transmission line conductor placed underground in this country and in other parts of the world that have been found to be extraordinarily reliable in operation.

(d) It is technically feasible to place ATC's proposed 345 kV transmission line underground without creating any power system problems on ATC's transmission system.

POWER SYSTEM ANALYSIS

Q. Please describe in layperson's terms the nature of the enhancement that ATC's Rockdale-West Middleton project is intended to bring to Dane County electric power transmission.

A. From the standpoint of power delivery, the proposed Rockdale-West Middleton line is a radial extension, that brings the higher voltage level from a point where it currently exists (Rockdale), to a point (West Middleton) at which significant load growth was anticipated at the time of ATC's filing. As a radial extension of the higher voltage 345 kV system, the Rockdale-West Middleton transmission line does not create a strengthened interconnection between two existing portions of 345 kV transmission.

The primary justification of an addition of a transmission line to the grid is almost always to increase the grid's ability to transfer and deliver active electric power, measured in megawatts (MW). While specific technical details govern any transmission study, as a rule, projects that strengthen interconnection between high voltage sections of the grid typically make the greatest contribution to grid reliability. This is not the nature of the Rockdale-West Middleton project.

In analogy to transportation grids, the existing 138 kV lines that make up the bulk of Dane County's transmission system may be roughly considered routes of the state highway class, while the proposed 345 kV line might fall into a class roughly analogous to interstate highway. In terms of this highway analogy, the proposed Rockdale-West Middleton line extends a larger, "interstate quality" highway closer to a point where a large volume of traffic is expected to enter or exit. In the highway analogy, the Rockdale-West Middleton transmission line does not link two existing portions of interstate-quality roadway – it just extends the higher capacity "on/off ramp" closer to where traffic is anticipated to grow.

Q. What is the capacity and expected MW operating level for the proposed Rockdale-West Middleton transmission line?

A. The Rockdale-West Middleton transmission line is a purely radial extension off the existing 345 kV transmission line, extending out to "feed" 138 kV (and lower voltage) portions of the grid to the west. Consequently, the Rockdale-West Middleton transmission line has a clear limit on its maximum power capability set by the transformer at West Middleton. As the name implies, a transformer is the equipment that converts between voltage levels. It is a concentrated point through which electric power must flow. Because a transformer can be subject to significant damage if overloaded, a transformer has clearly specified maximum power ratings: its "normal" limit, and an "emergency" rating at which it can operate for short periods of time. Transformer power ratings are provided in units of Mega-Volt-Amperes (MVA), rather than MW. The exact relation between MVA and MW requires an understanding of the concept of "reactive power" which will become relevant in discussion of voltage stability problems. However, here one needs only to understand the simple fact that MW power transfer is always less than or equal to power transfer in MVA.

ATC's filing specifies the 345 kV-to-138 kV transformer at West Middleton to have a normal rating of 500 MVA, and a short term emergency rating of 625 MVA. Accordingly, except for short-term emergencies, the overall equipment associated with the proposed Rockdale to West Middleton 345 kV project could deliver no more than 500 MW. This conclusion is confirmed by other engineering details of ATC's filings that report the maximum current the 345 kV overhead line is expected to carry (as part of electromagnetic field impact calculations). There, the maximum current the transmission line is predicted to carry (along its segment M) in the year 2023 is 755 Amperes. Standard power systems computations translate this figure to a maximum power of 451 MVA: 1.73x(345,000 Volts)x(755 Amps) = 451 MVA. In other words, peak power transfer predicted for the year 2023 translates into power delivery of no more than 450 MW on the Rockdale-to-West Middleton line.

Q. How does this power delivery capability of the proposed Rockdale-West Middleton transmission line compare to typical levels for other 345 kV transmission lines in the United States?

A. The 450-500 MW power delivery capability of the Rockdale-West Middleton transmission line is abnormally low for a 345 kV line. For a given voltage level, the exact power handling capability for transmission lines vary with the geometry and electrical characteristics of the transmission line's design. Standard textbook treatments[1] and industry literature[2] often characterize the power handling capability of an overhead line as a multiple of its surge impedance loading (SIL). A typical overhead 345 kV line has a SIL of approximately 400 MVA; the well-known "St. Clair Curve" then establishes the power handling capability (on lines up to 50-100 miles in length) to be 2 to 3 times that SIL value; i.e. 800-1200 MVA. Similarly, U.S. Department of Energy tutorial literature

[1] e.g., A.R. Bergen, V. Vittal, Power Systems Analysis, Prentice-Hall, 2000.

[2] American Electric Power Company, http://www.aep.com/about/i765project/docs/AEPInterstateProject-765kVor345kV.pdf

characterizes 345 kV lines as typically being employed for power delivery of 800 MW and above.

Q. If the proposed Rockdale-to-West Middleton 345 kV line is projected to carry 500 MW or less, and typical 345 kV lines in the U.S. can carry 800 MW or more, could a transmission line of lower voltage level serve the projected need for power transfer?

A. Yes, it could. Delivery of 450-500 MW is well within the design capability of typical 230 kV transmission lines, and 230 kV is another standard transmission level common in the U.S., and used in portions of ATC's system near Milwaukee. Even a sufficiently robust design of a multi-circuit 138 kV line could yield power handling capability above 400 MW range. For example, assuming a maximum conductor current of 900 Amps, two circuits at 138 kV on a line of this length could deliver up to 430 MW.

2x1.73x{138,000 Volts}x{900 Amps} = 430 MW.

Q. Given these observations, did ATC conduct sufficiently thorough transmission studies considering lower voltage alternatives?

A. No, it did not. The possibility of new 230 kV lines was not considered in any of the transmission studies reported in ATC's filings for this project. As reported in Appendix C of ATC's October 2007 filings, ATC did study what it termed the "All 138 kV Alternative." Based on those studies, ATC's Appendix C shows the All 138 kV Alternative resolves the "Dane County Problem" identified, but for the specific scenarios studied, did so at greater cost and with less versatility than the Rockdale-West Middleton 345 kV proposal. However, the All 138 kV Alternative studied was not, as the section title might suggest, a substitution of a 138 kV transmission line for the proposed 345 kV Rockdale-to-West Middleton line. Rather, the configurations studied in that option involved a set of upgrades to existing lines at the 138 kV or lower voltage level, along with some new 138 kV lines along paths shorter than the complete Rockdale to West Middleton path. In particular, the All 138 kV Alternative did not consider creation of a new, dedicated transmission path from Rockdale to West Middleton, as would be created by the proposed 345 kV transmission line. Transmission studies beyond those conducted by ATC in the filing documents would be necessary to decide whether a dedicated Rockdale to West Middleton multi-circuit 138 kV transmission line would have changed the conclusion regarding an All 138 kV Alternative. However, failure to examine this seemingly obvious alternative leads me to conclude that the transmission studies of ATC's filings were not sufficiently thorough.

Failure to consider lower voltage alternatives along the Rockdale-West Middleton path particularly handicaps underground alternatives, as lower voltage underground options might provide considerable savings relative to a 345 kV underground line. In particular, a 138 kV underground option would admit the use of pipe-type HPGF transmission cable, which can be a particularly cost effective option for underground installations. A HPGF pipe-type system contains no fluid, and, like other pipe-type underground transmission, could have part or all of its length installed using horizontal directional drilling. Directional drilling is an installation method in which there is no trenching excavation along the path of the line, but rather only periodic drilling and "pipe pulling" at work locations that can be as far as 5000 feet apart (i.e., the above ground environment is undisturbed along sections of up to nearly a mile in length). Any credible effort to explore the underground alternative would have explored the viability of this very attractive option. To see the shortcomings of ATC's study that failed to consider pipe-type systems, one need only look at industry best practice as specified by the Regional Transmission Operator, PJM. In its requirements for underground transmission[3], PJM states: "Underground transmission lines 230kV and above should generally be

[3] Section V.B of PJM TSDS Technical Requirements: "PJM DESIGN AND APPLICATION OF UNDERGROUND TRANSMISSION CABLES," http://www.pjm.com/planning/design-engineering/~/media/planning/design-engineering/maac-standards/20020520-vb-transmission-cables.ashx

pipe-type. Pipe type systems are preferred due to their extremely high reliability."

VOLTAGE STABILITY ANALYSIS

Q. What is voltage instability?

A. Voltage instability is a particular mechanism by which a power system can "run away" from its normal, desirable steady state operating condition. It contrasts with another instability phenomenon, generally termed "electromechanical instability." The dominant manifestation of voltage instability is a declining voltage level, ultimately running away to voltage "collapse." The dominant manifestation of electromechanical instability is growing oscillations in power and frequency among generators on the grid. Voltage instability is most strongly associated with insufficient reactive power (units of MVARs) support in a system, and tends to be localized to the portion of the grid it affects. Voltage instability is often, but not always, preceded by relatively depressed voltage levels in the steady state. Electromechanical instability is most strongly associated with imbalances in "active" power (units of MWs), and oscillatory exchanges of MWs between generators, over relatively large areas within the grid.

Q. Is the use of a 345 kV line to address the voltage stability phenomenon described by ATC in this proceeding consistent with best utility practices?

A. No, it is not. The positive objective of improved "voltage stability" should be to increase the operating margins, to keep the system sufficiently far away from operating conditions that result in instability. While a new transmission line can help improve operating margins, a new line is not the most directly effective "fix" for voltage problems from a purely technical standpoint, and it is certainly not the most cost effective means of improving voltage stability. Voltage instability is a relatively local phenomenon, associated with insufficient reactive support at one bus (i.e., major substation), or at a small set of closely grouped buses. The most effective means to increase the operating margin away from voltage instability conditions is to increase reactive support at the critical bus(es). In the vernacular of power engineering, it is common to observe that "VARs don't travel." This is an informal expression of the best practice – it is not very effective to try to "move" VARs from a stronger area of the system (e.g., the 345 kV substation at Rockdale) to help support voltage in a "weaker" area of the system (e.g., West Middleton). To achieve significant improvements in voltage stability by a transmission line "fix" requires a very strong line, which seems to have been the approach in ATC's proposal.

Q. Is there a more effective means by which the voltage instability phenomenon can be mitigated, rather than by ATC's design?

A. Absolutely. A more directly effective and much more cost effective improvement, rather than a transmission-line fix to voltage stability problems, is to provide local reactive support. Local reactive support can most effectively be provided from an engineering and cost perspective by a mix of continuously variable dynamic reactive support and capacitor banks. The most common and cost effective form of dynamic reactive support today is offered by the technology known as a "Static VAR Compensator (SVC)." No consideration appears to have been given in ATC's studies to SVCs as a part of the solution to the described voltage stability concern. Switched capacitor banks offer the "first tier" of industry best practice in solving voltage problems, and are an extremely robust and cost effective technology. The only shortcoming of simple switched capacitors for local reactive support improvements is that they can only be switched in "lumpy," large steps, and the speed and frequency with which they are switched must be modest. For more rapidly evolving situations, typical best practice in the industry is to supplement the slower, "lumpier" switched capacitor banks with fast, continuously variable dynamic reactive support.

Q. How do you define best utility practices as applicable to voltage stability concerns?

A. Much industry best practice in the U.S. appears through the publications of the Institute of Electrical and Electronics Engineers (IEEE), and its Power & Energy Society. Over the past twenty years, the issues relating to voltage stability have been a widely studied topic within the IEEE, and many papers and reports have emerged describing best practices. Among these is the Working Group Report I co-authored, "Voltage Stability Assessment: Concepts, Practices and Tools," IEEE PES Power System Stability Subcommittee Special Publication, IEEE # SP101PSS. Having been a topic of significant interest for more than twenty years, power industry oriented texts have also been written on the topic. One of the most respected is by Carson Taylor, a National Academy of Engineering member who spent his long career with the Bonneville Power Administration, where much of his work centered on improving the resilience of Bonneville Power Administration's system with respect to voltage instability problems. His practical experience is reflected in his 1993 text, Power System Voltage Stability. I see no evidence in ATC's voltage stability studies that they met the level of best practice reflected in this classic text on the subject. Moreover, since 1993, the increasing penetration of electronic loads (predominantly computers), and even more significantly, the growing percentage of summer load devoted to residential air conditioners, has created a new form of threat to voltage stability. This is known as the "Fault Induced Delayed Voltage Recovery" (FIDVR) problem. I saw no evidence that ATC's engineers considered this threat to voltage stability. The FIDVR problem is less likely to be effectively mitigated by a large transmission line than by appropriately designed VAR support schemes. In particular, the threat of FIDVR makes the careful balancing of dynamic VAR sources (of the type not considered in ATC's studies) and switched capacitors even more important. Dane County is a perfect example of a region in which residential air conditioners were historically insignificant. But with the rapid growth of new residential construction, and the relative decline in manufacturing, residential air conditioners now play a much larger role in electric demand. This is precisely the scenario in which FIDVR-type voltage instability is a threat to reliable operation. It appears that ATC personnel have not addressed the FIDVR problem in their voltage stability studies.

Q. If an underground line, whether at 345 kV as studied by ATC, or at 230 kV or 138 kV, were selected for the Rockdale West Middleton corridor, would use of such an underground line undermine the voltage stability within Dane County.

A. No, it would not. In fact, to a modest degree, the added capacitance of an underground line can actually help improve voltage stability. But, whether underground or overhead, the transmission line should be evaluated and "right-sized" based on its requirements to deliver active power (MWs). Then the appropriate switched capacitors and dynamic VAR sources should be placed at those locations where improved voltage support is needed. Because voltage instability is a local problem, the most cost effective solution is not some single number of VARs to be added at one location in Dane County. Rather, an effective voltage support solution needs to be tailored to those individual buses that need it, whose locations may or may not coincide with the two buses at which a new line terminates, such as Rockdale-West Middleton.

TECHNICAL FEASIBILITY OF UNDERGROUND TRANSMISSION LINES

Q. Is it technically feasible to place the 345 kV transmission line proposed by ATC underground?

A. Yes. There exist numerous successful underground transmission projects at the 345 kV voltage level in operation in the United States and around the world. Examples of recent 345 kV underground transmission projects in the United States include the NSTAR Boston to Stoughton Transmission Reliability Project; the Northeastern Utilities Bethel to Norwalk Transmission Project; the ComEd Transmission Reliability Reinforcement Project in Chicago; and the ITC Transmission Bismarck to Troy project near Detroit. I will describe two of these examples in greater detail.

NSTAR recently successfully energized an 18 mile 345 kV underground transmission project connecting from the town of Stoughton, Massachusetts, into Boston. NSTAR's project cost was estimated in 2005 as approximately $225 million by the New England Independent System Operator. This system was a pipe-type cable underground installation, and the NE-ISO studies concluded its cost was lower than overhead transmission alternatives to serve the same need. From the transmission operation standpoint, the NSTAR project is similar to ATC’s proposal in that neither is an interconnection between two 345 kV points in their respective grids. Rather, both are radial extensions of 345 kV. ATC's project and NSTAR's project simply move the step-down point from 345 kV to lower voltage closer to a load center (the step down is to 138 kV for ATC, to 115 kV for NSTAR). Also significant to this testimony is the power delivery capability for NSTAR’s 345 kV underground project. In its present configuration, NSTAR states that its 345 kV underground line provides 800 MW of additional power delivery capability into the Boston area. With upgrades to other equipment in the surrounding grid, the enhanced power import capability is expected to rise to 1200 MW. This contrasts markedly with the power handling capability of less than 500 MW for the Rockdale-West Middleton project. This observation also reinforces a point in my testimony above: the transmission enhancement needs of Dane County could be served by a Rockdale to West Middleton line of lower voltage level than 345 kV. By “right-sizing” the line’s voltage level for its power handling needs, the job of placing the transmission line underground becomes easier.

The technical feasibility of an underground alternative is also confirmed by the recent experience of Northeast Utilities in installing 345 kV underground lines near Bethel and Norwalk, CT. In its January 2008 issue, the trade publication “Transmission and Distribution World” reports:

"The Bethel-Norwalk (B-N) project is a significant component of a suite of 345-kV and 115-kV system upgrades in this area.... The B-N project entailed more than 11 miles (18 km) of new 345-kV underground transmission cable, two new 345-kV gas-insulated substations, three transition stations and more than 20 miles (32 km) of new overhead 345-kV line. Yet, Northeast Utilities (NU; Berlin, Connecticut, U.S.) energized this landmark project two months ahead of schedule and US$15 million under budget."

Q. What is ATC's position concerning the technical feasibility of placing the 345 kV transmission line underground?

A. ATC concedes that the construction of its 345 kV transmission line underground is technically feasible. The feasibility of constructing a portion of the proposed Rockdale to West Middleton line underground is primarily addressed in Appendix J of the ATC's filing documents. The majority of Appendix J is composed of various separate subsections, authored by a group of outside engineering consulting firms that ATC employed to conduct the studies. A succinct summary of the conclusions of these studies may be found in the first page to Part 4 of Appendix J, which begins by stating:

"The overall goal was to identify major cost items and technical showstoppers for the new line" (here "the new line" is understood to be the 25 mile underground portion of the 345 kV line being studied in Appendix J). After briefly summarizing three classes of additional electrical equipment necessitated by the underground option (variable shunt reactors, upgraded circuit breakers with pre-insertion resistors, and upgraded surge arrester voltage ratings and insulation levels at the Cardinal substation), the overall conclusion is summarized by stating:

"There were no technical showstoppers identified."

To put this conclusion in context, it is worth examining the three firms that contributed to the technical studies of undergrounding in Appendix J, and their respective roles.

i) POWER Engineers developed the electrical and installation specifications for the underground portion of 345 kV line considered. Having proposed the specifications, POWER Engineers also conducted an analysis on what could be roughly termed the "stand alone" electrical characteristics of the line, which comprise those aspects of performance that require little or no information regarding the characteristics of the surrounding grid into which the line is placed (in technical terms, POWER Engineers conducted electrical transient analyses on the proposed underground section of line).

ii) HBK Engineering (working with Kenney Construction Co.) analyzed the civil engineering related aspects of trenching, conduit construction, and site management, based on requirements for the installation and trenching provided by POWER Engineers. The report reflects significant collaboration and exchange of information between Power Engineers, HBK, and ATC in the writing of these portions.

iii) Analysis of the overall electrical characteristics of the underground 345 kV line, and its integration into the operations of ATC's transmission system was performed by EnerNex. Here, the text strongly suggests that exchange of information and cooperation between EnerNex, ATC and the other contractors was not adequate. EnerNex states in Appendix J that "While EnerNex's work was in progress, ATC had not completed load flow and other planning studies of this line. Therefore, some assumptions were necessary in order to evaluate the project design options and major cost elements. This appendix describes a conceptual design for cable, shunt reactor, and switchgear arrangements of the ATC Rockdale-West Middleton (Cardinal) 345-kV line. It was developed in May 2007, and then used to guide subsequent study work by ATC and EnerNex. These design elements were subject to revision after completion of ATC's full suite of planning studies." In my professional opinion, ATC's failure to provide necessary power flow data would have caused EnerNex's studies to err on the side of conservatism, in some places employing worst-case assumptions. This adds even greater weight to EnerNex's conclusion that "there were no technical showstoppers identified" in their study of underground placement for a portion of the Rockdale-West Middleton project.

Q. The outside contractors who studied the underground option on behalf of ATC described three classes of additional electrical equipment necessitated by ATC's underground option. What observations can you provide regarding the need for additional equipment related to ATC's underground option?

A. By design, underground transmission lines place their conductors in closer physical proximity to one another, and obviously, closer to the ground. This inherently creates a greater electrical capacitance per unit length relative to a comparably rated overhead line. Important to the objectives of this testimony is that ATC's specifications significantly oversized the current carrying capacity ("ampacity") of the underground line relative to the power handling needs of the Dane County transmission system. This has the consequence of requiring a relatively large conductor size (3000 kcmil), and two parallel circuits. In describing the consequences of these design choices, the EnerNex engineers anticipate the desire to reduce the ampacity, and therefore the underground line's capacitance, and ultimately reducing cost and complexity. In Appendix J of ATC filings, EnerNex states: "The cable size and configuration have been selected to satisfy ATC's reliability requirements, and reasonably foreseeable future expansions. On the other hand, any possible reduction in total cable capacitance would produce the following important cost reductions and technical benefits:

- Smaller shunt reactors
- Lower impact on circuit breaker capacitive current ratings
- Less risk of harmonic resonance
- Less risk of dynamic overvoltage after energizing the Cardinal autotransformer
- Lower TOV levels, and lower required voltage rating of surge arresters, leading to better protection of equipment insulation."

The key assumption here is that the current carrying capacity is actually appropriate to and for the "reliability requirements, and reasonably foreseeable future expansions." As the EnerNex report points out, ATC had not performed nor shared with EnerNex powerflow studies on the underground line. Without such data, EnerNex could not independently assess the need for a double circuit underground line with the relatively large diameter conductor of 3000 kcmil. The EnerNex report *does* comment upon the significant savings that could be provided if the underground line had not been specified with such large current carrying capacity, and hence such high capacitance. The EnerNex engineers state: "Methods of reducing the cable capacitance include:

 Limiting the total installed length of underground line segments.

 Using smaller cable than 3000 kcmil XLPE, although this may have an undesired effect of lowering the line's total ampacity.

 Leaving the second cable un-energized as a spare, although this may present a risk that the spare cable's insulation will become compromised, and not ready for service when needed."

To EnerNex's list of capacitance reducing options, I would add one very significant one: reduction of the voltage level chosen for the underground line. More generally, the initial design specification that limited investigation to 345 kV XLPE cable eliminated a range of other, very credible underground design options (such as pipe-type cable, or lower voltage) that likely would have yielded lower cost and fewer technical challenges than the configuration that was chosen for study.

Q. In your testimony, you describe the design choice for the underground 345 kV option as studied by ATC as oversized. Can you elaborate on the impact of that conclusion?

A. Yes, I can. Section 2.4.2 of ATC's Appendix J specifies the design criteria employed for the underground line. The ampacity (i.e., current carrying capability) specified is a summer normal value of 2385 Amps, and a summer emergency value of 3151 Amps. Recall that the radial configuration of the line implies that essentially all its current must pass through the 345 kV/138 kV transformer at the West Middleton termination, which is also specified as part of this project. As previously noted, that transformer has a summer normal rating of 500 MVA, and a summer emergency rating of 625 MVA. Converted to equivalent current ratings, the transformer is limited to 830 Amps summer normal, 1045 Amps summer emergency rating. Hence, ATC specified that the underground line must have a summer emergency current capability more than three times greater than its terminating transformer could possibly handle. If one compares to values predicted in the overhead line option, for which full power flow studies were performed, the contrast is even more dramatic. Recall the peak current the overhead 345 kV line is predicted to carry in year 2023 is 755 Amps. This unrealistic oversizing of the underground line greatly increases its capacitance, thereby severely handicapping the underground design relative to the overhead option. Again, as the EnerNex engineers state in their study for ATC, "any possible reduction in total cable capacitance would produce … important cost reductions and technical benefits."

Q. Does this conclude your prefiled direct testimony?

A. Yes, it does.