Cable Train: A Platform for In-Situ Manufacturing of Underground Cable

Luke A. Gray [A] Alexander H. Slocum, PhD. [A] Qi Du [B]

Submitted to the
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Signature of Author: Signature redacted
Department of Mechanical Engineering
May 11, 2018

Certified by: Signature redacted
Alexander H. Slocum
Walter M. May and A. Hazel May Professor of Mechanical Engineering
Thesis Supervisor

Accepted by: Signature redacted
Rohit Karnik
Associate Professor of Mechanical Engineering
Undergraduate Officer

[A] Massachusetts Institute of Technology (MIT), Department of Mechanical Engineering
[B] Dongfang Electric Corporation (东方电气)

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ABSTRACT

As the demand for and viability of renewable energies has increased, connecting remote power generation stations to demand centers has become more important. High Voltage Direct Current (HVDC) transmission systems offer efficiency and cost effectiveness over long distances, allow for the linkage of incompatible AC grids, and can be immune to telluric currents and aggressive EMP attacks, which all make these systems particularly applicable to connecting to remote renewables. With the current state-of-the-art in HVDC, overhead lines (OHL) are several times cheaper than underground cables (UGC). However, OHLs have security risks and create substantial visual pollution, which has resulted in significant public opposition and lengthy delays in project permitting. Project developers have reluctantly agreed to replace portions of overhead line with underground cable as a concession to these stakeholders. One way to make UGCs more attractive to developers is to reduce cost by locating UGC systems along railroad right of ways. The increased mobility of heavy machines and materials on railroads and the state-of-the-art in railroad construction machinery provide both precedent and process advantages, which make the concept of augmenting railroads with underground cable systems an attractive one. The practice of installing and maintaining such systems could be less complex than traditional methods required by independent transmission corridors. The use of private railways may avoid conflicts with external stakeholders and eliminate the regulatory delays that have plagued many renewable energy transmission projects. Additionally, taking advantage of the increased accessibility of railroads by in-situ manufacturing high voltage, extruded cable in lengths far greater than what is currently able to be transported by road haulage, may reduce overall project costs by eliminating expensive and vulnerable cable splices. To accomplish this, here we present a method for continuously manufacturing and installing high voltage underground cable from a moving "Cable Train" using public-private railway systems. There are three primary challenges associated with such a mobile platform – extrusion, curing, and degassing. Several promising countermeasures have been presented, which require varying levels of further development - continuous extrusion, horizontal curing, and inline degassing. Herein, further discussions on standards, system topology, earthworks, practical limitations to cable production length, and cost estimation, can also be found. The technology and methods to accomplish this vision can be achieved by a pre-competitive technology consortium with member companies capable of completing and fully realizing the proof-of-concept designs proposed.

Thesis Supervisor: Alexander H. Slocum

Walter M. May and A. Hazel May Professor of Mechanical Engineering

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I would like to express my sincerest gratitude to **Professor Alexander H. Slocum** and Mr. **Qi Du** for their extremely valuable insights throughout the course of this project. Professor Slocum has brought his precision machine design experience to bear on all aspects of the project and Qi Du never stopped reminding me to "expand my mind" despite the increasing level of detail my tasks acquired.

I would also like to thank **Mr. Peter Stewart-Hay** of Stewart-Hay Associates, **Dr. Cory Liu** of Southwire Company, LLC., **Mr. Eugenio Urbina** of TROESTER GmbH & Co., and **Mr. Tim Murphy** of Bartell Machinery Systems LLC. for volunteering their expertise on several occasions and offering to continue to make themselves available to the needs of the project. Young people like myself are truly blessed to receive such a reception from such high-quality people in industry.

Biographical Note

Luke A. Gray is originally from Exeter, New Hampshire, where he attended Phillips Exeter Academy. He loves running, hiking, and woodworking and has a great interest in renewable energy development and medical devices. The author would invite anyone from Phillips Exeter and MIT, or anyone with interest in the Cable Train project, to reach out to him to discuss.

Notable Content in this Thesis

Of particular interest is the development of a "space-saving inline handling system for roll-to-roll processing" as a countermeasure for degassing extremely long lengths of cable onboard the Cable Train. Degassing is a crucial step in cable manufacturing. It must be performed after initial insulation extrusion and before solid metallic shielding. This is usually achieved by heating the cable, below the de-crystallization temperature of the insulation, for periods of up to 40 days. Insufficient degassing can result in artificially high dielectric strength measured during cable qualification, altered electrical and thermal properties, and ongoing evolution of gases that pressurizes and damages the cable. If cable is to be completely manufactured onboard the Cable Train, degassing must be done between initial extrusion and waterproof shielding. If cable is simply conveyed down the length of the train while degassing is allowed to occur, typical production rates, multiplied by desired degassing times, can require a railcar section in excess of 100 kilometers. Such an arrangement would be capital intensive, cumbersome, and energy-consuming. The inline system developed as a countermeasure decreases the length of this section of the train by approximately 40x. The system accomplishes this by continuously processing cable over a plurality of rotating drums. The system uses stationary helical guides to control the motion of the cable as it makes multiple passes around each drum. This handling topology essentially allows the continuous processing of reel-to-reel products while reducing the volume in which the environmental conditions necessary for the process – temperature, pressure, atmospheric composition, for example – must be controlled. Therefore, this concept may have applications to other fields that require roll-to-roll processing. One application could be the production of extraordinarily long factory-made cable.

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Background and Concept Introduction

International, national, and municipal resolutions to decarbonize industry and energy consumption have been on the rise during the last decade. California and Massachusetts, for example, have both committed to ambitious renewables development plans. The former has promised to reduce greenhouse gas emissions by 40% below 1990 levels by 2030 (SB 350) and the latter has promised to achieve 100% de-carbonization by 2050 (An Act Relative to Energy Diversity).[1] These are two of the many initiatives instigated all around the world that manifest an increasing desire for renewable grids. This evolution in energy portfolios requires not just the redistribution of power, but also the utilization of new, and often remote, renewable energy resources to meet current and future demand. Long distance transmission connections will be critical in achieving renewable grids.

Why Direct Linkages? Today's transmission systems carry power across large distances through exposed cable strung high above the ground. The systems are exposed to the elements and the joineries that connect these highly segmented systems are particularly vulnerable to damage and costly to repair and replace. Because transmission lines are low resistance and highly interconnected, they are especially vulnerable to penetration by Geomagnetically Induced Current (GIC). While several improvements have been implemented to reduce the risk introduced by solar weather, including capacitor blocking systems, back-up generating capacity, more regular maintenance schedules, and load shedding, these methods are costly, and don't address the fundamental physics that enable induction - loops.[2] Using *direct* transmission in future grid development will help the grid become resistant to solar phenomena and EMP attacks. Lastly, direct links for bulk power transfer are the most common-sense ways to bring renewable power to the marketplace and also to allow more robust and efficient energy exchange and price stabilization across energy markets.

Why HVDC Direct Linkages? HVDC systems are financially attractive options for connecting remote renewable power stations over long distances. Over long distances, the cost of HVDC converter stations are offset by the elimination of capacitive, inductive, skin effect, and dielectric charging losses as well as intermediate reactive power compensation requirements associated with long-distance HVAC. This leads to a break-even-point where, for a given transmission goal, HVDC becomes more feasible than HVAC above a certain transmission distance. These systems also allow AC grids operating with different frequencies or phase to efficiently exchange power. HVDC systems require less cable material and narrower right of ways compared to 3-phase AC systems.

Why Underground HVDC Direct Linkages? Land-locked renewable resources are critical to meeting future renewable energy needs. Some of the best renewable energy resources in the world are in the land-locked geographic centers. Wind resource assessments done by the National Renewable Energy Laboratory show the highest wind speeds are in the flat lands in the

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1 http://www.energy.ca.gov/sb350/ ; Veazey Shelby, "Energy Efficiency: How Boston and New York are Ahead of the Game," Phoenix Energy (October 27, 2017) http://www.phoenixenergygroup.com/blog/energy-efficiency-how-boston-and-new-york-are-ahead-of-the-game (accessed 11/02/2017).

2 Molinski, Tom S., Feero, William E., Damsky, Ben L., "Shielding Grids from Solar Storms" IEEE Spectrum, http://spectrum.ieee.org/energy/the-smarter-grid/shielding-grids-from-solar-storms (accessed 05/04/17), 60.

middle of the country.[3] Similar solar resource assessments show the highest solar fluxes are in the dry southwest regions of the U.S.[4] Similar trends exist in continents all across the world. While undersea burial is a developed and convenient method for laying very long lengths of cable, terrestrial installation, both UGC and OHL, still requires costly piecemeal construction methods. Of particular note, HVDC cable for underground use is significantly larger in diameter than an unshielded overhead AC line; hence bending limits and transportation weight limits restrict the length of HVDC cable that can be spooled at the factory and transported to the installation site. This creates the requirement for expensive joints between cable sections as often as every kilometer. There is no limit on the length of HVDC cable other than the cable weight and drum diameter that is compatible with road haulage. If the delivery of finite shipping lengths of cable could be replaced by in-situ production, this would lead to the elimination of splices and, consequently, large cost reductions.

While OHL systems are currently more convenient than UGC systems, the visual footprint of OHL architecture is proving to be a major obstacle to completing long distance HVDC projects. There needs to be an improvement to methods for laying terrestrial underground cable to reach resources inaccessible, due geographical or socio-political reasons, by OHLs or undersea cable.

Does a Solution Exist? There are many challenges associated with building UGC systems. Cable manufacturing is a very sensitive process, logistics and transportation place limits on cables lengths, and construction methods are labor intensive. Offshore cables, on the other hand, are laid in a continuous fashion using a highly automated process. We thus propose a mobile manufacturing platform, hereafter referred to as the "Cable Train," which would run on standard railroad tracks, to in-situ produce continuous lengths of cable which exit the train and are directly laid into trenches that have been created alongside the tracks. In the trenches, concrete galleries could have been similarly formed in a continuous manner. In both cases, the key is the use of the train tracks for transporting materials and the use of the existing right of ways. Railroad companies could thus also expand their business model to include transport of electrons in addition to transport of cargo.

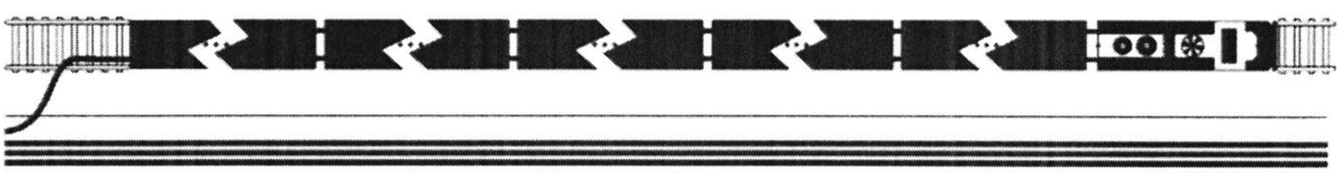


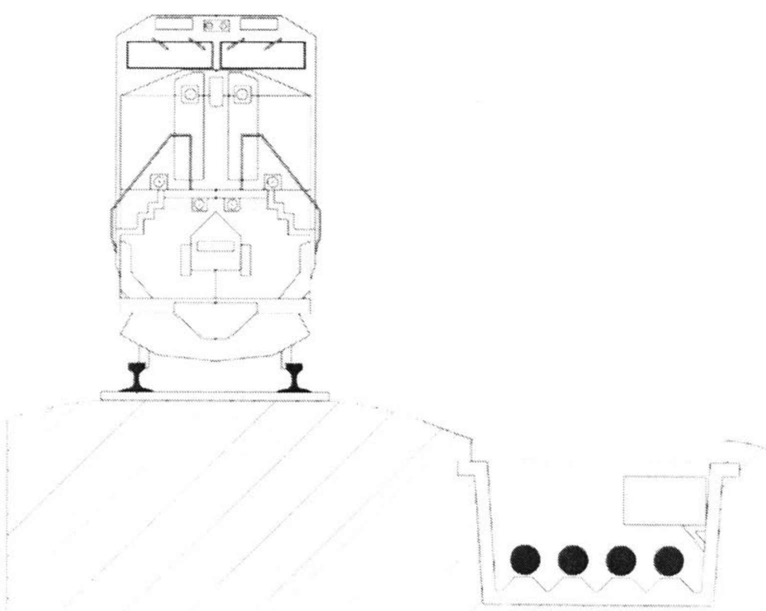
Figure 1: Schematic, top-down representation of the "Cable Train," which lays in-situ produced high voltage cable into an adjacent, open trench. The train comprises a number of modules necessary to manufacture high voltage cable – wire stranding, extrusion, curing, and degassing, among others.

[3] AWS Truepower, "United States – Land-Based and Offshore Annual Average Wind Speed at 100m," National Renewable Energy Laboratory (September 19, 2012) https://www.nrel.gov/gis/images/100m_wind/awstwspd100onoff3-1.jpg (accessed 01/01/18).
[4] Roberts, Billy J., "Concentrating Solar Resource of the United States," National Renewable Energy Laboratory (September 19, 2013) https://www.nrel.gov/gis/images/eere_csp/national_concentrating_solar_2012-01.jpg (accessed 01/01/18).

What is the Cable Train? The Cable Train would be a mobile manufacturing platform that is constructed from modified or dedicated rolling stock. In theory, it will incorporate all the manufacturing abilities of a stationary, state-of-the-art cable manufacturing facility and produce continuous lengths of cable in essentially the same way as it is manufactured for offshore cable systems. Railways are most suitable for this purposing because they extend over great distances, are standardized, and meant for the translocation of heavy industrial equipment. This strategy may enable the development of novel technologies and methods that make the production and installation of UGC systems less costly. There are three main categories of challenges which require further investigation to prove the viability of the Cable Train:

1. **Manufacturing and Qualification** – Can current or future technology enable the Cable Train to produce reliable, cost-competitive, and continuous lengths of cable on a moving train?
2. **Land Use, Earthworks, and Installation** – Is it possible to locate high-capacity UGC transmission systems in trackside spaces, to directly receive the cable made on the Cable Train?
3. **Lifetime Cost, Business Models, and Operations** – Can railroads, cable manufacturers, utilities, and/or public agencies arrive at a model to operate the Cable Train with the goals of creating public good and private incentive?

There are many issues that need to be identified, considered, and solved, and this is best done by an industry-led pre-competitive technology consortium that includes companies with the knowledge and/or proprietary ability to make this technology a reality. With this vision in mind, this text explores some of the issues that will need to be addressed with the goal of helping people realize the viability and potential of the Cable Train project



1. Cable Manufacturing and Qualification

1.1 Functional Requirements for the "Cable Train"

With standardized sizes for rolling stock and shipping containers as the design space for the Cable Train, a large amount of design attention will be paid to the miniaturization of machines and processes so they can physically fit onto a standard railcar. The functional requirements for the Cable Train should be driven by the necessity to produce cable that is low cost and high quality. This means the train must provide manufacturing capabilities equivalent to those of a state-of-the-art facility and there must be an operational plan which makes provisions to perform thorough qualification of each cable, the resources required to do so being housed all, or in part, within the Cable Train.

1.1.1 Cable Manufacturing

High voltage cable consists of many concentric layers applied around a central conductor. These layers serve to electrically insulate and mechanically protect the cable underground. Current cable designs have the following features, described, in order, from innermost to outermost layer. Refer to Figure 3 for an illustration of these components.

Conductor – Copper or aluminum wire drawn and wound in a variety of orientations. This core must meet ASTM standards concerning material, shape, size, orientation, coatings, and heat treatment, tensile strength, elongation factor, electrical resistivity, dimensions, geometric tolerances, joint creation method, and surface finishes. There may be retaining tape applied, after winding, to help maintain the structure.

Semiconducting Tape (optional) – Allows expansion of the core without damaging the conductor or metallic shielding. If tape is used it must not exceed a certain electrical resistance.

Conductor Shield – An extruded thermosetting plastic. This layer must meet thermal elongation, brittleness, resistivity, and crosslinking requirements and the interface between the shield and insulation must be cylindrical, free from any protrusions, and any voids greater than a specified size. The material can be either semiconducting or non-conducting for EPR insulated cable, but must be semiconducting in XLPE insulated cables. The material must be compatible with all surrounding materials and its operating temperature must be equal to, or greater than, that of the insulation. This layer must be bonded to the insulation and separate from the conductor.

Insulation – A relatively thick layer of XLPE or EPR. The wall thickness is determined by the limit on electrical stress at the proximal surface of the layer. The insulation must meet restrictions on the eccentricity, tensile strength, elongation, and creep, before and after aging, resistivity, dielectric, dissipation factor, electrical integrity, and shrink-back. The insulation must not have voids, ambers, gels, agglomerates, or contaminants above specified sizes or densities.

Extruded Insulation Shield – A thermosetting and semiconducting plastic. It must be bonded continuously to the insulation and compatible with all surrounding materials. It is subject to the same categories of requirements as the conductor shield but specified values may vary.

Semiconducting Tape (optional) – Tape serves the same purpose as previously described and must meet restriction on electrical resistivity.

Metallic Shielding – A nonmagnetic, electrically continuous metallic layer. It must be unaffected by bending, free of burs, able to withstand fault current for specified duration. The shield must be in good contact with the underlying layer. There are several types of metallic shields used:

- Helically Applied Tape: Copper foil with optional tin coating. The tape must overlap by a specified amount and the shield is made contiguous by welding, brazing, or soldering.
- Longitudinally Applied and Overlapped Corrugated Tape: Annealed copper. Tape must be overlapping by specified dimension, corrugations are 90° to the axis of the cable, corrugations must exactly overlap at the interface of longitudinal sections, and the shield is made continuous by welding, brazing, or soldering.
- Wire Shield: Tin coated or uncoated copper wire wound helically or laid longitudinally. Wire must have a specified diameter and spacing. The lay length (period of the wrap) is defined by the diameter over the entire shield.
- Flat Strap Shield: Tin coated or uncoated copper straps wound helically or laid longitudinally. The straps must have a minimum thickness, width, and spacing. The lay length (period of the wrap) is defined by the diameter over the entire shield.

These shields may not qualify as radial moisture barriers for cables intended for use in wet locations. Radial moisture barriers include, but are not limited to, metallic sheaths and bonded metallic foil laminates. Metallic Shields that also qualify as radial moisture barriers are:

- Lead Sheaths: Extruded lead with a specified thickness to accommodate fault current.
- Aluminum Sheaths: Alloy with a specified purity and thickness longitudinally applied and seam welded.
- Corrugated Sheath: A flat metal tape longitudinally applied, folded, and seam welded, then corrugated. Tape can either be copper or an aluminum alloy with a specified purity, each with specified thicknesses.

There is great variety designs, materials, and properties that may be tuned to provide the desired function and economics according to application. This process is called shield optimization.

Semiconducting Film – In accordance with ANSI/ICEA S-108-720, a semiconducting film, usually graphite, should be coated onto metallic shields for field qualification upon installation, and periodically thereafter, with the purpose of measuring jacket insulation integrity, which can change drastically over time.

Jacket – Made from a non-conducting thermoplastic - polyethylene (black), PVC, or another material agreed on between manufacturer and buyer. LDPE, LLDPE, MDPE, and HDPE must meet standards for tensile strength, elongation, before and after aging, heat distortion, stress cracking, absorption coefficient, and base resin density. PVC must meet the same physical and aging requirements as well as heat distortion, heat shock, and cold elongation characteristic requirements. The jacket must have a specified thickness and make good contact with underlying material.

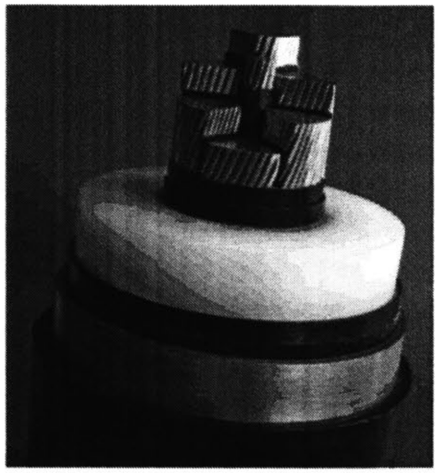


Figure 3: The basic structure of a XLPE insulated cable.[5]

The process for manufacturing high voltage cable depends on the cable design. Selection and differentiation of the aforementioned elements is driven by the intended operating environment, duct bank design, voltage, and ampacity. Without focusing on a specific cable design, the basic steps involved in manufacturing are describe hereafter. There are 3 manufacturing steps that are identified as significantly challenging to replicate inside a moving and space-poor Cable Train.

Wire Drawing Rolling mills compress and smooth copper rods while drawing to a specific diameter. Welding wires in-line is possible to increase the length of these wires indefinitely. Relevant coating and heat treatment may also be performed. Product stored in baskets for easy transport and wire discharge into cable winding machines.

Conductor Stranding Multiple rounds of winding depending on number of strands and the orientation of the wind. Winding is immediately followed by tandem disc reduction. Modern facilities often have automated systems for refilling bobbins.

Triple Extrusion Often semiconductor screens and insulation made of a similar base-polymer and are co-extruded. Extrusion should provide a smooth mechanical interface between the conductor and the insulation. Co-extrusion evens out local electrical voltage stresses and protects insulation. Pre-extruded insulation granulate lot must be clean to

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[5] ABB, "World's most powerful underground HVDC cable," http://www.abb.com/cawp/seitp202/debdfbaa3ccb037fc125797c003de13b.aspx (accessed 11/07/2017).

avoid electrical and thermal faults. Extrusion compound is filtered through extruder screens that must be cleaned between extruder runs. This is a slow, but very critical step in production.

Curing Cross-linking chemicals can be mixed with the extrusion material before extrusion. They are activated by high temperature and pressure (to prevent gaseous byproducts from forming bubbles), before cooling in a subsequent length of pipe. There are several processes for curing distinguished primarily by the chemicals used: Engel Process (peroxide), Sioplas Process (silane), Monosil Process (vinylsilane). Cross-linking transforms the thermoplastic insulation into a thermoset, which improves temperature resistance, tensile strength, non-corrosion characteristics, creep-resistance, crack resistance, and chemical resistance. Vulcanization processes happen in tall Vertical Continuous Vulcanization (VCV) towers or in long Catenary Continuous Vulcanization (CCV, Figure 4 Above, Right) pipes, which maintain the concentricity of the conductor and the distill annular layers until the cross-linking is complete.

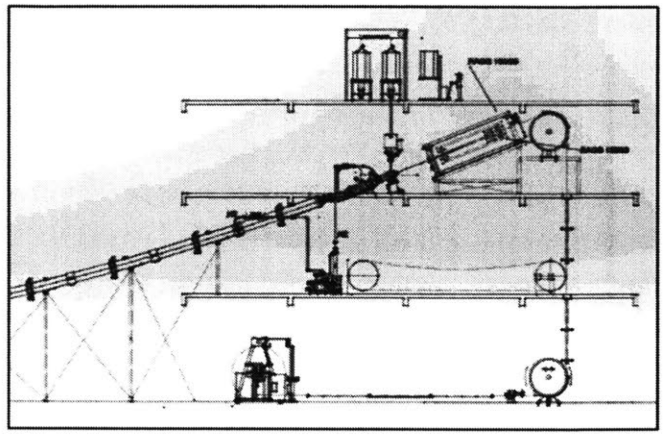

Figure 4: A Catenary Continuous Vulcanization high voltage cable manufacturing line. The extruder can be seen on the third floor. A person is placed on the fourth floor for scale. The catenary pressure vessel contains the pressure and temperature necessary to facilitate vulcanization while allowing the cable to fall naturally, maintaining its internal concentricity, without making mechanical contact with the walls of the pipe. In order to provide enough time for the curing process to fully take place at the desired extrusion rate, these catenary vessels are typically tens of meters tall by hundreds of meters long.

Degassing This step is necessary to remove cross-linking byproducts because they can affect the electrical and thermal properties on the cable, they can effect partial discharge testing (discussed later), and ongoing generation of gases throughout the lifetime of the cable can pressurize cables with a solid metallic shield.[6] A variety of times and temperatures have been encountered that are used by manufacturers. 20 to 40 days is the typical range for this process. Heating helps accelerate this process, but temperatures must be kept below the de-crystallization temperature of the insulation material.

Metallic Shielding Longitudinal or helical metal tapes are overlapped and seam welded, brazed, or soldered to achieve electrical continuity. Alternatively, molten lead can be extruded by a Hansson-Robertson extruder. Metal foil laminates are glued on, longitudinally, as required.

Jacket Extrusion Purity requirements for this extrusion step are lower. Jackets must be marked with all relevant information.[7]

[6] Insulated Cable Engineers Association, Inc. "Standard for Extruded Insulation Power Cables Rated Above 46 Through 345Kv" ANSI/ICEA S-108-720-2012, November 27, 2012, Page 81.

[7] Thue. William A., "Electrical Power Cable Engineering," Third Edition, CRC Press: 2012, https://eds.b.ebscohost.com/eds/detail?sid=6dc48675-3e52-4380-8dee-1a23d9051b3b@sessionmgr104&vid=0&format=EB&rid=1#AN=413393&db=nlebk (accessed 11/25/17).

1.2 Primary Manufacturing Challenges

Three manufacturing steps have been identified as presenting major challenges to adapting this process to the Cable Train. **(1) Insulation extrusion** requires screen-packs to filter impurities out of the extrusion melt. Traditionally, replacing screen-packs requires interrupting production. During **(2) Curing** it is critical to maintain concentricity. To this end, most facilities use VCV or CCV lines which require significant height and distance not available on standard rolling stock. **(3) Degassing** is a critical step often accelerated by placing finished shipping lengths of cable on large reels inside large heated chambers. In order to maintain a continuous length of cable, the Cable Train must have provisions to degas cable inline without the need to make the train many tens of kilometers long.

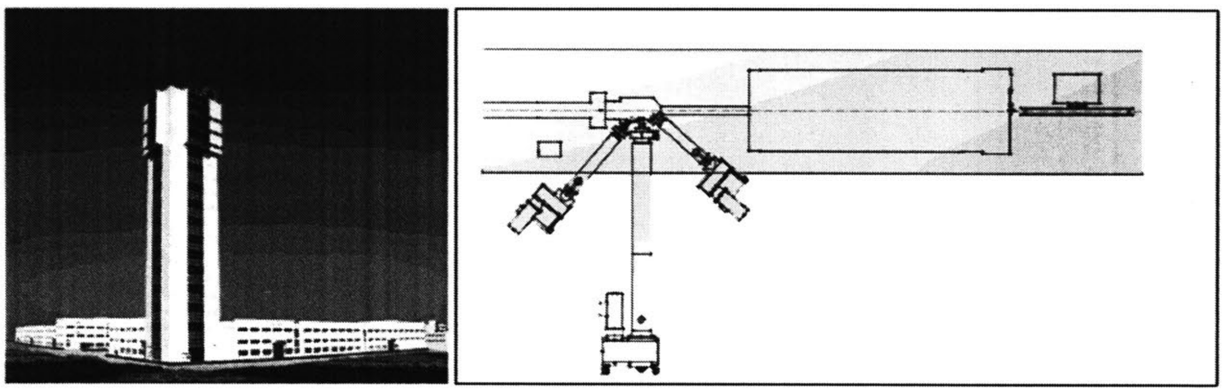

Figure 5: (Left) A VCV tower used to cure cable. (Right) Image of a TROESTER GmbH & Co. Triple Extruder and cable caterpillar superimposed on a CSX 50' Standard Boxcar.

1.3 Manufacturing Countermeasures

New systems must be developed to enable the Cable Train to achieve **(1) Continuous Extrusion, (2) Horizontal Curing,** and **(3) Inline Degassing**. Potential concepts are described hereafter with appropriate detail in accordance with the current state of the project.

1.3.1 Continuous Extrusion In order to allow longer extruder runs without the need to stop operation for replacing screen-packs, cleaning equipment, and reloading extrusion lots, redundant extruders can be used with a dual crosshead to provide indefinite operation. Discussions with one extruder manufacturer has further confirmed the feasibility of such an implementation. This arrangement is used regularly to achieve long extrusion runs and is illustrated in Figure 6, below. Screen-packs can be replaced, the equipment cleaned, and melt brought back up to temperature and homogeneity in one extruder while the other feeds the extrusion operation. After the active extruder reaches the end of its screen-pack lifetime, it is ramped down while the previously inactive extruder is ramped-up and excess melt is discarded through purge valves. The process for screen-pack ejection and replacement can be automated with hydraulic machinery.

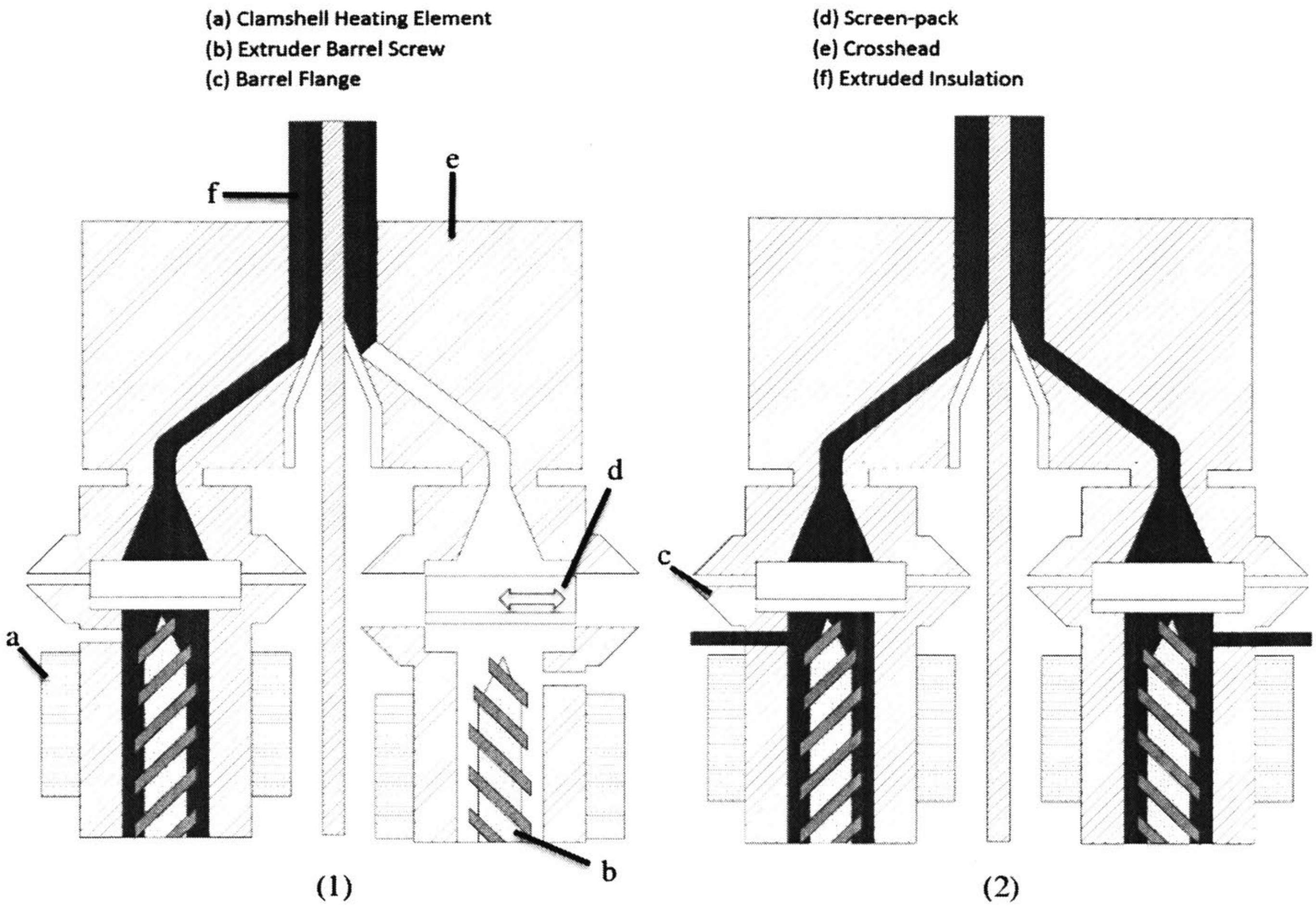

Figure 6: An extrusion concept based on a dual-crosshead. Image (1) shows normal, exclusive operation of one extruder while the screen-pack in the inactive extruder is replaced and the equipment cleaned. Image (2) shows the simultaneous ramp-up and ramp-down of the previously inactive and active extruder, respectively. Melt is partially discarded through purge valves on each side until the change-of-duty has been completed. This setup will allow for the continuous insulation and jacket extrusion aboard the Cable Train.

Using semiconductor-insulation-semiconductor triple-extrusion will require multiple redundant extruders. As illustrated in Figure 6, these extruders will be subject to significant space restrictions. The orientation of extruder barrels must be changed in order to conform to this constraint.

1.3.2 Horizontal Curing To accomplish perfectly axisymmetric curing without a vertical tower or catenary pressure vessel, an equivalent horizontal curing process must be devised. The Mitsubishi-Dainichi Continuous Vulcanization (MDCV) process provides this capability. MDCV uses an extended extrusion crosshead, which relies on residual extrusion pressure and heat to achieve concentric curing while the extrusion remains constrained within a segmented "longland die" (LLD). The process relies on the high viscosity of specifically chosen insulation materials, kept perfectly cylindrical by the extended extrusion die, to provide sufficient viscous resistance to conductor sagging. The conductor may be continuously rotated to ensure that it stays at the center of the die despite circumferential flow of insulation material.[8] This machinery has been used to produce cable up to 550kV. A schematic of this LLD attachment is shown below.

(a) Adapter Retainer
(b) Die-to-Segment Adapter
(c) Lubrication Port
(d) LLD Forming Section (< 1m)
(e) LLD Vulcanizing Section
(f) Cooling Element (water)
(g) LLD Cooling Section
(h) Cable with Extruded Insulation

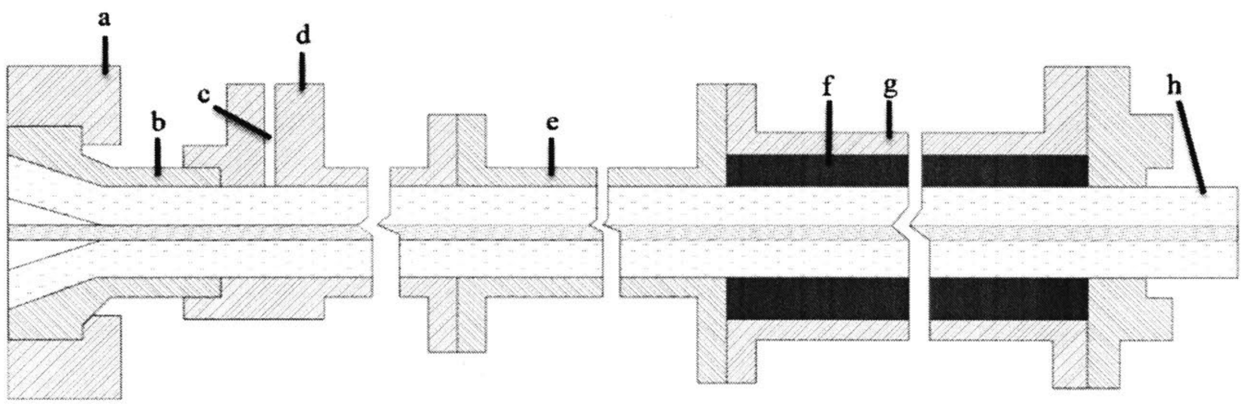

Figure 7: Above is an MDCV schematic from an outdated design released by the Mitsubishi Cable Industries Ltd. and Mitsubishi Petrochemical Co. Ltd. (previously Dainichi Chemical Company of Japan) partnership.[9]

The time required for vulcanization can be reduced by increasing temperature. Traditional vulcanization processes that use steam cannot increase temperature without also increasing pressure. The extent of this optimization is limited, then, by the strength of the pressure vessel used to house this reaction. By contrast, the MDCV/LLD process temperature is independent from the pressure inside the die. Therefore, higher temperatures and vulcanizations speeds can be achieved with this process.[10]

In the original patent, the authors discuss the use of forming co-agents at the interface between the die and the formed piece (injected through lubrication port illustrated in Figure 5) to prevent the formed material from adhering to the inside of the LLD and being burnt from shear heating. This co-agent must have several characteristics: (1) high viscosity and (2) low absorption ratio to ensure a uniform boundary is maintained over the cable. Additionally, the co-agent must not (3) gel when in contact with vulcanization chemicals or (4) boil at the temperatures and

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[8] Peter Stewart-Hay, "The MDCV Process," Stewart-Hay Associates, Engineering and Computer Services, http://www.stewart-hay.com/pshmdcv.htm (accessed 01/11/2018).
[9] Ibid.
[10] Fuwa, et al., "Method for Forming and Vulcanizing Vulcanizable Materials," United States Patent 3928525 (Dec. 23, 1975).

pressures used for vulcanization, in order to avoid affecting the surface of the vulcanized material. The original patent lists many materials that are appropriate to use.[11]

There are several challenges believed to stand in the way of implementing MDCV on the Cable Train. According to the original patent for the technology (1975), the cumulative length of the sections illustrated in Figure 5 is between 1 and 20 meters long (boxcars are commonly produced with interior lengths between 15 and 30 meters).[12] There is reason to believe, according to discussions with previous licensees, that the requirements for the cooling section make the actual length of these lines much greater. In addition to the energy and spatial requirements directly associated with the MDCV line, the process requires several pieces of accessory machinery, including a Class 100 cleanroom for opening and loading plastics, and machines for circulating and storing cooling water contaminated by lubricants and co-agents. Additionally, the LLD may require several operating personnel, including the main operator, a back-up operator, and a plastics specialist. It is unknown whether or not, if needed, sections of the LLD can be broken to add degrees of freedom in order to span multiple railcars. Past MDCV lines have featured air gaps of several feet where separate conductors can be spliced together, gases exhausted, and cooling water and lubricant released.

While only several of these LLD machines have apparently ever been licensed, they have been proven commercially viable and this process represents a promising curing countermeasure for the Cable Train. Alternatively, a solution that will require more experimentation and development is being called "asymmetric extrusion." If the extrusion head is modified such that the center of the conductive core is "anchored" above the center of the cylindrical, extruded insulation, the extruder can ride horizontally inside of a pressure vessel, on air-bearings for example, under high heat and pressure for a requisite distance to achieve crosslinking. Precise controls may be devised to ensure the exact settling of the conductive core at the center of the insulation. A third solution may involve Electron Beam radiation (for voltage classes up to 35kV), which can penetrate insulation through a shallow distance, to immediately add rigidity to the outer surface of the cylindrical extrusion. The cable can then be supported by mechanical contact and transported horizontally through a pressured vessel as the conductor is kept concentric by continuous rotation and the curing process is completed. These solutions will require significant development. MDCV is currently considered the most promising countermeasure.

1.3.3 Inline Degassing Cable must constantly progress through the train without holding up production. If degassing cable traveled straight down the length of the train at a typical rate for cable production (100 meters per hour is a reasonable goal using triple-extrusion), a series of cars extending tens of kilometers would be required to achieve the desired degassing time. Such a

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[11] Fuwa, et al., "Method for Forming and Vulcanizing Vulcanizable Materials," United States Patent 3928525 (Dec. 23, 1975), 4.

[12] Fuwa, et al., "Method for Forming and Vulcanizing Vulcanizable Materials," United States Patent 3928525 (Dec. 23, 1975), 9.

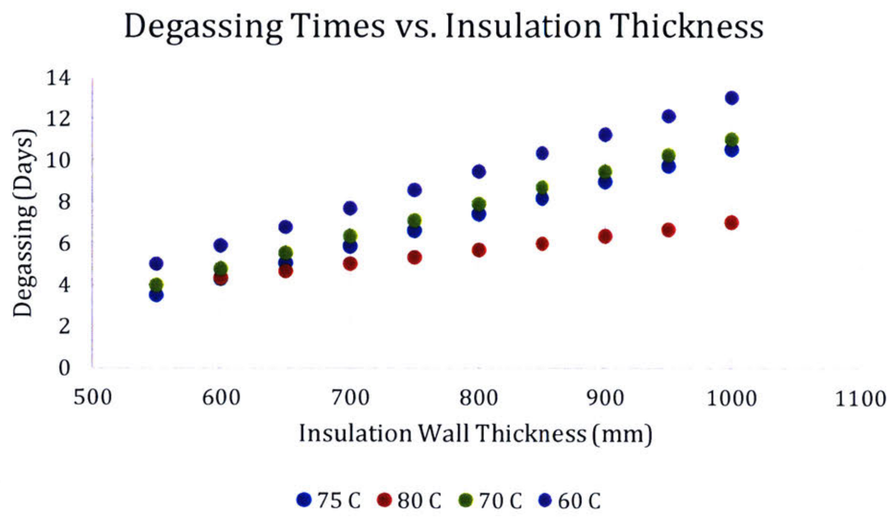


Figure 8: Times and temperatures used by manufacturers in insulation of different thickness. Data is taken from a poll conducted by the Insulated Cable Engineers Association, Inc.[13]

Alternatively, a dedicated piece of rolling stock has been conceived as part of this thesis to both heat the cable, after insulation extrusion, to accelerate degassing, while also using a new, inline, reel-based cable handling system to increase the amount of cable contained in a single railcar, thereby reducing the number of cars required to reach the degassing time required and without affecting the cable production speed.

The design would utilize boxcars equipped with servo-actuated reels upon which the cable winds on, and then off, from one reel to another, thereby effectively increasing the path-length the cables take through each car, so as to increase the amount of cable present in a car at any given time. This will greatly decrease the required number of cars to achieve the desired degassing time. Because the metallic shield, the component most sensitive and readily damaged by bending, is not added until after the insulation degassing, these cars can use reels of diameter less than that recommended for handling finished shipping lengths of cable (usually 20-35x the total diameter of the cable). A design model has been developed to maximize the length of cable able to fit inside containers and railcars of varying sizes as well as calculate the stresses at various danger points in the cable throughout the cable handling system due to bending, tension, torsion, and side-wall pressure.

[13] Insulated Cable Engineers Association, Inc. "Standard for Extruded Insulation Power Cables Rated Above 46 Through 345Kv" ANSI/ICEA S-108-720-2012, November 27, 2012.

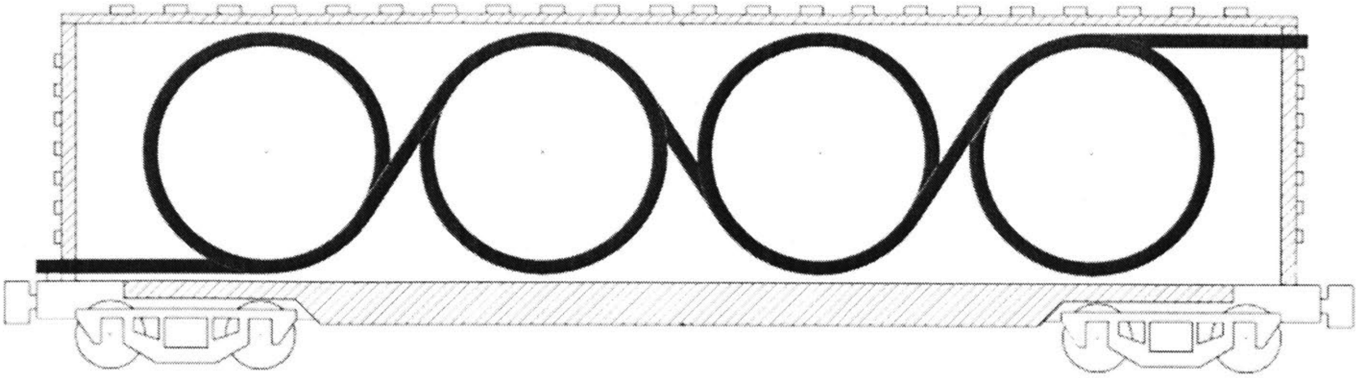
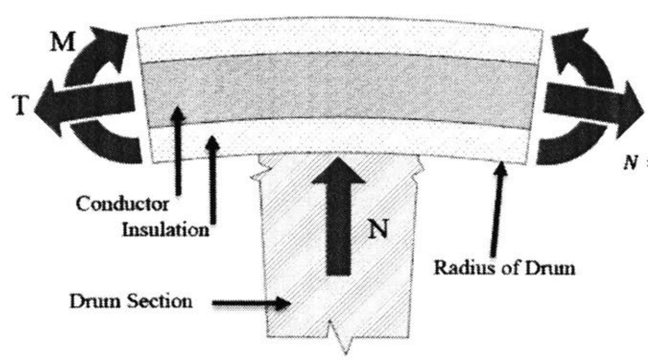


Figure 9: An illustration of an inline cable handling system that increases the length of cable that can safely fit into a single boxcar, thereby decreasing the number of cars that are needed to sufficiently degas the cable after insulation extrusion. On each reel, the cable travels across the width of the railcar/container, alternating direction with each reel. Spiral cable "combs" are necessary in order to guide the cable across each drum. Each comb is rotated on its axis 180° and the entry point of the cable into every drum also changes 180° with each transition. This ensures that the limited twist accumulated by the cables on the first drum is maintained in the same direction (not reversed) and also happens to mean that the spiral combs are all identical parts (of the same handedness) rotated along their axes.

In this model, the normal force (per meter) applied on a cable by a drum is calculated as the sum of the weight of a single revolution of cable and the normal force resulting from tension in the cable (which itself depends on the maximum hanging weight of cable between reels) and the wrap angle per meter of cable. This leads directly to the calculation of side-wall pressure where the cable contacts the drum. Maximum bending stresses are calculated, based on the chosen drum diameter, for the insulation and for a single conductor strand subjected to the minimum bending radius (individual strands do not share a neutral axis with the insulation). Reasonable values and conservative estimates are used wherever possible.



$$T \propto (Hanging\ Weight\ of\ Cable)$$

$$M \propto (Curvature)$$

$$N = f(Weight, Nuetral\ Axis\ Radius) + g(T, Curvature)$$

$$where\ f \propto (Cable\ Weight\ per\ Unit\ Length)$$

$$\&\ \ g \propto T \times \frac{\sin(Curvature)}{\cos(\frac{Curvature}{2})}$$

Figure 10: A free body diagram showing the internal tension, moment, and side-wall normal force experienced by a cable in bending on a drum. Tension is related to the hanging weight of cable. The internal moment is proportional to the curvature of the cable where a separate neutral axis must be used to calculate the moment in the insulation and in a single conductor strand at minimum radius of curvature. The normal force per unit meter is comprised of two terms related to the weight per unit meter of cable and the curvature of the neutral axis of the cable, respectively. Calculations of internal stress and Von Mises must be performed at two "danger points" – on the outer diameter of the insulation at the contact point with the drum, and in a single conductor strand of minimum radius of curvature.

The cable in this system must move axially across the length of one drum, as it rotates with the motion of the drum, before unbending and being passed to the neighboring drum, whereupon it travels axially in the opposite direction. Therefore, the cable moves side to side, perpendicular to the direction of travel of the train, as it moves down the length of the train by traveling from drum to drum. In order for cable to move axially down the length of each drum, it must slide axially, otherwise the cable would simply attempt to accumulate on each drum, leading to no progress along the length of the train, and likely leading to the cable breaking. To accomplish this axial sliding the cable must be "comb guided." In other words, hardware must be designed to guide the cable along a spiral path as it rotates on each drum. Three designs for such hardware are presented hereafter: (a) **a continuous helix**, (b) **discrete spiraling "fins"** and (c) **discrete spiraling rollers**. A common misconception upon presentation of these designs is that the "combs" rotate synchronously with the drum and cable. In actuality, the combs must remain stationary relative to the railcar/container, providing a spiral guide path for the cable to be pulled through under the influence of friction between it and the rotating drum.

An obvious manifestation of a spiral guide is a completely **continuous helix**, which makes constant contact with the cable to push it axially down the length of the drum. An illustration of such a guide is shown below. Pressure exerted on these flights due to the resistance of the cable is manageable. Calculations and finite element simulation suggest that these flights can be made as thin as ¼". These helices can be formed similar to how large sectional helices (auger flights) are made, in helical flight forming machines. Additional rigidity is added by cross bars which also provides a means of attachment to the A-frame supporting the drums.

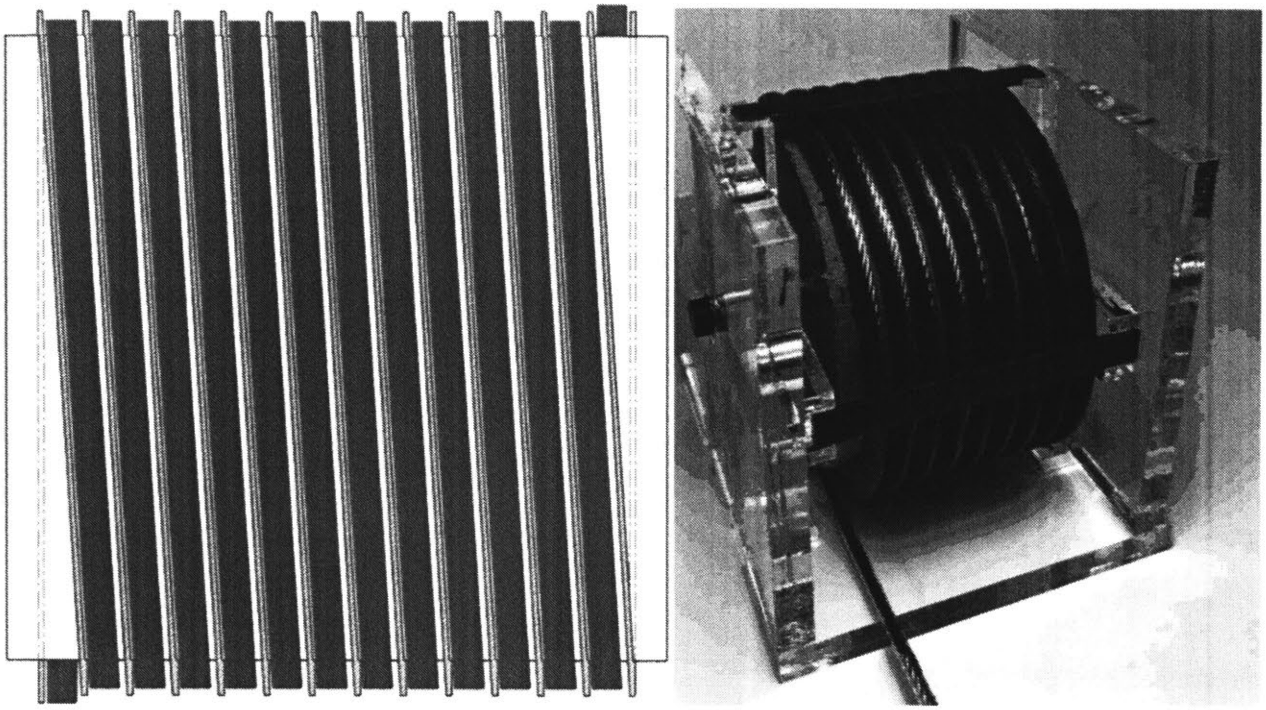


Figure 11: (Left) A top-down view of a continuous helical guide assembled around a rotating drum loaded with cable. As the drum and cable rotate, the cable is pulled through the spiral path created by the guide and it proceeds axially down the length of the drum. A complete design tool has been created to aid the design of this comb. As an example, assuming a largest cable OD of 125mm, analysis and simulation have shown that a comb with flight thickness 0.25" with a pitch of 138mm can safely handle the cable and decreases the length of this section of the train by approximately a factor of 40 (according to common reel dimension). (Right) A scale model of the continuous helical comb loaded with a coated steel rope of the same apparent stiffness as cable.

Breaking the continuous helix into **discrete fins** saves material cost while still enabling safe cable handling. The fins' surfaces are characterized by a flat section long enough to avoid dangerous cable side-wall pressure, a terminal radius large enough so as to not damage cable should, in a worst case scenario, a cable loses tension and becomes jammed between two fins. Finally, the space between the flat section and terminal radius can be a section of minimum length and constant curvature with tangency at both ends. Alternatively, this transitional surface can be designed to match the slope of a theoretical beam in simply supported bending with the same apparent stiffness as the thinnest conceivable cable. In this way, the surface can be calculated according to a moving contact point along the chosen minimum length assuming a distributed load, representing friction on the drum, is swept from 0 to the value expected for the largest cable. Such a profile may be worth exploring if the tribological effects between comb and cable prove to be significant. Calculations suggest that the fins can be made relatively short and thin while providing enough surface area and a sufficiently large terminal radii to ensure the safety of the cable. These fins can be made in a single machining operation (without re-fixturing) because there is no need to machine both sides.

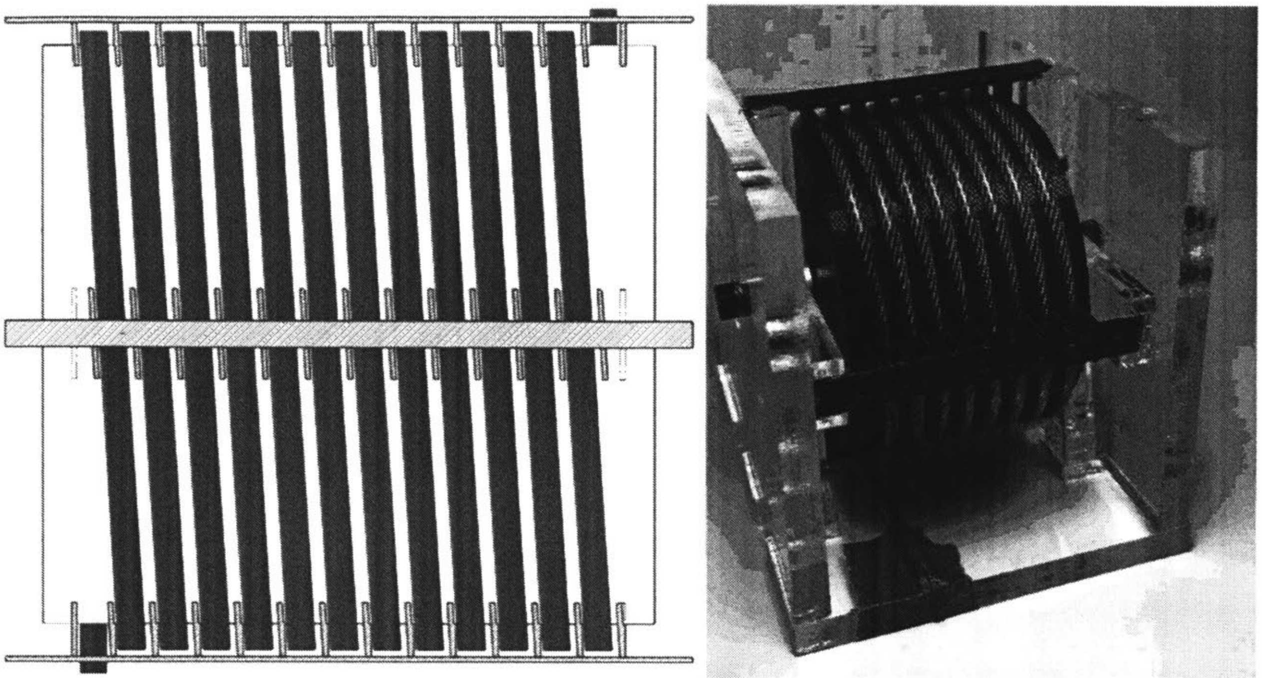


Figure 12: (Left) A schematic of a comb with discrete fins fixed around a rotating reel loaded with cable. The fins have less material than the continuous design and, according to analysis and simulation, can safely handle the cable and provide similar cable-packing advantage as the continuous design with approximately the same dimensions. A complete design tool has been created to ensure the saftey and optimize the cost of this design. (Right) A scale model of a comb with discrete fins loaded with steel rope of the same apparent stiffness as cable.

Replacing the discrete "fins" with **discrete rollers** increases cost and complexity, but it reduces the risk presented by the unknown tribological effects associated with the sliding contact between metal and insulation inherent in the previous two designs. Calculations suggest that these roller radii can be thin, maintaining the revolutions achieved by the previous designs, while also avoiding dangerous side-wall pressure on the cable. This design can be made with completely identical parts by shifting cross bars, relative to a reference row of rollers, in order to achieve the desired spiral pitch.

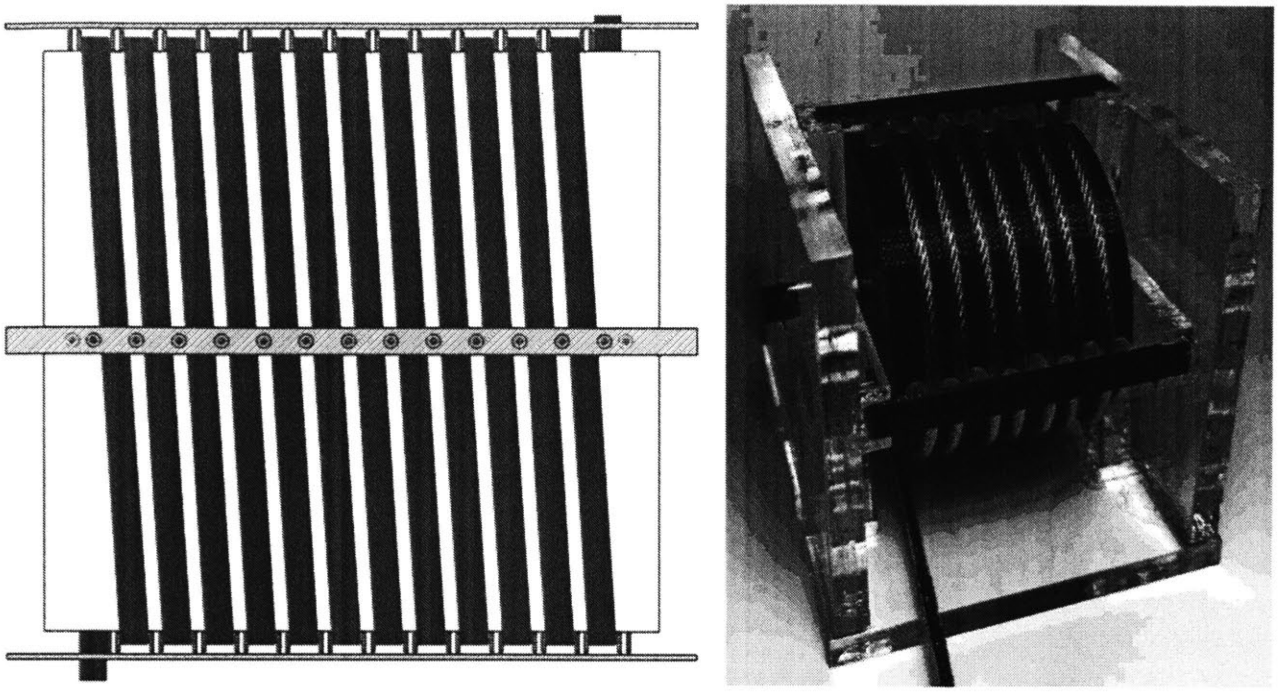


Figure 13: (Left) A schematic of a comb with discrete rollers fixed around a rotating reel loaded with cable. The rollers largely avoid the risk of tribological effects present in the previous two designs and, according to analysis and simulation, can safely handle the cable and provide similar cable-packing advantages as the previous designs. A complete design tool has been created to ensure the saftey and optimize the cost of this design. (Right) A scale model of a comb with discrete rollers loaded with steel rope of the same apparent stiffness as cable.

A complete design tool for all these concepts has been developed. All calculations relating to the design of these cable combs are based on the largest expected cable size at this point in manufacturing. Example numbers from this tool can be found in Appendix L.

The cable on these drums are not being "coiled" therefore it does not accumulate the 360° of twist per revolution that is associated with loading cable onto Cable Laying Vessel (CLV) coiling pads using wheel engines. In other words, this handling system does not compress cable into a coil therefore there is no twist caused by the topology itself. However, the cable may accumulate a limited amount of twist caused by moments applied by frictional forces from the comb and drum, causing it to roll down the axis of the drum, under the influence of the cable combs, before it begins to slide.

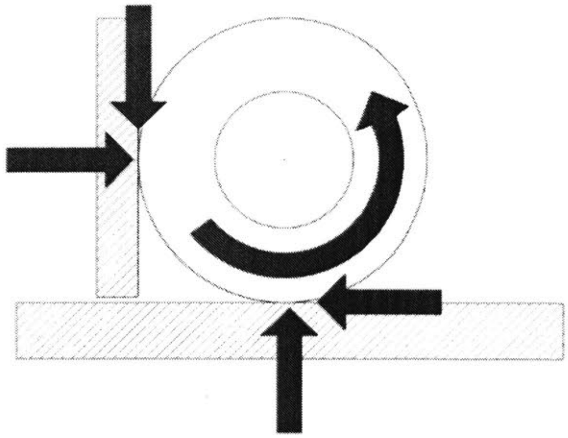


Figure 14: A free body diagram illustrating the forces acting on a differential slice of cable moving through the degassing section of the train. Moments, from friction, about the center of the cable are balanced by the internal torque generated by the torsional stiffness of the cable as it accumulates a limited amount of twist. Once this equilibrium is reached, the cable will begin to slide, instead of roll, across the drum under the influence of the spiral cable "combs."

Once the cable reaches this twisting limit, it will begin to slide axially instead of roll. This limited twist has been incorporated into all safety and design calculations, which suggest it is not a dangerous amount (twist per unit length < 0.001° for a 125mm OD cable). It is well-known that, because cables have conductors and armoring applied in specific stranding directions, S-lay or Z-lay, cable must be wound in the correct direction in order to prevent the strands and straps from opening or kinking. The correct choice for the direction of the spiral guide and cable thereupon will ensure the accumulated twist is in the appropriate directions, according to the cable's internal chirality. With the intention of maintaining the limited twist introduced by the first drum, not removing it, or worse, reversing it, all drums will have the same spiral direction, or "handedness," and the cable will alternate from entering and exiting each drum on the top and bottom or the railcar. This is illustrated in Figure 9 above. This means each drum will be rotated on its axis 180° relative to its immediate neighbors, but it has the added benefit of making all the spiral guides identical.

It has been shown that, for a variety of cable outer diameters, D, using reels with outer diameter 22D, the hanging weight of the catenary lengths between reels and the imposed radius of curvature and side-wall pressure is nowhere near that required to exceed the maximum tensile loads or Von Mises stresses on those cables at their danger points. As an example, to degas a 166mm OD, *d*, cable with 126mm OD insulation and a 61mm diameter copper conductor (a normal cable size that may be used in 3000MW bipole systems) using drums of diameter 2772mm (D=22d) for 14 days, about 40 fifty-foot boxcars, each with four servo-actuated drums of the specified diameter, 22d, spaced evenly along its length can achieve the required path-length, with reasonable clearances in all directions, as shown in Figure 9. These numbers are derived from a calculator constructed to optimize the layout of reels with different sizes, so as to minimize the total number of car/containers used in this section of the Cable Train.

The feasibility of this cable handling topology has been proven with a scale model. When production starts, the initial length of cable can be guided through the combs using a pilot string. Theoretically, the servo-controlled reels will be able to control the amount of slack between reels such that there is never excessive axial load on cable cores. In order to avoid triboelectric buildup from moving contact between the cable, the combs, and the drums, everything in these cars should be electrically grounded.

While the cables pass through this series of degassing cars, a plenum with heating elements and circulation fans or a radiant heaters and reflectors mounted on the top of the boxcars will provide the heating power necessary to accelerate degassing. Radiant heating may provide the most efficient heating method by concentrating the power density at a wavelength for which the absorption by the cable insulation is maximized. This essentially mimics the process of placing cables in large kilns, typically performed at state of the art manufacturing facilities.

Since there are no universal guidelines governing degassing nor reliable sensors, identified as part of this thesis research, capable of measuring the extent of degassing, a mass and heat transfer model needs to be developed to calculate the heating power necessary to achieve degassing (Current manufacturers follow empirical guidelines for how long, and at what temperatures, to degas cable).

The chain of degassing cars will need to be thermally insulated and continuously sealed with intermittent bellows and silicone curtains. The interior can be covered with refractory material or aluminized surfaces to increase the heat transfer to the cable. There are several other design parameters that may be tuned to reduce the degassing burden. Some curing processes and materials (EPR vs. XLPE for insulation) produce less byproduct. If this were to ever change, passive spring-loaded pulleys can be employed to support the weight of these hanging sections. Soft materials can be used as the materials on the outer surfaces of the drums to decrease sidewall pressure.

To be clear, the degassing of the insulating polymer (XLPE) must occur before metallic shielding, whereas degassing required after final jacketing extrusion can be allowed to passively occur after cable installation, contingent on these byproducts not significantly affecting qualification test performance. A scale model showing a 50:1 scale model of a degassing car, utilizing the helical combs discussed above, is shown in Figure 15 below. The model successfully handles stranded-coated wires with an approximately equivalent apparent stiffness to common high voltage cable with metallic shields.

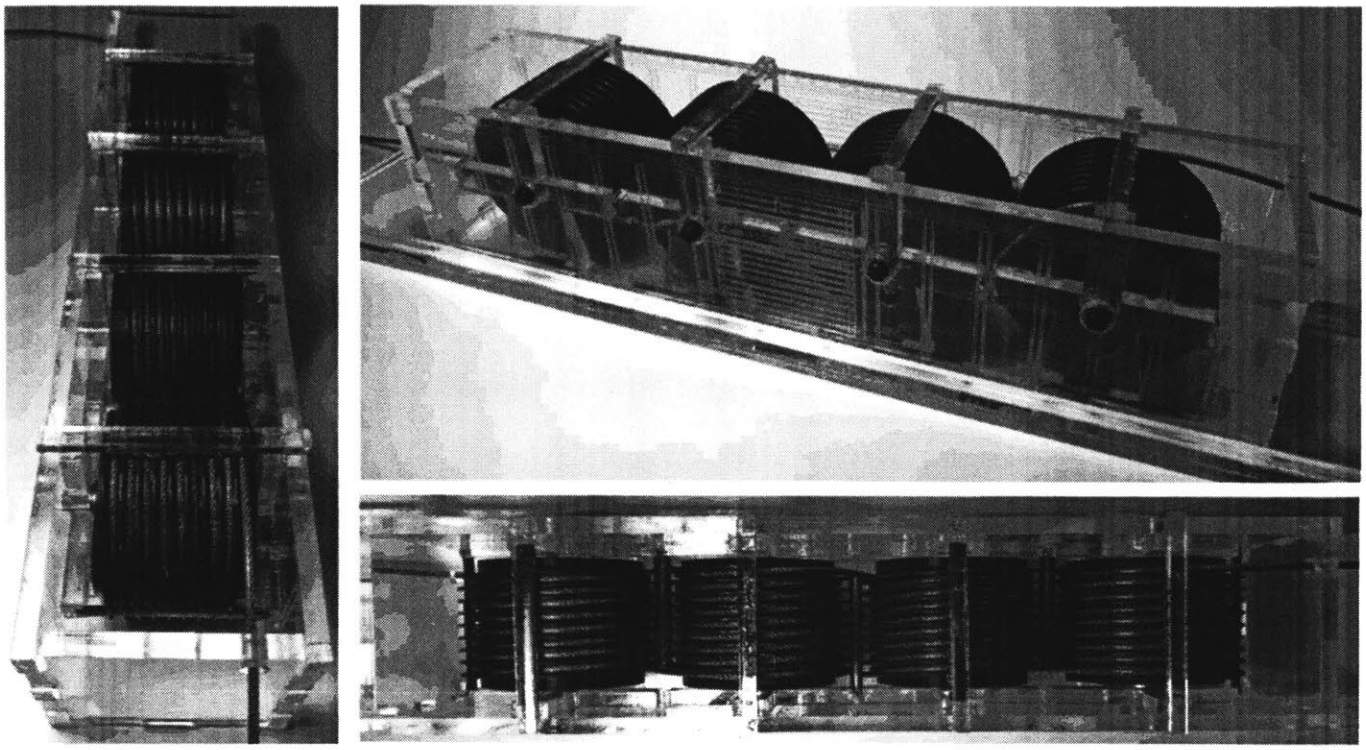


Figure 15: A 50:1 scale model of a concept for a "degassing train" capable of greatly increasing the amount of cable in a series of railcars while continuously processing it as the trains moves relative to it in an inertial reference frame. The cable proceeds down the length of the train by passing from reel to reel, moving axially across the length of each reel under the influence of non-rotating helical guides. According to analytical models, the bending, tension, sidewall pressure, and accumulated twist in the cable are safe. This accomplishes approximately a 40x decrease in length in the degassing section of the train.

1.4 Cable Stranding, Taping, and Armouring Onboard the Cable Train

Wire stranding is the first additive step in cable manufacturing. While many different kinds of conductor stranding orientations may be used, by far the most common is concentric lay where layers of wire of the same diameter, each with six more wires than the last, are wound in alternating directions around a core conductor. Figure 16 shows the geometry of a concentrically stranded conductor. This geometry can be achieved with a variety of stranding machines that offer different benefits.

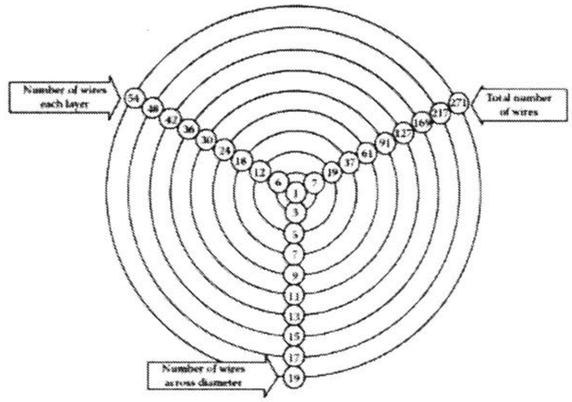


Figure 16: In a concentric stranded wire, each layer has 6 mores wires than the last. The diagram show the accumulation of total wire and the diameter of the conductor, as a function of the constituent wire diameter.[14]

A stranding and taping line will typically include a central wire payoff, a stranding machine (of a variety to be discussed), a closing die or "bench," and taping machine, and a caterpillar or capstan.

Tubular stranders are machines that accomplish wire stranding by feeding in wire from bobbins that are all located on the central axis of the machine. Planetary stranders are typically larger and deliver wires to a strand from bobbins that rotate/orbit around the axis of the machine. In constrast to tubular stranders, planetary stranders have a larger footprint, but they accommodate much larger conductors passing through their axis and can deliver more wires at a time to a given layer (and therefore produce larger conductors). Tubular stranders are limited to cables of a certain size because larger cables also require relatively more strands per layer and it becomes impossible for a tubular strander to both convey and feed the layers of large cable with enough strands inside of its small footprint. Because of this difference, tubular stranders are typically used in low voltage and medium voltage applications, whereas planetary stranders are more applicable for high voltage (HV) and extra-high voltage (EHV) cables. While planetary stranders have a larger footprint than tubular stranders, planetary stranders can have shorter stage lengths to produce a layer of the same number of wires, because bobbins are off axis. Both tubular and planetary stranders provide up to 100% backtwist, meaning that they can remove

[14] Thue. William A., "Electrical Power Cable Engineering," Third Edition, CRC Press: 2012, https://eds.b.ebscohost.com/eds/detail?sid=6dc48675-3e52-4380-8dee-1a23d9051b3b@sessionmgr104&vid=0&format=EB&rid=1#AN=413393&db=nlebk (accessed 11/25/17).

the acquired twist that would normally be associated with the stranding process. Figure 17 shows both a tubular strander and a planetary strander.

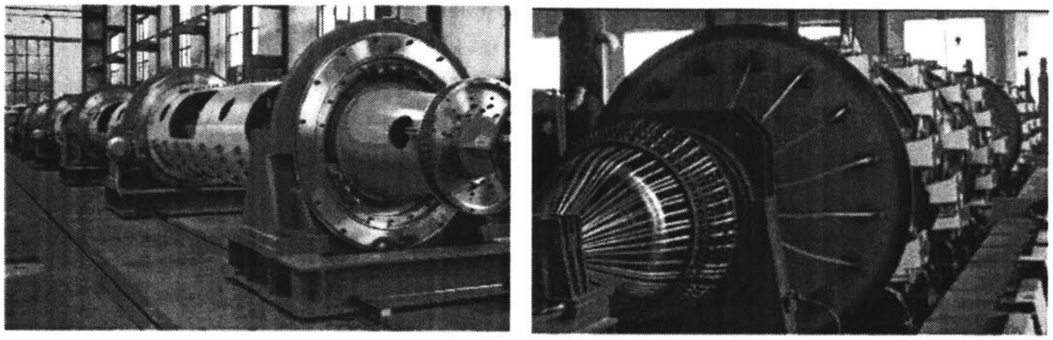


Figure 17: (Left) A tubular stranding machine terminated with a closing die.[15] (Right) A planetary stranding machine.[16]

A combination of these two machines may be used onboard the Cable Train in order to achieve a wide range of cable sizes. There is a large precedent for automated bobbin changing using either automated dollies or hydraulic, floor-mounted jacks.

Taping and armouring machines have much smaller footprints than stranding machines. A typical armouring line will include either an armouring machine, perhaps fed by multiple payoffs depending on the type of armouring, or a metallic shield extruder and either a caterpillar or a capstan.

One disadvantage that comes with the continuous production of long lengths of cable is that there is no ability for product reentry. In other words, a wire stranding machine cannot be reused to produce the successive layers of the conductor. One stranding machine must be dedicated to the production of each layer. This is accounted for in the overhead cost estimates presented in Section 1.6. On the other hand, a single Cable Train with multiple stranding machines could achieve high production rates while eliminating the need to transport finished cable on reels to the site to be spliced which carries its own costs and risks.

[15] Pourtier Gauder Group, "Tubular Stranders," http://en.pourtier-setic.com/Site.aspx?P=11823 (accessed 04/29/2018).
[16] Jinye Electrical Machinery Co., LTd, "Steel Wire Armouring Machine" http://en.chjinye.com/ (accessed 04/28/2018).

1.5 Manufacturers' Standards for High Voltage Cable

For a developer and/or grid operator to purchase underground cable for use in their systems, they must meet quality standards set by the relevant regulatory body. The standards for these cables are achieved by manufacturing facilities built for the production of specific types of cable – Low Voltage (LV), Medium Voltage (MV), High Voltage (HV), Extra High Voltage (EHV), "Ultra-" High Voltage (UHV), as well as exotics used in nuclear power plants and other dedicated operations. Such facilities feature clean environments to prevent materials contamination, vertical towers hundreds of meters tall for perfectly radially symmetric curing, and large heated chambers for efficient cable degassing. It is critical that the radically new mobile manufacturing platform can achieve performance equivalent with these state-of-the-art operations.

Ultra-High Voltage systems represent the new frontier in HVDC development. The materials, system topologies, and technological infrastructure will soon enable such systems to become commonplace. There will always be motivation to increase the voltage capabilities of these systems for more efficient bulk power transmission. There are currently no international standards that exist for UHV underground systems. Therefore, for the purpose of setting functional requirements for the manufacturing performance of the Cable Train, we would propose to use the current standards for EHV HVDC cable and make conservative assumptions, wherever possible, when synthesizing requirements based on standards and tests, which are particularly likely to be affected by increasing voltages in the future.

The International Electrotechnical Commission (IEC) and the Insulated Cable Engineers Association (ICEA) produce manufacturing standards for the international community and the U.S., respectively. High level functional requirements for the Cable Train are hereafter derived from these standards. Descriptions are given for all requirements present in one or both of the standards publications. Where the standards disagree, the more restrictive stipulation has been presented.

It is worth repeating that while standards are only recommendations for the purchaser to expect from the manufacturer, there is always room for negotiation. However, in order to be competitive and make cable that contributes to a robust grid for the future, the Cable Train is intended to be capable of meeting and verifying, at least, all the standards described below.

Testing Requirements In order to sell products of the Cable Train, the following qualification tests must be performed on the mobile platform, or during installation, the ensure the qualification of each standard as well as the performance and durability of the cable as a whole. Below is a summary of the tests required for cables rated up to 550 kV and their implication on the functional requirements of the Cable Train. Sample specifications, frequency, and test types may vary according to the unique features of the cable in question. Many combinations of conditions and stipulations are made governing all steps of each testing procedure. This summary focuses on the **Production Tests** and **Qualification Tests** as they relate to the equipment requirements and physical capabilities of the Cable Train. The requirements presented here are tailored to those required for cross-linked polyethylene (XLPE) insulated cable, the state-of-the-art in cable insulation, which has replaced paper and high-pressure fluids.

1.5.1 Production Tests – There are many ongoing tests that must be performed, during and after production, on material lots and cable samples, to ensure cable integrity in many dimensions:

DC Resistance Test

Cross-Sectional Area Determination

Diameter Determination

Thickness Measurements

Tensile Strength Test (aged and unaged)

Elongation Test (unaged and aged)

Oil Immersion Test (PVC Jacketed cable)

Hot Creep Test

Wafer Boil Test

Amber, Gel, Agglomerates, Contaminant, Protrusion, Irregularity, and Void Test

Elongation Test on Extruded Semiconductor Samples

Dimensional Measurements of Metallic Shield

Diameter Measurement of Insulation and Insulation Shield

Heat Shock Test (PVC Cable)

Heat Distortion Test

Cold Elongation Test

Volume Resistivity Tests

Shrink-back Test

AC Voltage Test

Partial Discharge Test

Water Content Test

Adhesion Test for Metallic Foil Laminates

Adhesion Strength of Metallic Foil Laminates

Many of these tests require samples taken directly from the finished cable with varying specified lengths and using different cutting and dissection methods. Much of this work requires manual attention to perform inspection, operate the testing equipment, and make decisions regarding resampling, retesting, repairing, and discarding of finished cable. The most logical countermeasure to this challenge is to provide dedicated rolling stock outfitted with the necessary testing equipment and personnel to perform production tests.

The goal of the Cable Train is to make continuous lengths of cable that are longer than those currently moveable by means of industrial transportation. Restrictions, related to the production tests described above, on the frequency of sampling present a direct obstacle to accomplishing this. The most restrictive frequency requirement is for the verification of diameters of the insulation and insulation shield and inspection for voids, contaminants, and protrusions in the conductor and insulation shields, respectively. These tests must be performed every 3,000m according to ICEA standards. As described above, checking for voids and protrusions is an invasive procedure, which requires severing the cable completely. As it is a goal that the Cable Train far exceed this shipping length, the Cable Train must utilize countermeasures to replace these two production test procedures with equivalent, but less invasive methods for inspection.

Diameter measurement of insulation and insulation shields with diameter tape can be replaced with on-line laser micrometers or other continuous optical measurement technologies.

The detection and counting of voids can also be replaced by on-line scanning using ultrasonic transducers or continuous x-ray imaging.

In short, the product tests enumerated above require expert personnel – QC engineers, machine technicians, craftsmen, etc. – in addition to well-equipped workspaces and several large facilities and testing machines including, but not limited to:

Tensile Testing Machine

Forced Air Convection Oven

Boiling Pool

Transformer

5kAV Generator

Weathering Machinery

These amenities can be readily incorporated into dedicated rolling stock as is currently done with large CNC machinery, autoclaves, and other large equipment. An alternative solution is to transport samples along the railway to centers with the capabilities to perform these tests. This increases the time and capital necessary to test samples, and leaves less time for negotiating and critical decision-making, but it eliminates the need to have extensive personnel on board this portion of the Cable Train.

1.5.2 Qualification Tests - In addition to production testing, several tests are required before a cable is installation-ready and qualified for use at the rated voltage and power. These tests are described in more detail in Appendices A-E.

Cable Qualification

Resistance Stability Test

Cable Bending Test

Thermal Cycling Test

Hot Impulse Test

AC Voltage Test

Partial Discharge Test

Dissipation Factor Measurement

Dissection Investigation

Jacket Material Qualification

Environmental Stress Cracking Test

Absorption Test Coefficient

Sunlight Resistance Test

Other Qualification Tests

Insulation Resistance

Accelerated Water Absorption Test

Resistance Stability Test

Brittleness Temperature for Semiconducting Shields Test

Equipment related to these tests should be incorporated into rolling stock that can easily access the finished cable being produced, onsite, by the Cable Train. It is worth mentioning, again, that these standards are likely to be reproduced to address cable intended for higher voltages. They are meant as recommended expectations that purchasers impose on manufacturers, but are also meant to be reasonably fair to the manufacturers themselves. In the end, purchasers and manufacturers will come to the ultimate agreement concerning what is acceptable and what is not. Because the Cable train is an unprecedented design challenge, there must be discussions between manufacturers, standards organizations, and other stakeholders, about what UHV cable standards might look like and what methods are acceptable for replacing the current product and qualification tests in order to increase onsite cable production length and speed.

1.6 Overhead Cost Estimation for the Cable Train

In order for a complete economic and profitability analysis to be done to evaluate the suspected cost benefits of railroad transmission systems augmented by in-situ cable manufacturing by the Cable Train, the approximate overhead costs of each of the major pieces of the equipment required by the train are presented below. All numbers are the averages of at least two quotes solicited from major competitors in each industry. Components serving the same function are grouped and their costs lumper together. In order to not betray the trust of these contributors or give any one of them a competitive advantage over the other, the quotes will not be broken into constituent amounts or associated with the name of the entity that provided them. Any request to divulge exact costs or identities must be denied.

Capital Components Grouped by Function	Approximate Cost (USD)
Wire Payoff, Planetary Strander, Closing Die/Bench, Taper, Caterpillar/Capstan, Dancer, (Installation)	\$2,000,000 to \$2,500,000 (+\$600,000)
MDCV Line w/ Triple-Extrusion and LLD Curing (Installation)	\$15,000,000 to \$17,000,000 (+\$5,000,000)
Degassing w/ 80 Cars, 4 Drums per Car, Capable of 28 Day Degas at 80 m/hr Production Rate (Installation)	\$10,000,000 to \$12,000,000 (+\$3,000,000)
Armouring Payoff, Armouring Machine, Caterpillar/Capstan, Dancer, (Installation)	\$500,000 to \$700,000 (+\$150,000)
MDCV Line w/ Single-Extrusion and LLD Curing (Installation)	\$6,000,000 to \$8,000,000 (+\$3,000,000)
Caterpillar, Dancer, Buffer, (Installation)	\$300,000 to \$400,000 (+\$100,000)
QA: Tensile Testing, Weathering, Boiling Pool, Convection Oven, Generators, Transformer, (Installation)	\$500,000 to \$600,000 (+\$100,000)
Primary Mover 6,000hp ×2	\$6,000,000 to \$8,000,000
Total Cost for Major Machinery, Rolling Stock, and Installation	\$52,250,000 to \$61,150,000
Fuel Cost (\$/Km)	\$20,000 to \$25,000

The fuel cost per mile is calculated based on a first order analysis of the power required by the the stranding, taping, armouring, and extruder machines, the LLD heating and cooling requirements, the plurality of industrial motors needed throughout the extrusion lines and degassing cars, and two 6000hp diesel locomotives. There is an assumed efficiency of 60% for all industrial motors, 50% efficiency for all heating processes, and an 80% efficiency assumed for diesel generators and traction motors combined. The energy density and cost of diesel fuel were taken as 110 MJ per gallon and \$3.00 per gallon (USD), respectively.

2 Vision for Topology of Railroad Transmission Systems

2.1 State-of-the-Art in Civil Works and Installation

As an example, consider the "Northern Pass" project in New Hampshire that attempted to bring 1090 MW of Hydro-Quebec's hydroelectric generation through 192 miles of the state's mountainous terrain, to the rest of New England. Eversource Energy (PSNH) pushed to use existing OHL right-of-ways (ROW) to accomplish this feat, but substantial stakeholder upheaval forced developers to commit to 60 miles of underground cable to avoid affecting scenic areas like the White Mountain National Forest, Franconia Notch, Rocks Estates, and the Appalachian Trail. It has been almost 7 years since the public announcement of the Northern Pass project, which was originally planned to be finished by 2015. While similar projects in the Northeast aiming to meet the goals outlined in "An Act Relative to Energy Diversity" have relied on cable ships to lay cable through the Atlantic, the Great Lakes, and the Hudson River, among other bodies of water, the Northern Pass project developers have been struggling to walk the line between their own desires to keep cost down with OHL and being accepted by outside stakeholder's concerned with preserving the natural beauty of the state.

The traditional method for installing OHL starts with clearing vegetation to make way for pylons and 15 to 20 foot wide roads made of gravel, wooden ply, or native soil to accommodate construction equipment. At the location of each pylon, a large, level area must be prepared for drill rigs and cranes. Sensitive natural environments like wetlands must be protected by silt fencing and wooden mats. Foundations for each pylon must be drilled and poured with concrete. Each pylon and grounding terminal takes several days to install. Helicopters and/or "pulling stations" are used to string the bare conductor.

Underground cable installation uses the traditional "cut-and-cover" method. In paved parts of the route, the pavement is first saw-cut then excavation is performed before PVC conduit, thermal backfill, concrete protection, sand, dirt or asphalt are replaced. Trenchless parts of the route are those which require crossing under rivers, highways, railroads, or culverts. This is accomplished by horizontal directional drilling / horizontal boring where the cutting tool carries a pilot string, which is later used to pull the cable through. "Splice Pits" are open-air, concrete galleries where these sections of cable are joined. Each pit takes several days to install as the cable splicing itself is done, by hand, by skilled craftsmen. Likewise, joint repair requires several craftsmen and several days of work. By nature, UGC is less susceptible to certain kinds of weathering damage, compared to overhead lines, but it is arguably harder and more costly to repair when problems do arise. It is estimated that UGC projects can be up to 10 times the cost of OHL.

Clearly, both OHL and UGC require large capital expenditure. However, civil works and cable installation account for approximately a third of the costs of these projects.[17] An accurate model for comparing lifetime economic costs of OHL and UGC systems must be developed comprising:

[17] Cost breakdown of 220 kV UGC project in Iceland (source: Landsnet)

(1) **Capital Costs**
(2) **Energy Losses**
(3) **Environmental Burden**
(4) **Operation and Maintenance Costs**
(5) **Decommissioning Costs**
(6) **Random Repair Costs**

Business models outlining the hypothetical operation of the Cable Train can be evaluated and recommended based on these calculations. The Cable Train concept, if implemented, may reduce costs in categories (3)-(6) above. While the kilometric capital costs of UGC systems with shunt compensation are expected to be higher than those for OHL systems, the goal of these calculations will be to search for a break-even point between OHL and UGC systems that may result from implementing the Cable Train. With novel methods for construction and installation, UGC may be a financially attractive option for a wide variety of future project specs.

2.2 Considerations for Transmission in Railway Systems

It is envisioned that the repurposing of railways systems will significantly streamline the process for earthworks and civil installation. State-of-the-art in railway construction features multitudes of rolling stock machines for foundation installation, ballast cleaning (gravel replacement), rail installation, track welding, tamping, and track lifting. Also common are repurposed bogie-mounted machinery including backhoes and heavy-duty cranes, among other machinery used for various construction and maintenance procedures. Railways are already dynamic construction environments that are accessible by many enabling technologies.

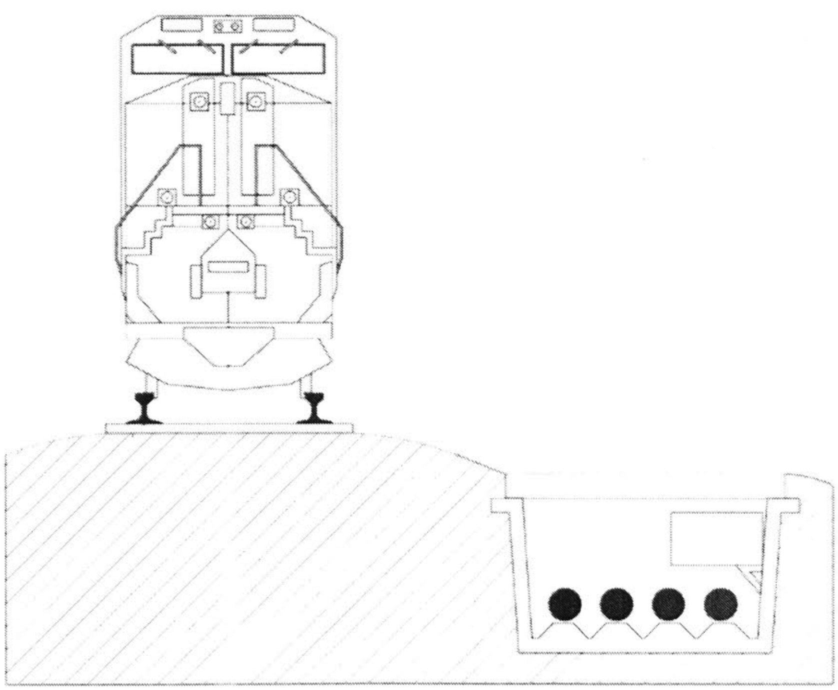


Figure 18: A concept for a trackside, open-air cable gallery with a slip-formed concrete trench and precast concrete cover.

Figure 18 shows a representation of an open-air gallery used to house a UGC system. Because railroads often enjoy right of way upwards of 50 ft, many locations would be accessible by the necessary trenching and concrete slip-forming machinery to make the system in Figure 18 a reality. In locations where clearances are unusually narrow, this infrastructure may be installed by rolling stock equipped with trenchers and/or backhoes, followed by concrete slip-formers that has a tread width large enough to straddle the tracks. These machines are designed to operate on steep grades in order to slip-form drainage and culverts. Concrete can be mixed and transported in dedicated rolling stock, or mixed on-site, to keep the slip-formers fed. Precast concrete slabs can be delivered in the same fashion and installed over the trenches with a gantry crane similar to that currently employed for laying concrete railroad foundations or with a repurposed backhoe. Common railway construction machinery such as bogie-mounted backhoes, railway cranes, ballast, tamping, and are all shown in Figure 19 below.

Figure 19: (Top, Left) A rolling stock machine used to make or replace railroads. The various sections of the train accomplishes operations like ground preparation, ballast pouring, foundation installation, rail pulling, ballast tamping, and rail welding. The existence of these machines allows convenient maintenance and repair of railways. (Top, Right) A view of the same rolling stock railroad-building machine installing concrete foundations at a train station. (Bottom, Left) A commonly found bogie-mounted backhoe capable of fluid operation on and around railroads. (Bottom, Right) A gantry crane capable of traveling from car to car to shuttle pre-cast concrete railroad foundations along the length of a railroad building machine, from "sleeper cars," to where the pieces are being installed.

These and similar machinery may be used to make the installation of trackside duct bank simple and cheap. Before this process can explored in further detail, it is necessary to have a discussion about the requirements of the concrete infrastructure so that the system can house the maximum foreseeable planned transmission demand from a remote location and exist compatibly with the neighboring railway.

The design of the trackside systems – the number and spacing of cables and the utilization of one, or both, sides of the tracks – will be defined by heat management and cable ampacity. Based on an interpolation calculator that uses a matrix constructed of data taken from guidelines and past projects completed by top HVDC system developers, it was shown that railroads provide ample abutting space to accommodate UGC with a high limit on system transmission capacity. In other words, the spacing between cables historically used to ensure cables are able to be cooled by passive heat transfer to the environment allow for large capacity to be installed next to railways.

Three Gorges Dam in Hubei, China has a generation capacity of 22500MW. Taking this power as the maximum capacity that will be provided by remote renewable plants in the foreseeable future, the dimensions of a trackside-side gallery system were calculated to show the feasibility of using track-side systems to accommodate extremely high levels of power transmission. It was shown that, according to prior project data, 22,500MW of transmission could be accomplished by fourteen 153mm OD cables, used as monopoles with ground return, divided into two 3m-wide trenches located on either side of a railroad. Example numbers are shown in Figure 20.[18]

Using so many monopoles in parallel is not necessarily a desirable system configuration, however, this assumption allowed the broad integration of data from many projects to build a tool that could produce results for a large range of voltages and ampacities. While it is unreasonable to assume that a single line would carry 22,500MW (the actual bipole HVDC line from 3 Gorgers Damn to Shanghai is only 3,000MW) this exercise simply shows that railroad right of ways provide a great deal of space to push power, while still staying within ideal operating conditions.[19] In the future, advances in system design and cable technologies could make even higher capacities feasible, even in narrow spaces.

[18] NEXANS, "60-500Kv High Voltage Underground Power Cables – XLPE Insulated Cables," https://www.nexans.no/eservice/Norway-no_NO/fileLibrary/Download_540199654/Norway/files/Underground_power_cables.pdf (accessed 12/12/17).
[19] ABB, "Increases the amount of power delivered from central China to the eastern coast," http://new.abb.com/systems/hvdc/references/three-gorges---shanghai (accessed 05/01/2018).

Grid Voltage (kV)	540
Length of Connection (km)	320
Power (MW)	22500
Copper?	Yes
Installation Method	Cut'n'Cover
Installation Depth (m)	1.5
Short Circuit Current (A)	n/a
Short Circuit Duration (sec)	n/a
Ground Temp (C)	35
Air Temp ©	40
Thermal Resistivity of Ground (K*m/W)	8.33
Cable in Gallery?	YES
Cable Direct Buried?	YES
Current (A)	41666.667
Number of Cables	14

Current Per Cable (A)	2976.1905
Voltage Lower Bound (V)	420
Voltage Upper Bound(V)	550
Postion of Lower Bound in Col. C	23
Postion of Upper Bound in Col. C	24
Current Lower Bound (A)	2965
Current Upper Bound (A)	2990
Postion of Lower Bound in Row 13	104
Postion of Upper Bound in Row 13	105
UL Value	142.66667
UR Value	145.33333
BL Value	153.33333
BR Value	154.5
Weighted Average UL and UR (mm)	143.86032
Weighted Average BL and BR (mm)	153.85556
Diameter of Cable (mm)	153.08669
Width of Monolithic Trench (m)	4.2864274
Trenches on both sides of tracks	Yes

Figure 20: Shows example numbers from a calculator that uses a matrix of data from many past HVDC projects in order to correlate voltage and amperage to cable size, recommended spacing, and overall duct bank width. The calculations show that, based on past data, large transmission capacity can be fit into trackside real estate with current cable technologies.

The formation of such trackside galleries can be accomplished with a concrete slip-former that is railroad compatible, or wide enough to straddle standard gauge tracks. There is a tremendous amount of precedent for the forming of roadside water ducts and drainage paths using specially made slip-forming molds and outrigger forming machines as shown in Figure 21.

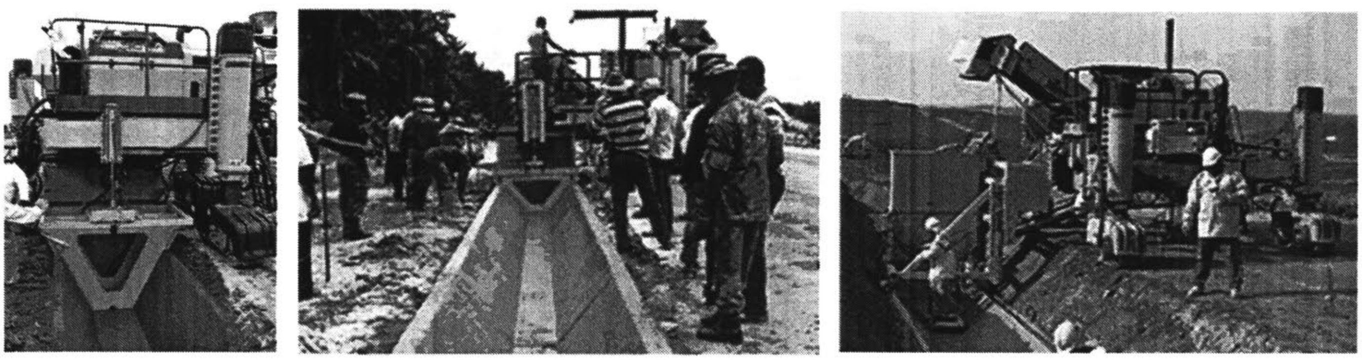


Figure 21: Various slip-forming molds and machines used to create road-side water drainage channels. The machines are arranged so that the forming head, and the formed features, are off-center. Such arrangements may be advantageous to cable duct bank formation abutting railroads. The machines are the GOMACO Commander III (left and right), the GT-3600 (center).

Cooling these open-air galleries in another major challenge to making these system topologies a reality. While it is often sufficient to bury cable under soil and space them according to guidelines in order to avoid excessive mutual heating, the discussion hereafter explores the possibility of having open-air galleries adjacent to railroads for ease of access to instruments and cable. Thermal simulations and a separate analytical model have shown that it is necessary to provide forced convection over the cables in order to keep the cable conductor cores below an allowable temperature of 90°C. The simulation results were produced in SolidWorks Flow and Thermal Simulations and confirmed by calculations that used an isothermal assumption and shape factor abstraction to check the heat removal from the isothermal control volume meets the nominal heat generation in the cable conductor (70 W/m).

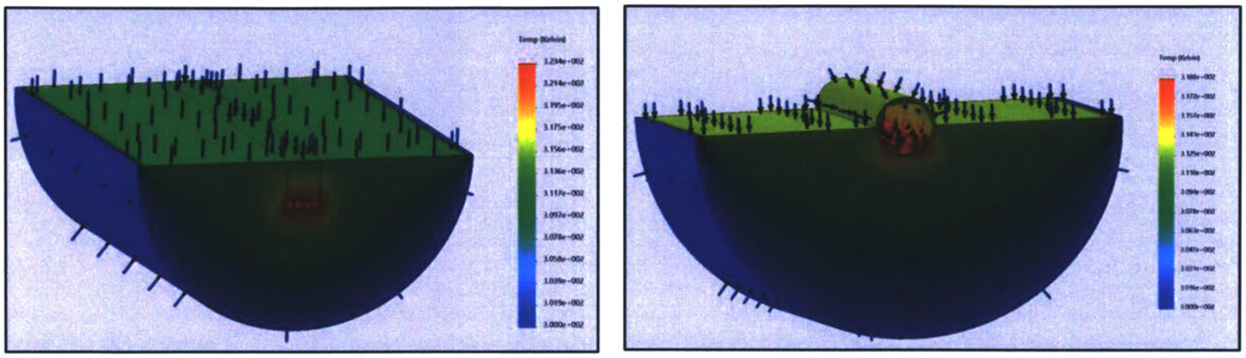


Figure 22: (Left) Validation of model using current topology for cable burial. Four cables are buried under a thermal backfill (compacted sand, k=8.33 W/m*K).[20] (Right) A model contained a slip-formed concrete trench and four cables at the same spacing. A calculated heat transfer coefficient of 16 W/m^2*K from laminar air flow over the cables, at 3 m/s, was determined to be sufficient to keep the cable conductors at an appropriate temperature, but this model assumes the air temperature remains constant as it flows down the length of the tunnel.

A separate analytical model confirms the need for forced convection and the results, illustrated in Figure 23, shows the relationship between the fluid flow velocity and the maximum distance between inlets and outlets as a result of the fluid heating up as it flows down the length of the tunnel section. The model conservatively assumes that there is no conduction between the tunnel and the surroundings and that there is no convection between the top of the tunnel and the outside air (tunnel may be completely buried). The model makes simplifying assumptions such that the flow is well-mixed (it is turbulent in all scenarios) and that the tunnel can be approximated as a cylindrical pipe. Equations relevant to the calculation of this model are also shown below.

[20] Electrical Power Cable Engineering - *Carl C. Landinger (Chapter 15 – Thermal Resistivity of Soil - Pages 288-311).*

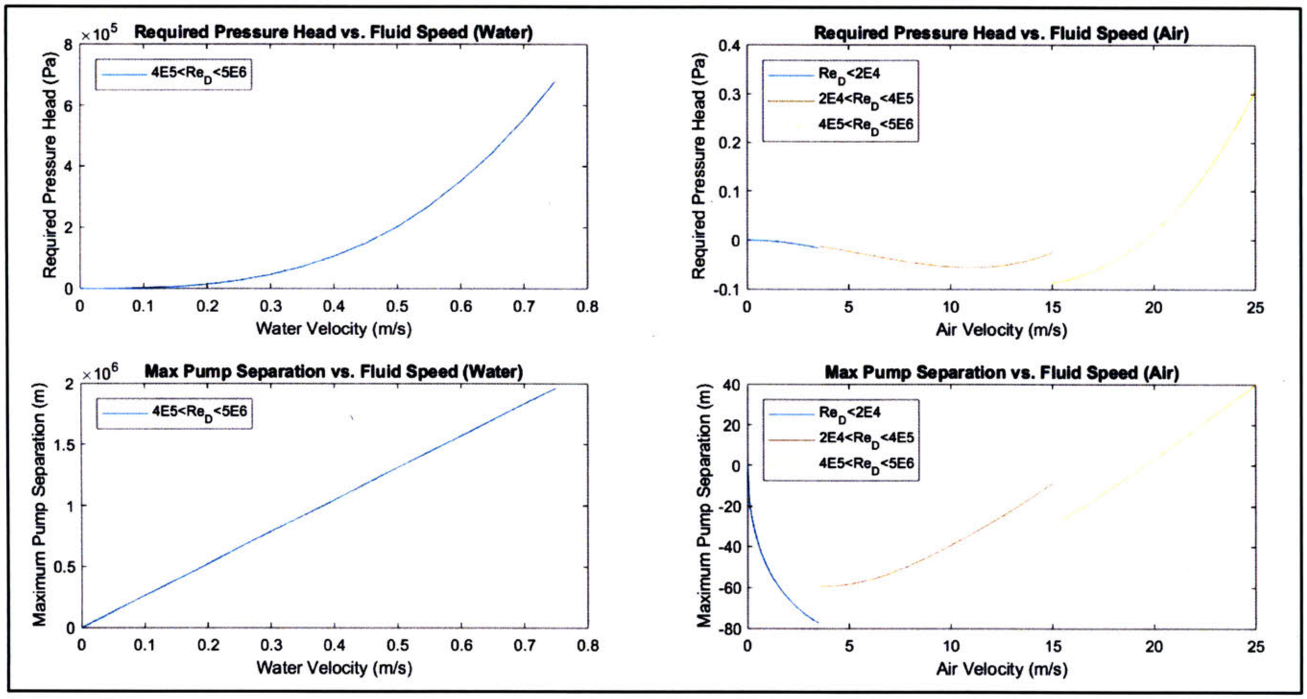


Figure 23: Results from an analytical model showing the relationship between the maximum distance between inlet/outlet locations and the flow velocity of the fluid and assumes 70 W/m heat generation and steady state operation. This relationship is shown for both water and air. The model also produces the pressure head required to create these flow scenarios according to Darcy's Law. It shows that many solutions exist using water as the flowing fluid, but air must be provided at a minimum bulk velocity of approximately 23m/s. This model can be used to do cost optimization, taking into account the length of the transmission line and the total heat generation of the cables in the tunnel. Results are for the largest conceivable open-air gallery intended to house 22500MW of capacity using current cable technology.

Air: $$\rho_a V c_a \frac{dT_a}{dt} = 70\ [Watts] \xrightarrow{T_a(t=0)=40°C} T_a(t) = \frac{70}{\rho_a V c_a} \times t + 40\ [°C] \xrightarrow{t=\frac{x}{v_a}} T_a(x) = \frac{280x}{\rho_a \pi D^2 c_a v_a} + 40\ [°C]$$

$$Nu_D = 0.3 + \frac{0.62 \times Re_D^{1/2} \times Pr^{1/3}}{(1 + (\frac{0.4}{Pr})^{2/3})^{1/4}}\ for\ Re_D < 10^4, \mathrm{Pr} > 0.5$$

$$Nu_D = 0.3 + \frac{0.62 \times Re_D^{1/2} \times Pr^{1/3}}{(1 + (\frac{0.4}{Pr})^{2/3})^{1/4}} \times \left(1 + \left(\frac{Re_D}{282{,}000}\right)^{1/2}\right)\ for\ 2 \times 10^4 < Re_D < 4 \times 10^5$$

Water: $$\rho_w V c_w \frac{dT_w}{dt} = 70\ [Watts] \xrightarrow{T_w(t=0)=40°C} T_w(t) = \frac{70}{\rho_w V c_w} \times t + 40\ [°C] \xrightarrow{t=\frac{x}{v_w}} T_w(x) = \frac{280x}{\rho_w \pi D^2 c_w v_w} + 40\ [°C]$$

$$Nu_D = 0.3 + \frac{0.62 \times Re_D^{1/2} \times Pr^{1/3}}{(1 + (\frac{0.4}{Pr})^{2/3})^{1/4}} \times \left(1 + \left(\frac{Re_D}{282{,}000}\right)^{5/8}\right)^{4/5}\ for\ 4 \times 10^5 < Re_D < 5 \times 10^6$$

$$70 = hA\left(T_{cable} - T_{fluid}(x_{MAX})\right) required$$

$$\Delta P = f \times \frac{L}{D} \times \rho \times \frac{v_{Avg}^2}{2}$$

This analytical model suggests that it would be possible to cool the cables sufficiently with water flowing at a bulk velocity of 0.05 m/s with a maximum inlet-outlet separation of approximately 120km, as an example. The model provides data for other flow scenarios using air as the fluid, and these results can be used to perform a cost optimization of duct bank design according to the length of the transmission line and the total heat generation of the cables in the tunnel.

While this was a useful exercise it may still be cheaper and easier to use native or thermally engineered backfill to cover cable. Even though a theoretical solution exists that can remove the desired amount of heat, the flow rate resulting from 0.05m/s fluid flow and the corresponding model geometry, combined with the pressure heads required, push typical pumping technologies to the limit. This will become expensive and essentially offset the cost savings, through the elimination of intermediate cable instrumentation, achieved by in-situ cable manufacturing.

Further work needs to be done to confirm the ability of track-side land to accommodate UGC systems with large transmission capacities and what configurations might be applicable depending on the load and generation characteristics of the line. The aforementioned analytical model may be developed and tested further if one would like to confirm that the open-air galleries will be able to keep cables protected and sufficiently cooled to sustain reliable operation.

3 Case Studies

3.1 Northern Pass

The Northern Pass project is an excellent example of the difficulties inherent to current attempts to install terrestrial HVDC links. Because of a reliance on OHL, the project suffered major delays and, at the time this paper was written, suffered what many considered is a fatal blow. Hereafter, the technical challenges of the project and the possible application of the Cable Train are discussed.

The Northern Pass project attempted to bring 1090 MW of Hydro-Quebec's hydroelectric generation from Pittsburg NH to Deerfield NH through PSNH's 192-mile transmission system, through New Hampshire, to the rest of New England. 60 miles were planned to be underground to avoid affecting scenic areas like the White Mountain National Forest, Franconia Notch, Rocks Estates, and the Appalachian Trail – a concession made after much backlash from external stakeholders. It was self-proclaimed to decrease carbon emissions by about 3.2 million tons a year. The link planned to use existing (115 kV AC or 34.5 kV) and new right of ways. Because of permitting delays, it was delayed almost 7 years since the initial public announcement.

On August 10, The U.S. Department of Energy (DOE) released the Final Environmental Impact Statement (FEIS) for the Northern Pass transmission project (NPT). The project developers were still waiting for several federal permits: the DOE Presidential Permit, a U.S. Forest Service Special Use Permit, and the Section 404 Permit from the U.S. Army Corps of Engineers.[21] The project was supposed to start in 2013 and be finished in 2015, but it suffered major delays.[22] The approval process involved scoping (02/11/11-11/05/13), NEPA EIS drafting, public hearings and commenting on the EIS (07/31/15-04/04/16), before the completion of the final EIS late 2017.[23]

In March, 2018, the state of New Hampshire withheld a crucial permit and Massachusetts abandoned its contract with the Northern Pass Project, instead seeking a contract with Avangrid's (known locally as Central Maine Power) competing project, New England Clean Energy Connect – all after Eversource had spent nearly a quarter billion dollars to develop the Northern Pass project.[24] *Why did it take almost 7 years, since being conceived, for the Northern Pass project to gain the required approval an why was it eventually unsuccessful?* Public opposition.

People concerned about the use of eminent domain, environmental impact, and visual impact overwhelmingly wanted the cables buried (like undersea cable projects in other states), but the NPT conisistently refused. Compromises proposed by stakeholders included burying the cables in state transportation corridors (I-93) or using the new power capacity to replace PSNH's

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[21] Forward NH Plan, "Northern Pass Achieves Major Federal Permitting Milestone," http://blog.northernpass.us/2017/08/10/northern-pass-achieves-major-federal-permitting-milestone/ (accessed 10/01/2017).

[22] https://www.northernpasseis.us/faq/

[23] https://www.northernpasseis.us/faq/

[24] Chesto, Jon, "Mass., utilities cut ties with Northern Pass power line project," Boston Globe (Boston: March 2018) https://www.bostonglobe.com/business/2018/03/28/northern-pass-power-line-short-circuited/fwF8ceb54ccFjDyx8T1ifJ/story.html (accessed 04/24/2018).

gas-fired power plants. Northern Pass refused to concede or place the cable anywhere but the current PSNH transmission corridors.[25]

Meanwhile, the New England Clean Power Link in Vermont committed to completely burying their cables, mostly underwater in Lake Champlain, over the 150-mile distance. The project applied for a Presidential Permit in early 2014 and received it in late 2016.[26] Other projects are adopting the same architecture - the Maine Green Line is a 1200MW connection from Greater Boston to wind generation (in Maine) and hydropower (in Canada), through 220 miles of marine cable.[27] The Maine Power Express project is a 1000MW submarine HVDC line 315 miles long, extending from Maine into Boston Harbor.[28] Lastly, the Champlain Hudson Power Express project is a 1000MW installment from Hydro-Quebec to NYC, buried in the Hudson River, which was pursued by the same company involved in the New England Clean Power Link project in Vermont.

These projects managed to evade the regulatory hang-ups, which have plagued NPT. The Northern Pass DOE investigation received 1037 comments during the public review of their EIS alone[29] (Northern Pass Final EIS S.4.2.3 Draft EIS Public Review Period S-9). In stark contrast, during the New England Clean Power Link scoping period, the DOE received 12 comments and during the EIS public review/commenting process they received 1 comment from private individuals, government entities, and NGOs[30] (New England Clean Power Link Final EIS S-5 and S-6, Public Scoping and Draft EIS Public Review Period).

These submarine projects are being enabled by the presence of large water bodies as well as cable-laying ship technology owned by most HVDC providers. ABB, Nexans, and Prysmian Group, for example, have manufactured their own cable laying ships and subsequent submarine DC cable projects have achieved wild successes not just in the Northeastern U.S., but also in Europe – NorNed and NordLink are two of the longest cable projects in the world, carrying 700MW and 1400MW of renewable generation from Norway to the rest of Europe, respectively. Unfortunately, there are no major waterways in New Hampshire to conceal the cable and methods for undergrounding terrestrial cable are lagging behind marine burial - the Pemigewassat, Merrimack, and Connecticut rivers are noteworthy waterways in NH and run parallel to the direction of the planned NPT route, but it would be unreasonable to bury the cable underwater in these rivers because they cannot accommodate cable ships.

The NPT developers finally committed to 60 miles of traditional "cut-and-cover" underground cable to avoid affecting scenic areas like the White Mountain National Forest

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25 Courchesne, Christophe, "Lessons from 4 Years of Northern Pass Failures," Medium, October 17, 2014, https://medium.com/@courchesnec/lessons-from-4-years-of-northern-pass-failures-e255de34cc5c (accessed 10/01/2017).

26 http://www.necplink.com/schedule.php

27 http://mainegreenline.com/

28 Maine Power Express, "Proposed Route," http://www.mainepx.com/proposed-route#massport (accessed 11/01/2017).

29 U.S. Department of Energy: Office of Electricity Delivery and Energy Reliability, "Final Northern Pass Transmission Line Project Environmental Impact Statement," Summary, Washington D.C. (August 2017) http://media.northernpasseis.us/media/EIS-0463-FEIS-Summary_2.pdf (accessed 11/01/2017).

30 U.S. Department of Energy: Office of Electricity Delivery and Energy Reliability, "Final New England Clean Power Link Project Environmental Impact Statement," Volume I, Washington D.C. (Oct. 2015) http://www.necplink.com/docs/Final-NECPL-EIS-2015-10-27.pdf (accessed 11/01/2017).

(WMNF), Franconia Notch, Rocks Estates, and the Appalachian Trail.[31,32] Therefore, the "preferred" route for NPT, as presented in the DOE FEIS, includes overhead lines in existing PSNH transmission corridors combined with the 60 miles of underground cable along NH Routes 18, 112, and 116 and US Routes 3 and 302. (Alternatives for burying the cable along I-93 through the Franconia Notch and the WMNF are not feasible because of NHDOT policies on use of the public property.)

What if the terrestrial cable could be continuously extruded and laid from the Cable Train along one of the many standard gauge tracks passing through New Hampshire? The right of way provided by the railroads removes the need for new access roads, which require massive amounts of de-vegetation. Figure 24 shows the overlap between the proposed Northern Pass route and the current standard gauge tracks in the state of New Hampshire. The tracks are mostly scenic passenger tracks, but there is some freight, and all are privately owned. If the border crossing point was shifted south by 14 miles to the New Hampshire Central Railroad (NHCR) starting point in Colebrook (cutting through Vermont) then the cable could be laid continuously, rail-side, change to the St. Lawrence & Atlantic Railroad in North Stratford, reconnect to the NHCR line in Groveton and continue to Littleton[33], where it would transition from the railway to a portion of the originally planned 60-mile "cut-and-cover" underground route, crossing the WMNF to Lincoln where it could join the New England Southern Railroad[34] (will not utilize the scenic railroads in the WMNF) and continuously extrude cable until Concord where it can either transition to overhead HVAC or continue farther south on the Pan Am track before transitioning to overhead HVAC and heading east to Deerfield. Cutting through Vermont with a project intended to benefit New Hampshire may be difficult and so the cable can simply be buried, using traditional methods, from the current border-crossing point, in Pittsburg, NH, to meet the rail system in Colebrook, NH.

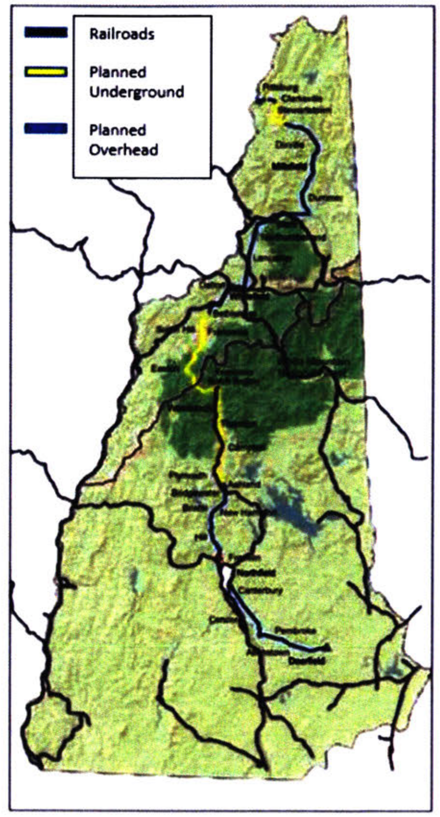

Figure 24: Overlap between NPT route and NH railroads.

An alternative route to the one above would be to use the Washington County Railroad[35] (part of the Vermont Rail System) to avoid leaving the rail system in the WMNF and continue laying cable (from the train) from Littleton to White River Junction, continue south on the New England Central Railroad[36] to Claremont and then turn east and follow the abandoned section of

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31 Forward NH Plan, "Northern Pass Achieves Major Federal Permitting Milestone," http://blog.northernpass.us/2017/08/10/northern-pass-achieves-major-federal-permitting-milestone/ (accessed 10/01/2017).

32 Forward NH Plan, "Project Overview," http://www.northernpass.us/project-overview.htm (accessed 11/01/2017).

33 http://www.newhampshirecentralrailroad.com/map.html

34 http://www.newenglandsouthernrailroad.com/

35 http://www.vermontrailway.com/maps/wacr_conn_map.html

36 https://www.gwrr.com/railroads/north_america/new_england_central_railroad#m_tab-one-panel

the Concord Claremont Railroad[37] to Concord. This route avoids the scenic railroads and circumnavigates the entirety of Franconia Notch and the WMNF. However, the gauge and condition of the abandoned track may prevent the deployment of certain rolling stock. These are just examples of routes that could be exploited with the current rail systems in the region.

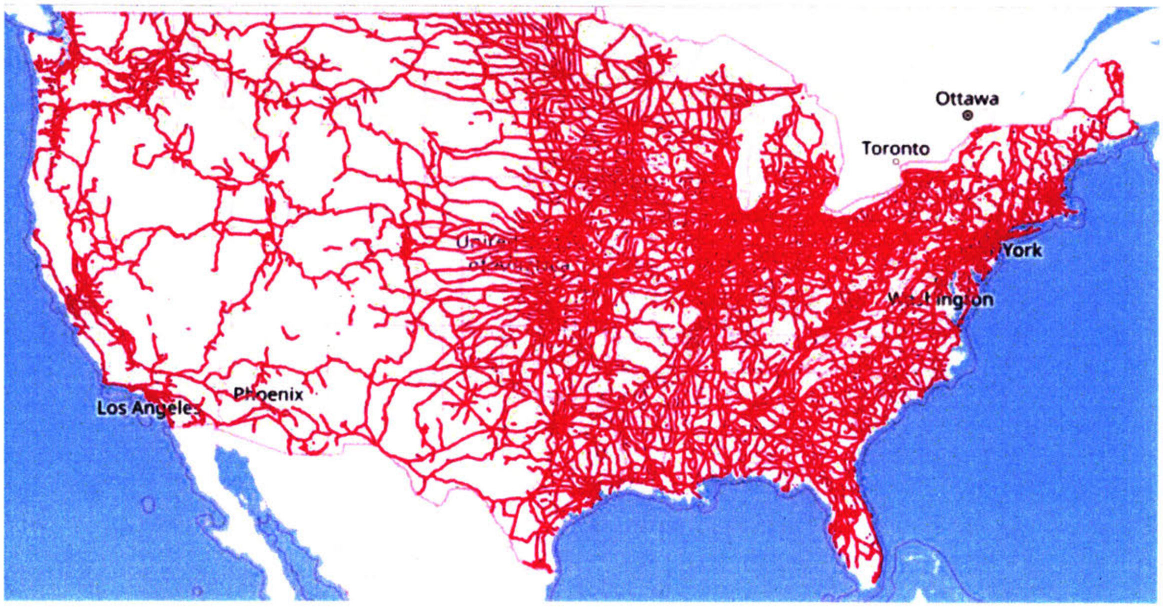

Figure 25: A map of known U.S. railroads constructed from GIS data.[38]

The U.S. rail system, with its hundreds of thousands of miles of privately owned track, provides many opportunities for an application of this mobile cable making and laying process, which could help reduce the regulatory burden of future HVDC projects without convenient access to ship-accessible waterbodies. In theory, this method will enable buried, cross-continent direct transmission installation.

3.2 Intermodal Passageways and Proposed Plans for a National HVDC Grid

Because of the intermittent and off-demand generation of renewable plants, grid managers' jobs in planning for energy demand has been complicated. Without infinite storage potential, building a grid that can allow high penetration of renewable energy, with little or no increase in the cost of electricity, is a problem that has been addressed by several parties over the last decade. There have been several attempts made to develop tools for optimizing a transmission system design that can incorporate variable wind and solar generation at low cost. In 2016, a study by NOAA scientists Alexander E MacDonald and Christopher T.M. Clack, et al.,

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[37] http://www.abandonedrails.com/West_Concord_to_Claremont_Junction

[38] Raquel Wright, "USA (Railroads, 2008)," Federal Railroad Administration (FRA), FDGC Metadata: FGDC-STD-001-1998, MIT GeoWeb: https://arrowsmith.mit.edu/mitogp/layer/MIT.SDE_DATA.US_P3RAIL100K_2008/ (accessed 09/14/17).

found that a large-scale, optimized HVDC grid could enable the U.S. to use wind and solar generation to eliminate up to 80% of CO2 emissions while meetings its energy needs at the same cost of electricity as in 2012.[39] This National Electricity with Weather System (NEWS) model incorporates high resolution weather data to calculate generation and demand. Unlike past studies, the NEWS model does not assume a constrained fossil fuel supply or cheap energy storage. While the exact locations of solar and wind generation may be changed with future models optimized using higher resolution data, the need for a large HVDC system that transcends balancing authority areas (BAAs), is clear.[40] The map in Figure 26 shows the potential to use intermodal railways as corridors for new HVDC transmission (as proposed by the NEWS model) to connect generation and demand nodes.

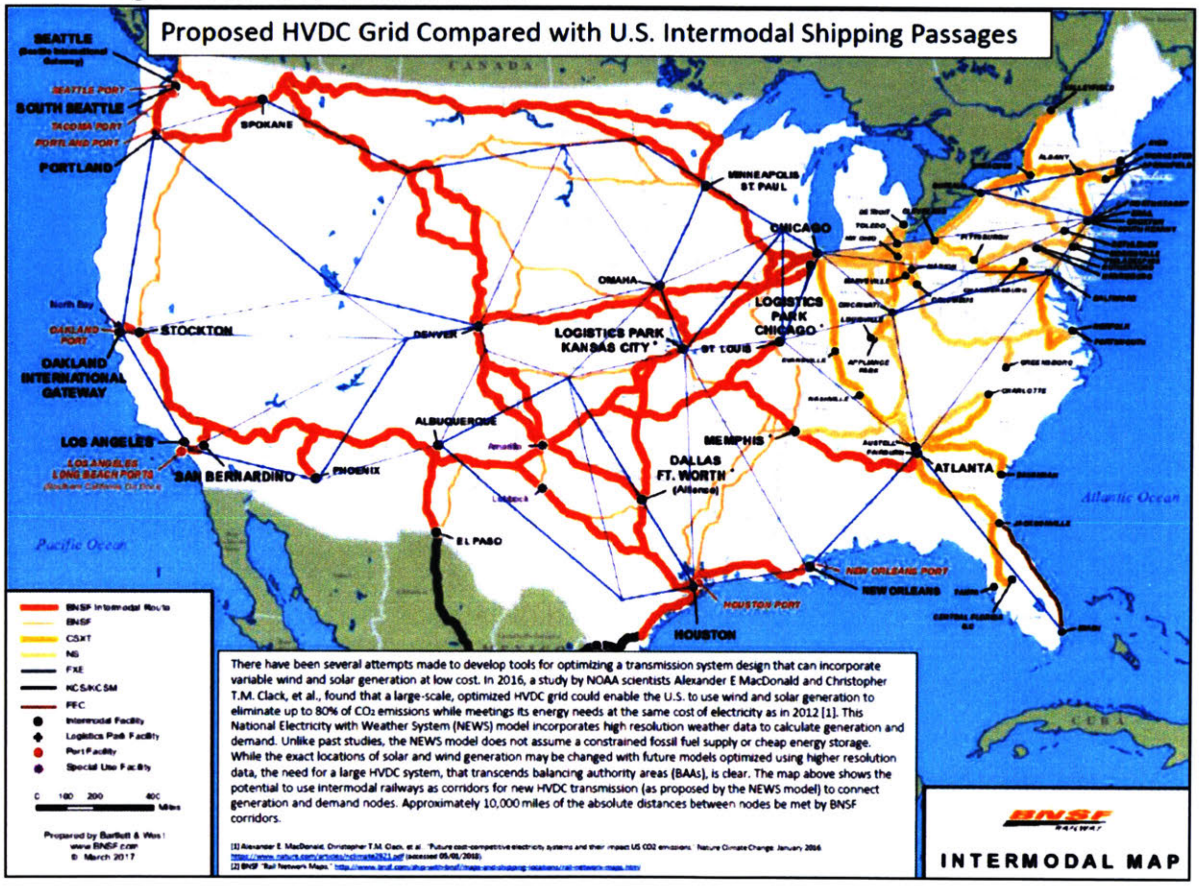

Figure 26: The map above shows the overlap of major intermodal railroads in the U.S. with an HVDC grid proposed that is optimized to allow maximum penetration of variable generation (renewable energy) while avoiding a significant increase in the cost of electricity. The underlying map is provided courtesy of BNSF Railway Company and the grid shown is proposed by Alexander E. MacDonald and Christopher T.M. Clack, et al.[41]

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[39] Alexander E. MacDonald, et al., "Future cost-competitive electricity systems and their impact on US CO_2 Emissions," Nature Climate Change (January 2016) https://www.nature.com/articles/nclimate2921.pdf (accessed 05/01/2018), 526-527.

[40] Ibid, 530.

[41] BNSF, "Rail Network Maps," http://www.bnsf.com/ship-with-bnsf/maps-and-shipping-locations/rail-network-maps.html; Alexander E. MacDonald, et al., "Future cost-competitive electricity systems and their impact on US CO_2 Emissions," Nature Climate Change (January 2016) https://www.nature.com/articles/nclimate2921.pdf (accessed 05/01/2018), 526-527.

A large portion of the HVDC links proposed by the NEWS model could be made using railroad corridors that already exist. Approximately 10,000 miles of the absolute distances between nodes could be met by BNSF railroads. As shown in Figure 27 and Figure 28, BNSF railroads encompass most of the area with the richest sources of renewable energy.

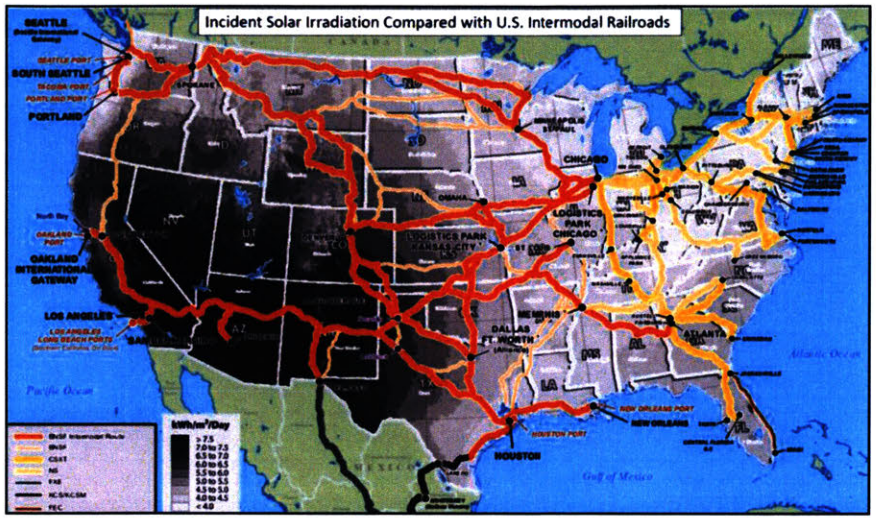

Figure 27: A map showing the overlap between the high solar irradiation in the U.S. Southwest and the intermodal railway system. The underlying map is provided courtesy of BNSF Railway Company and the solar irradiation data is taken from NREL.[42]

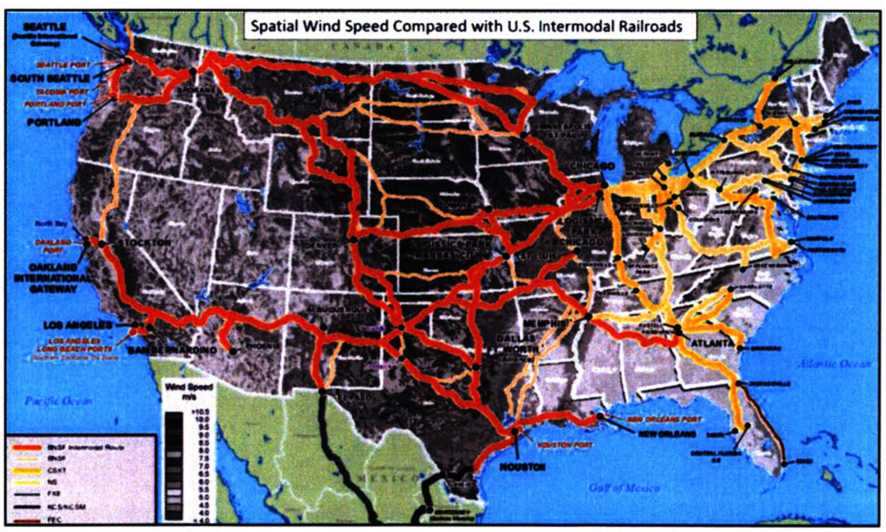

Figure 28: A map showing the overlap between the high wind speeds in the Great Plains and the intermodal railway system in the U.S. The underlying map is provided courtesy of BNSF Railway Company and the wind speed data is taken from NREL.[43]

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[42]Roberts, Billy J., "Concentrating Solar Resource of the United States," National Renewable Energy Laboratory (September 19, 2013) https://www.nrel.gov/gis/images/eere_csp/national_concentrating_solar_2012-01.jpg (accessed 01/01/18); BNSF, "Rail Network Maps," http://www.bnsf.com/ship-with-bnsf/maps-and-shipping-locations/rail-network-maps.html

[43] AWS Truepower, "United States – Land-Based and Offshore Annual Average Wind Speed at 100m," National Renewable Energy Laboratory (September 19, 2012) https://www.nrel.gov/gis/images/100m_wind/awstwspd100onoff3-1.jpg

4 Practical Limitations to Cable Production Length

4.1 Cable Temperature Monitoring

While the demand for higher voltages and longer cables is constant, and the Cable Train's ability to in-situ produce cable caters to this demand, there are several complications that may limit the length of cables produced by the Cable Train - namely, fault detection, localization, and repair, as well as the voltage limit of sheath voltage limiters used for metallic shield grounding and sheath dielectric strength.

Faults in transmission class systems can cause damage that create tremendous financial and social costs. The local temperature rise that is associated with the induced electrical phenomena in a cable during electrical fault is the most obvious way to detect faults in cable systems. An ideal fault detection system would not only detect faults with a high fidelity, but also localize the fault within a narrow section of cable to be serviced. The holistic and continuous monitoring of the temperature of hundreds of kilometers of transmission-class cable with traditional methods would be extremely costly – common temperature measurement schemes like thermistors, thermocouples, and resistance temperature detectors present large installation costs because, in order to achieve distributed sensing along and entire length of cable, they must be employed in mass quantities. On the other hand, Fiber Optic Sensors (FOS) may provide simple, distributed sensing that can be applied to long lengths of cable, perhaps even emplaced in the cable as part of the manufacturing process.

Fiber optic sensors can be broken down into phase-modulated sensors, intensity-modulated sensors, wavelength-modulated sensors, scattering-based sensors, and polarization-based sensors, which all make use of different optical phenomena to detect and measure environmental disturbance. Some rely on direct interaction with fiber, while others rely on mechanical transducers. The essential advantages of FOS are that they are relatively easy to install and they are unaffected by electromagnetic interference (EMI) and radio frequency interference (RFI). These sensors have already achieved wide-ranging industrial applications.

Temperatures can be accurately and spatially measured using a scattering-based sensor system that exploits Raman or Brillouin scattering as well as Optical Time Domain Reflectometry (OTDR). These systems can be distributed, meaning that a single fiber can act as a continuous sensor with resolution on the order of meters, a property unique to scattering-based systems. By deducing the temperature of a point by considering the ratio of temperature-dependent anti-Stokes backscatter intensity with temperature-independent Stokes backscatter intensity, these sensors are self-referenced and relatively unaffected by the transmitted laser light intensity – while signal must be integrated over .[44]

One single-mode fiber and an opto-electronics box, can continuously and accurately monitor the temperature of high voltage cables over distances of tens of kilometers.[45] The

(accessed 01/01/18); BNSF, "Rail Network Maps," http://www.bnsf.com/ship-with-bnsf/maps-and-shipping-locations/rail-network-maps.html

[44] Krohn David A., et al. "Fiber Optic Sensors: Fundamentals and Applications," Fourth Edition, Society for Photo-optical Instrumentation Engineers (SPIE): 2015, 182-187.

[45] Krohn David A., et al. "Fiber Optic Sensors: Fundamentals and Applications," Fourth Edition, Society for Photo-optical Instrumentation Engineers (SPIE): 2015, 28-29.

systems can last a long time and can be produced in a similar manner as telecommunications cabling. These fibers can be used to measure high temperatures despite their operating temperatures being around the same operating temperature as high voltage cable. FOS distributed temperature sensing (DTS) systems have been used for cable monitoring as well as ampacity optimization and there are several commercial products available. It may be possible to improve transmission and signal processes in order to achieve even greater distances, should the need for this monitoring system even become the limiting factor to cable length.

4.2 Cable Protection and Cable Length Limitations in DC Applications

HVDC cable lengths have no limit because they do not require intermittent reactive compensation and are free of charging currents. There is also no need for intermittent surge arresting because of the nature of fault modes in DC systems. There are several fault modes associated with the rectifier and inverter sides of converter stations in HVDC systems – AC line faults, arc back, arc-through, quenching, and misfire – due to valves and control equipment at converter stations.[46] Fault currents resulting from these modes are stopped by AC circuit breakers and disconnectors, fast-acting DC breakers and DC-side fault-blocking converters. Relays and current transformers used to detect faults do so based on endpoint impedance and current measurements.[47] These methods do not require cable accessories and so cable length is not affected.

The only fault modes that propagate in DC cables are Line-to-Ground and Line-to-Line faults, which are usually caused by rare events like lightning strike, switching transients (generation/load imbalances), and excessive mechanical stress – the former two happening over very short time-scales and the latter lasting longer. Strokes of lightning rarely directly strike transmission systems, but even an indirect strike or a lightning impulse entering a system from an overhead line can cause large surge currents in cables which move as "traveling waves" and reflect off of nodes, with change in impedance, until attenuated. Intermediate surge arrestors may be used to protect cable from lightning surge. These include spark gaps, valve arresters (SiC), and metal oxide varistors (MOVs).[48] When applied to cable metallic shields, these technologies are collectively referred to as sheath voltage limiters (SVLs). These may be used at cable terminations in cases where cable is connected to overhead line because lightning impulse is more likely. Submarine cables do not have these accessories. They are made to be robust and care is taken to avoid mechanical damage during and after installation. In the case of a large surge current, damage may be permanent and cable would need to replaced. This unlikely, but

[46] Khairnar, Ashwini K., et al., "Study of Various Types of Faults in HVDC Transmission System," 2016 International Conference on Global Trends in Signal Processing, Information Computing and Communication https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7955349 (accessed 04/15/2018), 483.

[47] The Institute of Electrical and Electronics Engineers, Inc., "HVDC Grids: For Offshore and Supergrid of the Future," John Wiley & Sons, Inc. (Hoboken, New Jersey: 2016) https://onlinelibrary-wiley-com.libproxy.mit.edu/doi/pdf/10.1002/9781119115243 (accessed 05/03/2018) 362-366.

[48] The Institute of Electrical and Electronics Engineers, Inc., "HVDC Grids: For Offshore and Supergrid of the Future," John Wiley & Sons, Inc. (Hoboken, New Jersey: 2016) https://onlinelibrary-wiley-com.libproxy.mit.edu/doi/pdf/10.1002/9781119115243 (accessed 05/03/2018), 345-366.

catastrophic, contingency is why submarine cable lines often have a redundant line to take the place of a damaged cable.[49] In addition to acute events like faults, overvoltage of a certain duration or severity may also cause premature aging or breakdown of the cable.

Detailed transmission system studies, considering the HVDC configuration, geography, potential weather effects, as well as the characterization of generation and loads, can inform the best use of redundant cables and surge arresters on DC lines. Nevertheless, it is maintained that, for HVDC systems, cable accessories used for surge arresting and cable protection do not affect the theoretical length of a single piece of continuous cable between two nodes. This validates the primary advantage of in-situ cable manufacturing using the Cable Train; increasing the theoretically limitless length of single HVDC cables and eliminating splices may lead to significant overall cost reductions for transmission lines.

4.3 Cable Protection and Cable Length Limitations in AC Applications

While the vision laid out in this paper is of long-distance HVDC transmission co-located with railroads, there is no reason the Cable Train could not be used to manufacture cable for AC systems. AC systems. Therefore, for the sake of thoroughness, the following discussion focuses on HVAC fault protection and the limits that protection schemes have on the theoretical length of a single cable.

Cable protection schemes attempt to provide ground, maintain a path to ground for fault-current, limit shield voltages, reduce shield losses, and limit transient overvoltages. For AC systems, these schemes achieve this by implementing surge arrester and grounding devices, as well as various shield bonding techniques. These devices and methods may present limits to cable length.

In high voltage AC cable systems, transient events can cause induced currents in metallic, water-proof shielding. These currents will run straight to ground and represent a 100% loss in energy. This loss manifests itself as heat which limits the overload operating capability of the cable. In order to reduce losses, the metallic shields used in high voltage cable are often segmented to interrupt this flow of current. While there are other methods for reducing metallic shield losses, shield segmentation is the single easiest and most effective. As a consequence of shield segmentation, transient events will cause voltage spikes in the shield. These can be very large and cause jacket breakdown and penetration. These openings can be locations for moisture ingress and cause total cable failure.[50]

While it is often not economical to fight losses in distribution-class systems, meaning that shields in these systems are commonly solidly bonded, transmission-class systems, characterized by higher voltages and longer distances, often call for special bonding techniques relating to how

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49 Worzyk, Thomas, "Submarine Power Cables: Design, Installation, Repair, Environmental Aspects," Springer Dordrecht Heidelberg (London: 2009) https://link.springer.com/book/10.1007%2F978-3-642-01270-9 (accessed 11/30/2017), 222.

50 IEEE Standards Association: IEEE Power and Energy Society, "IEEE Guide for Bonding Shields and Sheaths of Single-Conductor Power Cables Rated 5 kV through 500 kV (IEEE 575)" IEEE Standards Association, IEEE (New York: 2014) https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6905681 (accessed 04/18/2018).

cable metallic shields are connected to each other and to ground because losses can be greater and implementing special bonding can significantly increase ampacity rating, therefore decreasing cable conductor sizes and/or the number of cables required for a project. Special bonding methods comprise single-point bonding, multiple single-point bonding, impedance bonding, sectionalized cross bonding, and continuous cross bonding.[51]

Cross-bonding is often used in 3-phase AC power transfer, however, for the sake of simplicity, single-point bonding is considered here, where one end of a shield is grounded and the other end is isolated from ground by a special kind of surge arrester called a sheath voltage limiter (SVL). For longer lengths of cable, multiple single-point bonding can be used. Figure 29 illustrates the concept of cable segmentation and surge protection using SVLs in a single-point bonded configuration. SVLs are located at segmentation interfaces where they are housed inside of link boxes, or at underground cable terminations. The ratings of SVLs currently limit the length of single-point bonded cables to about 2km. While the size and rating of an SVL may be theoretically inflated to increase the possible length of single-point bonded cables, developers and utilities already struggle to fit the largest SVLs (~18kV) into standard link boxes. Therefore, the length of a cable is limited by the allowable standing voltage at the isolated end according to the rating of the SVL.[52]

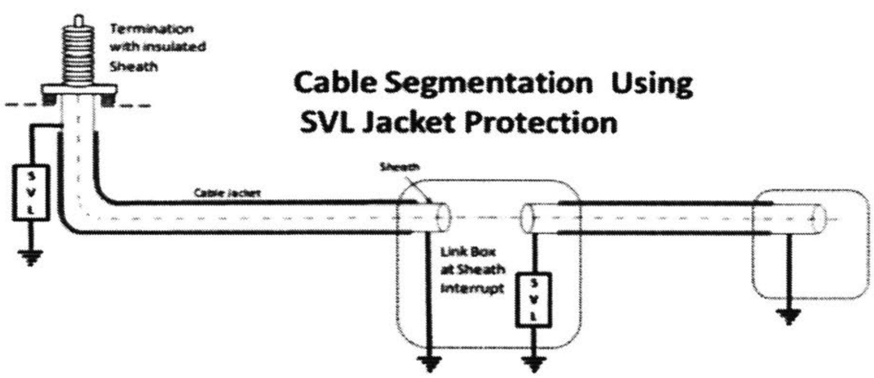

Figure 29: A common scheme for surge protection in high voltage cables using metallic shield segmentation and Sheath Voltage Limiters (SVLs). Shield segmentation stymies lossy current during transient events and SVLs limit the resulting induced voltage and protect the cable jacketing from electrical stresses. The rating of SVLs are limited by current production and this may place a limit on the length of cable produced by the cable train (schematic from IEEE 575).[53]

According to industry providers, SVLs are limited to those that are rated for 200V to 20kV maximum continuous overvoltage (MCOV). It is important to note that the size of the SVL increases with the rating. According to one transmission developer, 18kV is currently the largest

[51] IEEE Standards Association: IEEE Power and Energy Society, "IEEE Guide for Bonding Shields and Sheaths of Single-Conductor Power Cables Rated 5 kV through 500 kV (IEEE 575)" IEEE Standards Association, IEEE (New York: 2014) https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6905681 (accessed 04/18/2018).
[52] IEEE Standards Association: IEEE Power and Energy Society, "IEEE Guide for Bonding Shields and Sheaths of Single-Conductor Power Cables Rated 5 kV through 500 kV (IEEE 575)" IEEE Standards Association, IEEE (New York: 2014) https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6905681 (accessed 04/18/2018), 7.
[53] INMR "Sheath Voltage Limiters Protect HV Power Cables," INMR (May 2016) http://www.inmr.com/sheath-voltage-limiters-protect-power-cables/ (accessed 04/24/2018).

SVL used in their systems and that even this device cannot fit in conventional link boxes. As the distance between shield segmentation is directly related to the induced voltage buildup on the metallic shield, this rating and size constraint may present a limit to the possible production length of AC cable manufactured onboard the Cable Train.

The processes for calculating the standing voltage of a metallic shield and the voltage rise during fault are prescribed by IEEE 575 and Electra 128, respectively. In order to comply with surge protection standards, the calculated voltage rise during a transient event must be less than the temporary overvoltage (TOV) that the SVL is rated for, which is usually 20-30% higher than the MCOV.

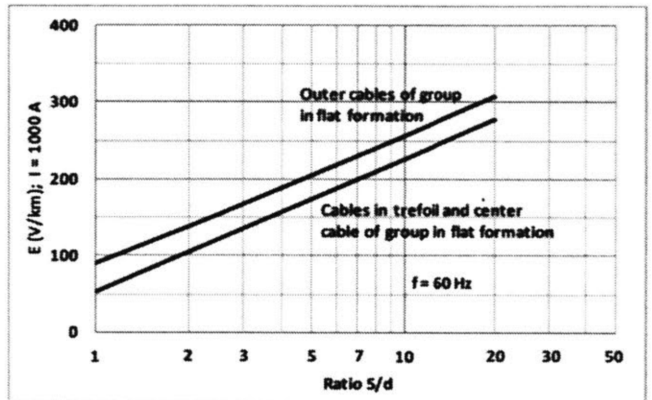

Figure 30: Induced shield standing voltage in a cable carrying 1000A with AC frequency 60 Hz. "S" in the center-to-center spacing of the cables and "d" is the mean shield diameter.[54]

In addition to the condition on SVL rating, the dielectric strength of cable jacketing must also be sufficient to withstand induced voltage rise during faults. Jacketing strength can be approximated as 5kV/mm up to a maximum of about 30kV (for a cable with jacket thickness of 6mm). Jacketing dielectric strength, and therefore the maximum cable production length, is then limited by what diameter of cable can be produced and safely handled.

The standing voltage on shields in the normal three-phase regime, as calculated from IEEE 575 for a cable carrying 1000A with an angular frequency of 60 Hz and with 175mm OD cables spaced 2×OD center-to-center, is about 140 V/km (from the graph in Figure 30). This means that the longest uninterrupted cable that could be protected under normal operating conditions (ignoring overvoltage scenarios) would be 128km, using an 18kV TOV SVL, and the cable jacketing would be required to be at least 3.6mm. It is usually not sufficient, however, to apply only the normal operating condition requirements when choosing an SVL – the TOV of the selected SVL should be greater than the largest conceivable overvoltage expected during a fault. The worst case overvoltage gradients that can be expected in practice can be calculated according to Electra

[54] IEEE Standards Association: IEEE Power and Energy Society, "IEEE Guide for Bonding Shields and Sheaths of Single-Conductor Power Cables Rated 5 kV through 500 kV (IEEE 575)" IEEE Standards Association, IEEE (New York: 2014) https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6905681 (accessed 04/18/2018), 11.

128. Formulas and example calculations which use conservative inputs are shown below and values are justified thereafter.

Phase symmetrical fault:[55]

$$E_a = j \times \omega \times I \times 2 \times 10^{-7} \times \left(-\frac{1}{2} \times \ln\left(\frac{2 \times S_{ab}^2}{d \times S_{ac}}\right) + j \times \frac{\sqrt{3}}{2} \times ln\left(\frac{2 \times S_{ac}}{d}\right) \right) = 8.362\ [V/m]$$

$$E_b = j \times \omega \times I \times 2 \times 10^{-7} \times \left(\frac{1}{2} \times \ln\left(\frac{4 \times S_{ab} \times S_{bc}}{d^2}\right) + j \times \frac{\sqrt{3}}{2} \times ln\left(\frac{S_{bc}}{S_{ab}}\right) \right) = 8.362\ [V/m]$$

$$E_c = j \times \omega \times I \times 2 \times 10^{-7} \times \left(-\frac{1}{2} \times \ln\left(\frac{2 \times S_{bc}^2}{d \times S_{ac}}\right) - j \times \frac{\sqrt{3}}{2} \times ln\left(\frac{2 \times S_{ac}}{d}\right) \right) = 8.362\ [V/m]$$

....

Phase-to-phase fault: [56]

$$E_a = j \times \omega \times I_{ab} \times 2 \times 10^{-7} \times \ln\left(\frac{2 \times S_{ab}}{d}\right) = 8.362\ [V/m]$$

$$E_b = -j \times \omega \times I_{ab} \times 2 \times 10^{-7} \times \ln\left(\frac{2 \times S_{ab}}{d}\right) = 8.362\ [V/m]$$

$$E_c = -j \times \omega \times I_{ab} \times 2 \times 10^{-7} \times \ln\left(\frac{S_{bc}}{S_{ac}}\right) = 0\ [V/m]$$

....

Single phase earth fault external to cable:[57]

$$E_a = I_{aE} \times \left(R_g + j \times \omega \times 2 \times 10^{-7} \times ln\left(\frac{2 \times S_{ag}^2}{d \times \gamma_g}\right) \right) = 12.04\ [V/m]$$

$$E_b = I_{aE} \times \left(R_g + j \times \omega \times 2 \times 10^{-7} \times ln\left(\frac{S_{ag} \times S_{bg}}{S_{ab} \times \gamma_g}\right) \right) = 5.997\ [V/m]$$

$$E_c = I_{aE} \times \left(R_g + j \times \omega \times 2 \times 10^{-7} \times ln\left(\frac{S_{ag} \times S_{cg}}{S_{ac} \times \gamma_g}\right) \right) = 5.997\ [V/m]$$

*The effect of R_c is usually ignored.

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[55] [24] CIGRE: International Council on Large Electrical Systems, "Guide to the Protection of specially Bonded Cable Systems against sheath Overvoltages," Electra 128, CIGRE (1990) https://e-cigre.org/publication/ELT_128_2-guide-to-the-protection-of-specially-bonded-cable-systems-against-sheath-overvoltages (accessed 04/15/2018), 57.
[56] Ibid, 57.
[57] Ibid, 59.

Where d is the mean shield diameter, taken to be 0.160 [m], S_{ab}, S_{bc}, and S_{ca} are the center-spacing distances between conductors *a*, *b* and *c*, taken to be 0.320 [m], I_{xy} is the fault current from cable *x* to cable *y* [A], I_{aE} is the fault current from cable *a* to ground conductor (all fault currents taken to be 80,000 [A] as a conservative estimate), γ_g is the mean radius of the earth conductor, taken to be $0.7 \times S = 0.217$ [m], R_g is the resistance of the ground continuity conductor (GCC), taken to be 6.9×10^{-5} [Ω/m], and ω is the angular frequency of the system, which here is $\omega = 2\pi f = 2\pi \times 60Hz = 376.99$ [radians/sec]. Assuming a flat cable formation and uniform center-to-center spacing, these fault scenarios produce the many of the same expected overvoltages.

The highest expected overvoltage gradient, using the aforementioned example numbers, is 12.04 V/m, caused by a single phase earth fault. Under the assumption of single-point bonding and using the maximum expected overvoltage calculated above, an 18kV TOV SVL, the largest rating offered by several manufacturers, would enable an AC cable length of approximately 1.5km, about the same length as current cable shipping lengths.[58] Clearly, if longer cable lengths are to be achieved in AC applications, SVL technology or other surge arresting schemes need to be developed. Theoretically, there is no limit to the TOV rating of an SVL. SVLs are simply metal oxide diodes (usually ZnO) that may be stacked to increase rating. The exact nature of the relationship between SVL height and TOV rating is unknown, however, taller SVLs will almost certainly run into space constraints imposed by link boxes and duct banks. SVLs are also vulnerable to the elements and can suffer violent explosive failure, which may further limit the potential for rating increase. Figure 31 shows an SVL as well as a link box with approximate dimensions that are typical of cross-bonded systems.

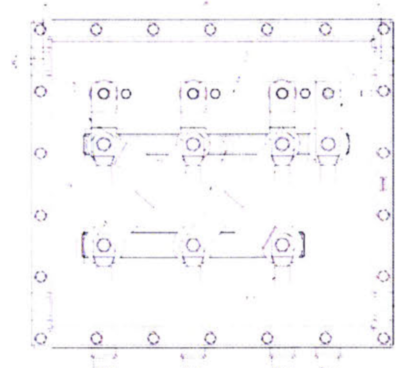


Figure 31: (Left) is a typical SVL use for surge arresting in high voltage cable. (Right) is a dimensioned drawing of a typical link box, here, to be used for a cross-bonding protection scheme. SVLs are vulnerable to the elements and can suffer explosive failure so they must be housed inside of link boxes. The boxes can be as large as 680mm×500mm×400mm. Taller SVLs can provide higher TOV rating and longer AC cable section lengths, but they are ultimately limited by the size imposed by link boxes and duct banks. (Images courtesy of an SVL manufacturer not to be named.)

[58] Politek A.S., "Sheath Voltage Limiters with Polymeric Housing PMSP-DD Catalogue" http://www.politek-emk.com/poleng/svl.html (accessed 04/24/2018); TE Connectivity "Raychem Link Boxes," http://www.te.com/content/dam/te-com/documents/energy/global/productdocuments/HV%20Cable%20Accessories/energy-hvca-linkboxes-us-en.pdf

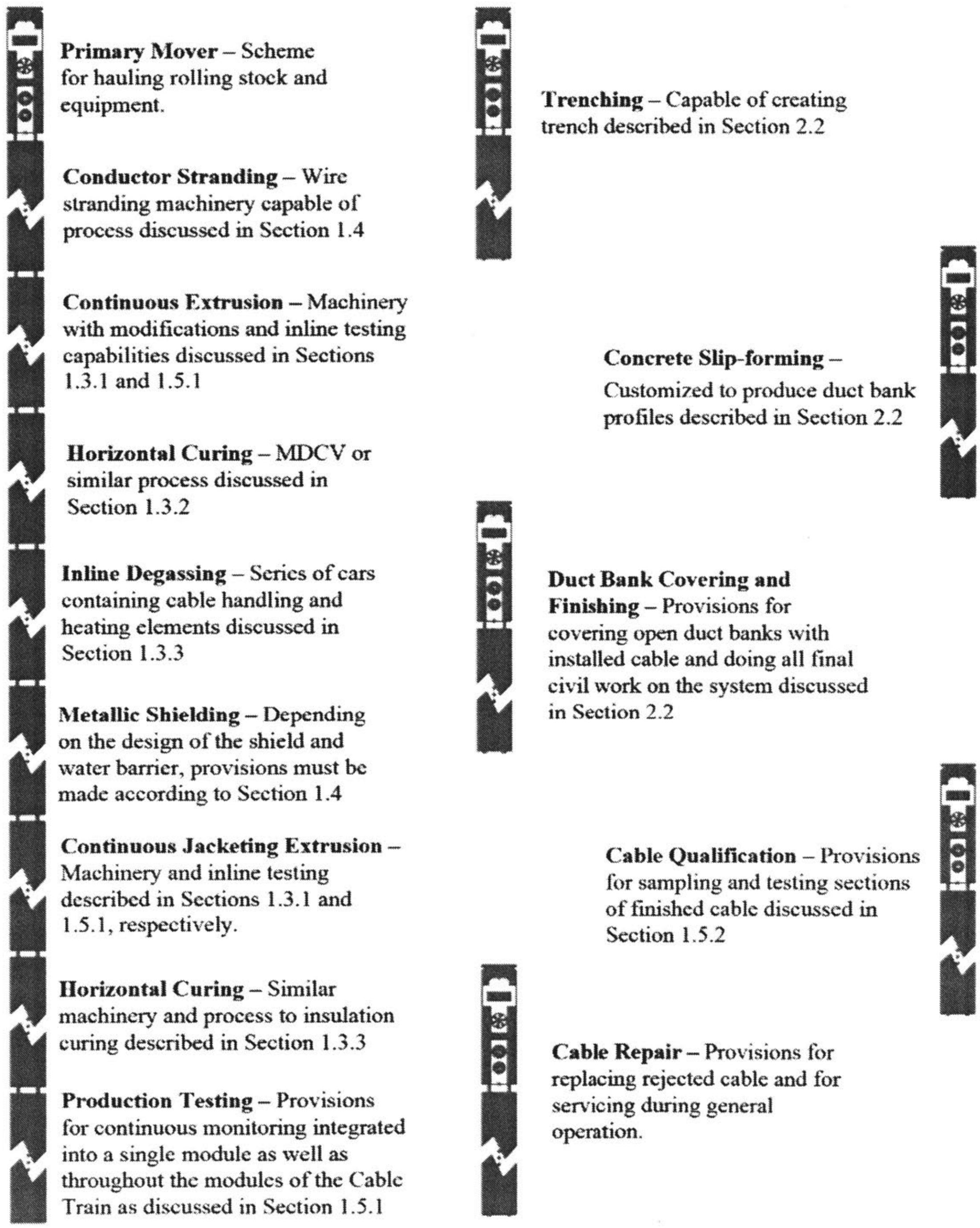
In summary, it may be possible to use the Cable Train, or a platform like it, to produce high voltage cable for AC applications, but there will need to be measures developed to combat limits on cable length imposed by surge arresters, jacketing strength, and the ultimate size constraints of the design space. Otherwise, cost reduction by eliminating cable splices via in-situ manufacturing cannot be achieved.

Even if SVL and jacketing considerations are eliminated, AC cable length will still be limited by the need for substations equipped with reactive power compensation, usually shunt capacitors, every 20-30 kilometers.

It should be re-stated that the above discussion focusses on the limits on cable length applicable only to AC systems. HVDC cable is not subject to the same limits on cable length as AC systems. This is why a platform like the Cable Train, capable of in-situ producing theoretically infinite lengths of cable and completely eliminating splices and cable accessories, is so attractive for underground HVDC cables.

5 Establishing Functional Requirements for Investigation by a Pre-Competitive Consortium

Immediate work will focus on the development of compact and modularized trenching, concrete slip-forming, and cable extrusion technology that can be integrated together on a mobile platform. Additionally, cable qualification, repair capabilities, and finishing earth-working capabilities must all be integrated into rolling stock. Each of these modules may be independently hauled in order to fully realize the maximum working speed of each module. Each module may be housed within more than one car. These modules are illustrated in the diagram below.



6 Conclusions and Recommendations

In summary, utilizing railroads as corridors for power transmission may provide a less costly means of connecting remote renewable power generating stations to the grids of the future. The increased mobility of heavy machines and materials on railroads and the state-of-the-art in railroad construction machinery provide both precedent and process advantages, which make the concept of augmenting railroads with underground cable systems an attractive one. The practice of installing and maintaining such systems could be less complex compared to traditional methods required by independent transmission corridors. The use of private railways may avoid conflicts with external stakeholders and eliminate the regulatory hang-ups that have plagued many renewable energy transmission projects.

The Cable Train, or a platform like it, capable of in-situ manufacturing of continuous lengths of high voltage DC cable, would virtually eliminate the need for costly and vulnerable splices. By replacing the cost of transporting finished shipping lengths of cable with the cost of transporting raw materials, the overall cost of cable manufacturing and delivery may be reduced.

As discussed in Section 1, there are challenges associated with the consecutive cable manufacturing steps of extrusion, curing, and degassing. Several possible design concepts to address these issues have been presented, which require varying levels of further development, but no fundamental issues were found that would prevent the success of the Cable Train.

In addition to cable manufacturing challenges, the requirement of meeting quality standards and conducting a thorough quality assurance program on the moving train must be met by non-obvious means. A compilation of the various tests required by IEC and ICEA provides an excellent reference and the discussion in Section 1.5 identifies the personnel and machines necessary. Further thought must be given to how qualification standards may change in the future according to new cable designs and systems topologies, in addition to engaging manufacturers and customers about how in-situ manufacturing may change quality standards.

An orthogonal discussion in Section 2 regarding the practical means of utilizing track-side real estate suggests that large quantities of transmission capacity may be installed in these corridors. A vision for the topology of combined railroad-transmission systems is illustrated and a summary of earthwork processes, including the machines required, is presented. The additional possibility of housing cable in open-air, concrete galleries, to allow easy access, was met with a discussion about cable cooling strategies.

Section 3 presented a case study on the failed Northern Pass project in New England and proposed an alternative railroad route that could potentially be used by the Cable Train to circumvent external stakeholder opposition. The discussion extends to a summary of the predicted energy shortage in China and goes a small way in substantiating the potential usefulness of the Cable Train in the People's Republic.

Practical limitations to cable production length are discussed in Section 4 – fault detection, localization, and repair, as well as surge protection, loss reduction, and jacketing strength. While surge arresting dielectric strength requirements do not affect the maximum length of a single strand of cable in the HVDC regime, AC cable would face a limitation in terms of length because of the need for surge arresting, bonding, and reactive compensation.

The technology and methods to make the Cable Train a reality might best be achieved by a pre-competitive technology consortium with member companies capable of completing and fully realizing the proof-of-concept designs proposed and this discussion can be found in Section 5. Questions the consortia should consider to develop this concept further include:

1. The implementation of in-situ cable manufacturing on Cable Laying Vessels (CVLs) could be simpler than on a train and enable the installation of extraordinarily long submarine cable, void of all factory joints.
2. What financing options and ownership models will lead to the most public good and private profitability of the railroad transmission? Public Private Partnership may be an attractive option if infrastructure improvements provide significant public good.
3. What ownership models and operational strategies would make the Cable Train most profitable as a private endeavor and maximize public impact?
4. While the original vision, laid out in this paper, focuses on the widespread use of railroad HVDC for bulk renewable energy transmission, could the elimination of joints, via in-situ production, provide a reduction in cost for AC systems as well?
5. The proximity of metal railroad tracks to high voltage cables, the effect this has on losses, cable ampacity, and system design, must be investigated.
6. Thermal management of trackside cable laid in duct bank using passive and active means needs to be studied further.
7. The effects of extraordinarily long cables on surge arresting devices and other cable accessories must be further investigated. If the requirements on these elements impose significant limits on cable length, countermeasures to further increase the length of cable that can be adequately protected must be devised.
8. The effect of standing voltage and overvoltage on jacket thickness, extrusion crosshead size, extruder barrel length and width, and the ability to fit such an extruder onto a railcar must be investigated.
9. The potential for railroad transmission to support the host railroad's electrification should be investigated. How will the future of railway electrification affect HVDC system design?
10. The potential for trackside HVDC to accommodate relatively small, intermediate energy plants and demand centers should be investigated. There will inevitably be new supply and demand centers appearing in the vicinity of the UGC. Will trackside transmission be solely for bulk transmission or is there a possibility for local integration?
11. The potential to carry oil, fiber optic communication, natural gas and other compatible resources cross-continent inside a trackside duct bank should be explored.
12. Several concepts of how to supply fuel and raw material to the Cable Train while moving are being considered. Using trenched, processed earth as building material may prove viable.

13. If the Cable Train proves feasible, the ability to move and deploy the manufacturing modules inside of intermodal containers, anywhere in the world, would be extremely desirable.
14. If in-situ production is proved infeasible or unproductive, what rolling stock-based technology and methods could enable the delivery of extraordinarily long lengths of factory-made cable to railroad sites? (Refer to Appendix J for a discussion on this.)

Company-specific capabilities will need to be brought to bear in order to make this platform a reality. A possible path forward is to form a pre-competitive consortium of companies and institutions willing to collaborate to develop methods that will expand the horizons of direct UGC. The following companies have been identified as potential members of a Cable Train consortia:

BNSF Railway Company (Fort Worth, Texas, United States) is a subsidiary of Berkshire Hathaway Inc., which owns and operates thousands of miles of freight and passenger railroads in the western U.S. Railway companies would be significant private stakeholders in a Cable Train project and, possibly, the largest beneficiaries. As the hosts, or potential operators, of the Cable Train, it will be important to engage a railway company about the future development of the Cable Train.

Swietelsky Baugesellschaft m.b.H (Linz, Austria) is a large construction company preeminent in the railroad construction industry. The company features hundreds of machines used for the construction and maintenance of railroads. They may provide key insights into the possibilities and limitations of adding and maintaining trackside infrastructure.

China Railway First Group Co. Ltd. (Xi'an, China) known as CRFG, is a subsidiary of the conglomerate China Railway Group Limited (CREC) owned mostly by China Railway Engineering Corporation (CRECG), a state-owned entity. CREC is one of the largest construction companies in the world and subsidiary CRFG has completed tens of thousands of kilometers of railways comprising hundreds of routes throughout China.

CRRC Corporation, Ltd. (Beijing, China) is a state-owned entity formed from a merger between China CNR Corp., Ltd. (CNR) and CSR Corp., Ltd. (CSR) in 2015 and is the largest rolling stock manufacturer in the world. They are currently establishing a factory in Springfield, MA, to make new MBTA cars for the city of Boston. They may have the capability to produce some of the specialty rolling stock discussed in this paper.

Southwire Company, LLC (Carrollton, Georgia, United States) is one of the largest high voltage cable manufacturers in the U.S. and around the world. They possess amazing resources and talent. It is important to have an HVDC developer and designer on board to give realistic, market perspectives on the developments of the Cable Train.

ABB Ltd. (Zurich, Switzerland) is one of the largest cable manufacturers and HVDC developers in the world. They have completed and won bids for ambitious projects across Europe and Asia. As a company that also has expertise in other industries like AC transmission, solar power, and railway, they would make an extremely versatile member of a Cable Train consortia.

TROESTER GmbH & Co. (Hannover, Germany) is one of the largest extrusion machinery manufacturers in the world. They may be extremely helpful in exploring the extrusion and curing countermeasures discussed in this paper.

Mitsubishi Corporation (Tokyo, Japan) is the original developer and licenser of the Mitsubishi-Dainichi Continuous Vulcanization (MDCV) machinery and process, which could provide the horizontal curing capability discussed earlier.

Oceaneering International, Inc. (Houston, Texas, United States) is an engineering services company involved in a variety of industries with experience adapting technologies to extreme environments. They have made use of modified extruders on cable laying vessels. This experience could be immensely useful in adapting machinery to operate aboard the Cable Train.

Bartell Machinery Systems, LLC (Rome, New York, United States) is a designer and manufacturer of specialty machinery for the twisting and winding of wire and other cable components.

GOMACO Corporation (Ida Grove, Iowa, United States) is a leading manufacturer of slip-forming and paving machinery. They may provide insights on the design and adaptation of molds and pavers, respectively, to accomplish the addition of duct banks next to railways.

The individuals at these companies would be great assets to the further development of the Cable Train. For the awareness of the reader, it is also important to mention a group that is actively advocating for the use of railroad right of ways as transmission corridors:

Solutionary Rail (Vashon, Washington, U.S.A.) is a project being pursued by the Backbone Campaign out of the state of Washington. The goal of this project is to realize widespread rail electrification in the U.S. as a means to improve our transportation and freight hauling capabilities, reduce greenhouse gas emissions, revitalize landlocked communities, and possibly co-locate transmission on railroads, with electrified railroads being the first customer. The individuals behind this movement have put a great deal of thought into the incentives of various stakeholders and propose interesting financing options and ownership models. Please refer to Appendix I for a more detailed discussion of their vision and relevance to the Cable Train.

7 Appendices

(A) Production Tests According to ICEA "Standard for Extruded Insulation Power Cables Rated Above 46 Through 345 kV" (2012)

There are many ongoing tests that must be performed, during and after production, on material lots and cable samples, to ensure cable integrity in many dimensions:

Conductor Tests – All tests default to ICEA T-27-581/NEMA WC-53 unless otherwise stated.

DC Resistance Test – Made on each shipping length after reaching thermal equilibrium for at least 12 hours.

Cross-Sectional Area Determination – Measured in accordance with ICEA T-27-581/NEMA WC-53.

Diameter Determination – Measured in accordance with ICEA T-27-581/NEMA WC-53.

Physical and Aging Tests - Performed at room temperature after at least 30 minutes of acclimation using machine specified by ASTM D 412.

Thickness Measurements – All thickness measurements can be made using a micrometer or an optical measuring device. Both must have a 0.025mm resolution. The average of four measurements will be used (max/min and halfway between both points on either side).

Tensile Strength Test – Specimen must be secured in jaws of testing machines without exceeding maximum distance between the jaws. The specimen will be stretched at a specified rate until break. Length, gauge distance, and jaw separation speed are all taken continuously to determine tensile strength, using the original cross-sectional area of the specimen.

Elongation Test – Elongation at break will be determined from the same test and same sample used for the tensile strength test. The elongation will be taken as the percent increase in the gauge length at rupture.

***** Tensile Test and Elongation Test must also be done with samples that have undergone accelerated aging and samples that have undergone an Oil Immersion Test (PVC Jacketed cable) – ASTM D471.**

Hot Creep Test – Creep measured according to ICEA Publication T-28-562.

Wafer Boil Test – A cross-sectional cut of at least 25mm will be taken and this wafer will be taken apart, into its constituent annular layers, keeping the shield layers attached to the insulation layer. These rings will be immersed in boiling decahydronaphthalene with 1%BW Antioxidant 2246 for the specified time. Then the continuity between the insulation and the shields with be observed with optical magnification. If the shields dissolve or crack the cable will be rejected.

Amber, Gel, Agglomerates, Contaminant, Protrusion, Irregularity, and Void Test – Many consecutive thin wafers will be taken and observed for voids, ambers, gels, agglomerates, or contaminants in the insulation, voids and protrusions between the insulation and the insulation shields, and conductor shield irregularities, all with the aid of optical magnification. Optical coupling agents may be used to increase visibility and a convenient method will be used to measure and count all artifacts. Measurement of artifacts will be aided by the use of an optical comparator and straightedge. If this test produces failure, there will be resampling from each end of the final shipping lengths.

Elongation Test on Extruded Semiconductor Samples – Each lot of material intended for extrusion must be tested to satisfaction.

Dimensional Measurements of Metallic Shield – A combination of micrometer calipers, micrometers, and/or an optical measuring device capable of specified accuracy is used to measure samples directly taken from each cable.

Diameter Measurement of Insulation and Insulation Shield – Diameter tape, optical measuring device, or calipers with sufficient accuracy may be used to measure this dimension for each cable.

Heat Shock Test (PVC Cable) – Calls for a preheated oven to heat jacket samples wound on a mandrel for the specified time. Samples must then pass a visual inspection.

Heat Distortion Test – Must be performed in accordance with ICEA T-27-581/NEMA WC-53.

Cold Elongation Test (PVC) – Test sample wound on a mandrel will be kept at -35° C for 1 hour before elongation test. Machine specified by ASTM D 412. The machine and all sensors must either be kept in the refrigerated environment for a minimum of 3 hours, or the sample must be tested within 15 seconds after transport from the cold environment to room temperature.

Volume Resistivity Tests – A series of electrodes and current electrodes are used to measure this quantity for samples of the conductor shield and the insulation shield and extruded semiconducting coating taken from the finished cable.

Shrinkback Test – Samples of each cable, at least 1.5ft in length, will be heated in a forced air convection oven for a period of time, perhaps multiple times, with intermittent cooling. The sample will then be measured for jacket shrinkback using an optical measuring device.

AC Voltage Test – A voltage will be applied between the conductor and the metallic shield, the metallic shield being grounded, at a specified voltage ramp rate, for each shipping length of cable. The voltage should be supplied by a transformer and sufficiently powerful generator capable of no less than 5Kva. The potential should be approximately sinusoidal with frequency between 49 and 61 Hz.

Partial Discharge Test – This test must be performed 20 days after jacket extrusion, or after appropriate forced degassing measures are taken. Dielectric constant and dielectric strength will be measured according to ICEA T-27-581/NEMA WC-53.

Water Content Test – The interfaces between the jacket and the metallic shield and the conductor core are first exposed manually and checked visually for water or signs of water. If there is suspicion of water ingress in the conductor, one end of the cable will be sealed with a rubber cap filled with anhydrous calcium sulfate pellets. The rubber cap should have a valve. Dry gas must be applied, at a specified pressure, from the opposite end, until the valve opens. After the stated amount of time, the color of the pellets can be checked to verify the level of moisture. If moisture levels in either layer of the cable are intolerable, sufficient methods to remove the moisture can be taken, or the cable can be discarded.

Adhesion Test for Metallic Foil Laminates – Dissection and visual inspection should reveal no separation of the metal layer, no cracks, and no other signs of damage.

Adhesion Strength of Metallic Foil Laminates – The metallic foil laminate will be peeled from the jacket using a tensile testing machine. The adhesion strength is calculated and normalized by the specified width of the sample. The same test will be performed to measure the adhesion strength between the metallic foil laminates in the overlapping regions.

(B) Qualification Tests According to ICEA "Standard for Extruded Insulation Power Cables Rated Above 46 Through 345 kV" (2012)

In addition to production testing, several tests are required before a cable is installation-ready:

Cable Qualification – Tests meant to qualify each cable for use at, or below, the rated voltage.

Resistance Stability Test – Must meet requirements set out by Parts 3 and 5 of ICEA T-25-425.

Cable Bending Test – Cables will be bent 360° around a cylindrical fixture of specified diameter, 3 times, forwards and backwards.

Thermal Cycling Test – The cable will be placed in a pipe with a 180° U-bend and specified diameter, then charged until the conductor reaches the emergency operating temperature. The cable will be held at this temperature and subsequently cooled and allowed to rest, each step having a specified time. 20 complete cycles of heating and cooling must be performed.

Hot Impulse Test – A specified length of cable will be placed in a PE or PVC conduit of specified diameter. The conductor will be charged such that it reaches the designated emergency overload temperature. The test will be run at multiple voltages.

AC Voltage Test – A specified length of cable must withstand a specified AC voltage and duration at room temperature. The waveform will be sinusoidal with a frequency in the range 49-61 Hz.

Partial Discharge Test – Cables must resist partial discharge at voltages above rated.

Dissipation Factor Measurement – Cables will be charged to until the conductors reach the rated emergency operating temperature inside a conduit of specified diameter and the dissipation factor will be measured.

Dissection Investigation – One sample, having undergone several of the previously described cable qualification tests, will undergo visual inspection.

Jacket Material Qualification –

Environmental Stress Cracking Test – Jacket specimen will have a slit partially cut into it with a razor blade. The entire specimen will be exposed to a cracking agent, while being heated, for a specified amount of time.

Absorption Test Coefficient – Optical absorption characteristics of polyethylene jackets will be measured with a spectrophotometer according to ASTM D 3349.

Sunlight Resistance Test – Using a carbon-arc or xenon-arc apparatus and water-spray apparatus, the samples will be exposed to radiation for a specified amount of time before unaged tensile and elongation tests are performed.

Other Qualification Tests –

Insulation Resistance – Resistance measured according to ICEA T-27-581/NEMA WC-53.

Accelerated Water Absorption Test – Insulation will be immersed in water for specified time. Changes in dielectric constant, capacitance, and stability factor must remain within limits.

Resistance Stability Test – Stability measured according to ICEA T-25-425.

Brittleness Temperature for Semiconducting Shields Test – Specimen of prescribed dimensions are cooled, allowed to rest, then clamped and hit with a striking edge at specified velocity. The brittleness temperature is determined according to ASTM D 746.

(C) Sample Tests According to ICE "Power Cables with Extruded Insulation and Their Accessories for Rated Voltages and Above 150kV (U_m = 170kV) up to 500kV (U_m = 550kV) – Test Methods and Requirements" (2011)

Several tests are required before a cable is installation-ready. Some of these tests are also required as routine tests throughout the operating lifetime of the cable:

Partial Discharge Test – PD test must not produce sensitivity above the allowable value. Must be performed in accordance with IEC 60885-3.

Voltage Test – Alternating voltage (applied relative to the metallic shield ground) must be withstood at room temperature at a specified frequency and for a specified duration without insulation breakdown.

Electrical Test on Oversheath of the Cable – Test according to IEC 60229:2007, Clause 3.

Conductor Examination – Visual, manual inspection of cable construction.

Measurement of Electrical Resistance of Conductor and of Metal Screen/Sheath – DC resistances measured at constant temperature. Values must not exceed those specified.

Measurement of Thickness of Insulation and Oversheath – Dimensions must be measured according to IEC 60811-1-1:1993, Clause 8, and Amendment 1:2001.

Measurement of Thickness of Metal Sheath – For sheaths that are lead, aluminum, or an alloy thereof, the thickness, measured with a micrometer and method according to the type of sheath, must not be outside the specified tolerance.

Measurement of Diameters – Must be measured according to IEC 60811-1-1:1993 and Amendment 1:2001.

Hot Set Test for XLPE and EPR Insulations – Depending on the curing process, a sample must be taken from the area with the most potential for incomplete curing. Test must be performed according to IEC 60811-2-1:1998 and Amendment 1:2001.

Measurement of Capacitance – Value must be measured between the conductor and the metallic shield at constant ambient temperature. Value must be within specified tolerance.

Measurement of Density of HDPE Insulation – Procedure must be performed according to IEC 60811-1-3:1993 and Amendment 1:2001.

Lighting Impulse Voltage Test – Conductor must be heated by electrical charging to a temperature above normal operating temperature and impulse voltage applied according to IEC 60230 will be applied several times with each polarity. Insulation must not be compromised.

Water Penetration Test – Specifically prepared samples from completed cable meant for operation in wet conditions must be subjected to the bending test and tested within the improvised test apparatus described in Annex E. Evidence of water penetration is not acceptable.

Tests on Components of Cable with Longitudinally Applied Metal Tape or Foil – For applicable cable designs, samples of specified cable from finished lengths will be subjected to visual examination, metal foil adhesion strength test, and metal foil peel strength test.

Resistivity of Cable Semiconducting Screens – Resistivity will be measured for a samples taken from the core of a finished cable, one aged and one unaged.

(D) Tests on Completed Cable According to ICE "Power Cables with Extruded Insulation and Their Accessories for Rated Voltages and Above 150kV (U_m = 170kV) up to 500kV (U_m = 550kV) – Test Methods and Requirements" (2011)

Bending Test – Sample must be bent around a cylindrical drum of specified diameter, at constant ambient temperature, in two opposite directions for the specified number of times.

Tan(δ) Measurement – Value for a sample, heated by conductor charging to a temperature above the maximum allowable operating temperature, must not exceed specified value.

Heating Cycle Voltage Test – A section of cable with a bend of specified diameter must be heated by conductor charging to a temperature above the maximum allowable operating temperature and held there for specified time. Then the sample must be allowed to cool for a specified time. This cycle must be repeated for the specified number of times while the shield and conductor are held at a specified voltage.

Partial Discharge Test – PD test must not produce sensitivity above the allowable value. Must be performed in accordance with IEC 60885-3.

Switching Impulse Voltage Test – A section of cable must be heated by conductor charging to a temperature above the maximum allowable operating temperature and held there for a specified amount of time. The voltage impulses must be applied according to IEC 60230. The cable systems must survive negative and positive impulses for the specified number of trials.

Lightning Impulse Voltage Test – A section of cable must be heated by conductor charging to a temperature above the maximum allowable operating temperature and held there for a specified amount of time. Then lightning impulse voltages must be applied according to IEC 60230. Subsequently, the cable must withstand a power frequency voltage test at the specified voltage for the minimum time. Insulation breakdown during any period of testing is not acceptable.

Tests of Outer Protection for Joints – Water immersion, heat cycling, and a variety of voltage tests must not produce signs of water ingress, corrosion, or other forms of deterioration during dissection and visual inspection of joint outer protection accessories.

Examination of Cable System with Cable and Accessories – Dissection and visual inspection of finished cable subjected to testing must not reveal any signs of deterioration.

Check of Cable Construction – Measurement of conductor diameter and all layer thicknesses according to the methods described in IEC 60811-1-1:1993, Clause 8, and Amendment 1:2001

Tests for Determining the Mechanical Properties of Insulation Before and After Ageing – Aged and unaged, pieces must undergo mechanical tests described in IEC 60811-1-1:1985.

Tests for Determining the Mechanical Properties of Oversheaths Before and After Ageing – Aged and unaged, pieces must undergo mechanical tests described in IEC 60811-1-1:1993.

Ageing Tests on Pieces of Complete Cable to Check Compatibility of Materials – Aging treatment described in IEC 60811-1-2:1985 and Amendment 1:1989 and Amendment 2:2000. Involves bouts of heating for repeated, extended periods of time.

Loss of Mass Test on PVC Oversheath of Type ST_2 – Tests must be performed according to IEC 60811-3-2:1985 and Amendment 1:1993 and Amendment 2:2003.

Pressure Test at High Temperature on Oversheaths – Tests on oversheaths must be performed according to IEC 60811-3-1:1985 and Amendment 1:1994 and Amendment 2:2001.

Tests on PVC Oversheaths (ST_1 and ST_2) at Low Temperature – Tests must be performed according to IEC 60811-1-4:1985 Clause 8 and Amendment 1:1993 and Amendment 2:2001.

Heat Shock Test for PVC Oversheaths (ST_1 and ST_2) – Tests must be performed according to IEC 60811-3-1:1985 and Amendment 1:1994 and Amendment 2:2001.

Ozone Resistance Test for EPR Insulations – Tests must be performed according to IEC 60811-2-1:1998 Clause 8 and Amendment 1:2001 with specified ozone concentrations.

Hot Set Test for EPR and XLPE Insulations – Depending on the curing process, a sample must be taken from the area with the most potential for incomplete curing. Test must be performed according to IEC 60811-2-1:1998 and Amendment 1:2001.

Measurement of Density of HDPE Insulation – Procedure must be performed according to IEC 60811-1-3:1993 and Amendment 1:2001.

Measurement of Carbon Black Content of Black PE Oversheaths (ST_3 and ST_7) – Measurement must be made according to IEC 60811-4-1:2004. Value must be within a certain range of that agreed upon.

Test Under Fire Conditions – Test must be performed in accordance with IEC 60332-1-2.

Water Penetration Test – Specifically prepared samples from completed cable meant for operation in wet conditions must be subjected to the bending test and tested within the improvised test apparatus described in Annex E. Evidence of water penetration is not acceptable.

Tests on Components of Cables with a Longitudinally Applied Metal Tape or Foil, Bonded to the Oversheath – For applicable cable designs, samples of specified cable from finished lengths will be subjected to visual examination, metal foil adhesion strength test, and metal foil peel strength test.

Additional heating cycle voltage tests, lightning impulse voltage tests, and subsequent cable examination are required for cable system prequalification.

(E) Background on Wire Rope Mechanics for Fatigue Analysis in Bent Conductor

Stranding in electrical cables with large conductors is necessary for handling purposes. The limit for using solid conductors depends on the alloy and temper of the metal. High voltage, high power cables will require conductors large enough that stranding is a requirement. Different types of cable stranding topologies are summarized below:[59]

- Concentric Stranding: Most common for electrical conductors. Consists of layers with increasing numbers of individual strands wound in alternating directions (left-handed and right-handed), around a central strand.
- Compressed Stranding: This geometry is the same is concentric stranding except forming results in overall diameter reduction (compared to concentric stranded cable). This reduces voids that exist on the outside of concentric stranded conductors, which causes over-extruded insulation adhere more strongly to the conductive core and develop unwanted irregularities.
- Compact Stranding: Forming results in larger diameter reduction (from concentric stranded cable) compared to compressed stranding.
- Bunch Stranding: This weave gives extreme flexibility for small conductor diameters.
- Rope Stranding: Typical wire rope construction uses a concentric strand on concentric or bunch stranded cables.

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[59] Thue, William, "Electrical Power Cable Engineering," Third Edition, CRC Press (Boca Raton: 2012) https://eds.a.ebscohost.com/eds/ebookviewer/ebook/bmxlYmtfXzQxMzM5M19fQU41?sid=d911aa07-f00f-4833-aee8-a426cd1095d5@sessionmgr4008&vid=0&format=EB&rid=1 (accessed 11/01/2017), 40-46.

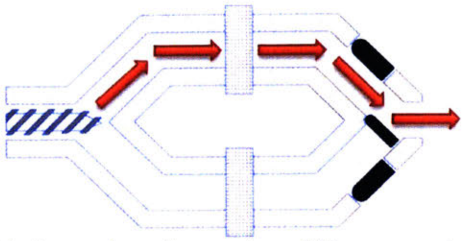
- Sector Conductors: Helical winding of separately wound lobes with circular-sector cross section combine to make a circular conductor. There is a reduction in conductor diameter compared to concentric cable and the proximity effect is slightly reduced.
- Segmental Conductors: Reduces Skin Effect by individually insulating constituent "segments."
- Annular Conductors: Here wires are stranded around a non-conducting core to eliminate the Skin Effect at the center of the cable.
- Unilay Conductors: The designs places all the strands in the same direction, along the axis of the cable.[60]

For purposes of cyclic fatigue analysis in conductors in the aforementioned cable degassing car, a concentric stranded topology will be assumed for all calculations. Many models for the mechanics of metallic helical structures have been built on Costello's original work "Theory of Wire Rope." Therein is a summary of fatigue life verification using a Goodman Diagram. This analysis has been brought to bear to confirm the safety of cable handling in the inline degassing countermeasure described in Section 1.1.1.3.3.

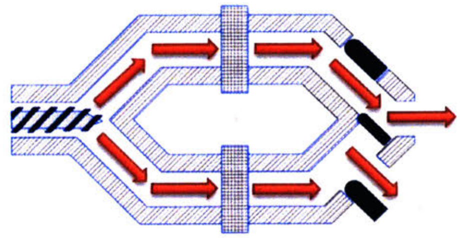
[60] Thue, William, "Electrical Power Cable Engineering," Third Edition, CRC Press (Boca Raton: 2012) https://eds.a.ebscohost.com/eds/ebookviewer/ebook/bmxlYmtfXzQxMzM5M19fQU41?sid=d911aa07-f00f-4833-aee8-a426cd1095d5@sessionmgr4008&vid=0&format=EB&rid=1 (accessed 11/01/2017), 40-46.

(F) Alternative Solution to Challenge of Cleaning Screen-Packs During Continuous Extrusion

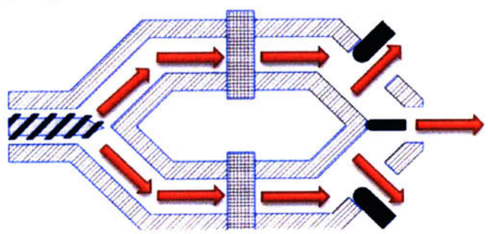
An alternative to the continuous extrusion countermeasure presented in 1.1.1.3.1 is described hereafter. While this solution has no precedent in manufacturing processes, it may require less space than the dual-extruder solution described earlier.



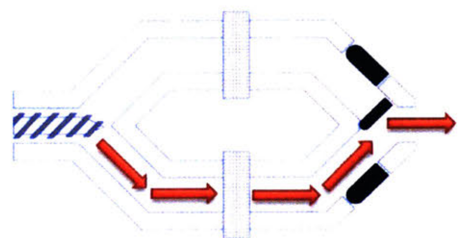
(a) Operation of extruder while screen cleaned.



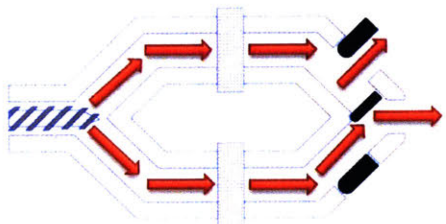
(b) Run-up of second extruder.



(c) Transition between two extruders.



(d) Operation of second extruder while screen is cleaned.



(e) Run-up of first extruder.

Figure X: Simplified representation of an extruder attachment that allows uninterrupted operation. This attachment is placed between the end of the extruder barrel and the extruder head. It allows for one screen to be cleaned while the other is operating.

This solution uses a sole extruder equipped with a "dual-feed" attachment show in Figure X. This augmentation would be placed between the end of the extrusion barrel and the inlet to the crosshead. It diverts the extrusion melt through two separate screen-packs. Such a design will allow one feed to be cleaned and the screen-pack replaced while the opposite side is operating. A purge valve system similar to that depicted in Figure X will allow for the discarding of melted material, during run-up, until an appropriate temperature is reached. During the hand-off between feeders, an additional kneading screw, downstream of the mixing point proximal to the crosshead inlet, can be used to ensure a thorough mixtures of the flow from both feeds. Meanwhile melt from the feed being shut down can be discarded through its own purge valve to provide a seamless transition and uniform material flow to the extruder head for virtually indefinite operation (only limited by the lifetime of the extruder head). Feasibility of such an approach was first proposed by *Severengiz. et al.*[61]

(G) Discussion of Solar Weather and its Historical Impact on Transmission Systems

HVDC technology offers many benefits including increased efficiency, versatility, and immunity to telluric currents. Telluric currents (GICs) are a consequence of the macro-patterns of solar weather. Solar weather can manifest itself as regularly occurring high-speed solar wind streams (HSSs), solar winds traveling faster than usual which overtake slower solar winds and create co-rotating interaction regions (CRIs), or Coronal Mass Ejection (CME) – an event that is characterized by tens and hundreds of millions of tons of plasma, and its accompanying magnetic field, being ejected from the sun. HSSs and CRIs are not so acute, but they can inject electromagnetic energy over a long period of time. CMEs can effect changes in the ionosphere, magnetosphere, thermosphere, and in the geomagnetic environment in the Earth itself. The NOAA's G-Scale attempts to describe space weather that propagates in the Earth's atmospheric domain that could possibly affect man-made infrastructure, by combining measurements of induced currents and magnetic variation.[62] Normal space weather causes natural currents in the upper atmosphere, the ground and the oceans that respond to changes in the Earth's rotation and changes in the solar irradiation over the course of each solar cycle. Acute events, caused by HSSs or CMEs, that exhibit dramatic changes in these phenomena on Earth are called geomagnetic storms.[63]

EMP events can be caused by solar weather from normal solar winds to Coronal Mass Ejections (CME) as well as from intentional discharges from satellites. Time changing magnetic flux through the atmosphere and surface of the Earth can induce massive currents, ranging from tens to hundreds of Amperes, depending on the resistance and length of the path, as well as the magnitude of magnetic energy released during the event. These currents can travel through loops formed by bedrock, water, and manmade infrastructure, including oil and natural gas pipelines, undersea communication cables, and transmission cables. This infrastructure dramatically reduces the equivalent resistance of the Earth and, as these systems grow larger and larger, the ability for destructive GICs to propagate through them, increases.[64]

Naturally occurring currents penetrating the power grid were first detected during the geomagnetic storm of March 1940. However, unexplained currents in the earlier versions of communication networks were also observed during the 19th century.[65] In recent history, several

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[61] Mustafa Severengiz, Tobias Sprenger, Gunther Seliger, "Challenges and Approaches for a Continuous Cable Production," Technische Universitat Berlin, Department of Assembly Technology and Factory Management, ProcediaCIRP 40(2016) 1 8 -2 3 https://eds.b.ebscohost.com/eds/pdfviewer/pdfviewer?vid=1&sid=630755b5-d921-43b3-8440-fceeb68baf1c%40pdc-v-sessmgr01 (accessed 11/15/2017).
[62] NOAA http://www.swpc.noaa.gov/phenomena/geomagnetic-storms (accessed 05/17/17).
[63] NOAA http://www.swpc.noaa.gov/impacts/electric-power-transmission (accessed 05/18/17).
[64] Molinski, Tom S., Feero, William E., Damsky, Ben L., "Shielding Grids from Solar Storms" IEEE Spectrum, http://spectrum.ieee.org/energy/the-smarter-grid/shielding-grids-from-solar-storms (accessed 05/04/17), 56-58.
[65] NOAA http://www.swpc.noaa.gov/impacts/electric-power-transmission (accessed 05/17/17).

events have occurred that confirm the real threats posed by GICs. Notable geomagnetic storms that affected the power transmission system occurred in 1958, 1972, 1982, 1989, 2003, and 2006.[66] In 1989, the solar storm caused a widespread power outage in Hydro-Quebec's transmission system, leaving millions of people without power for hours. In addition, a step-up transformer serving a 1000MW nuclear reactor was fatally damaged after a GIC from the same geomagnetic storm forced the transformer into a half-cycle, non-linear, saturation regime where the magnetic core was saturated and could not provide any "electrical inertia." Excess current in the overloaded transformer burned the outer shell of the machine beyond repair (GICs are quasi-static due to the low frequency of fluctuation in magnetic flux from solar weather, which is below 1 Hz. Therefore the damage caused by these events is due to current overloading, and not frequency fatigue.[67]). Half-cycle saturation in transformers can change the frequency of the power being transmitted (from a 60 Hz sinusoidal waveform) and this trips Volt-Ampere-Reactive (VAR) compensators and Capacitor Banks, which are critical for the normal operation of transmission systems. Losing these components could lead to large variation in voltage on the lines and an inability to provide the needed power, resulting in widespread black out.[68]

Higher GICs are especially likely to enter manmade infrastructure at higher latitudes where the resistance of the Earth's crust is higher. Other factors that control the penetration of these currents into transmission systems include the types of ground connections, the types of transformers in the system, the orientation of power lines as well as the length and resistance of the lines and transforming coils.[69] Building transmission systems that are immune to this phenomena is very important to national security.

(H) MATLAB Code Modelling Cable Cooling Regimes

Outside of cable must be kept at 45 C (in order to maintain the conductor core temperature at or below 90 C) and 70W/m must be removed in order for the cable to remain in this steady state condition. Analytical and finite element models have shown that natural convention using water or air are not feasible. Therefore there are two regimes for heat removal being considered: (1) moving water with forced convection and (2) moving air with forced convection. This calculator is used to double-check that the results produced by flow simulation are sufficient for removing 70W/m at the maximum distance, after the inputs to the simulation confirm that the cable is kept at the appropriate surface temperature up to that distance. The outputs of this model are the maximum distance between heat exchange points and pressure

---

[66] R.J. Pirjola, D.H. Boteler "Comparison of Methods for Modelling Geomagnetically Induced Currents," Annales Geophysicae, 32nd Edition, 1177-1187 (Copernicus Publications: September 2014) https://eds.a.ebscohost.com/eds/pdfviewer/pdfviewer?sid=726d0fe5-9502-4042-a0d6-412396e561f0%40sessionmgr4010&vid=3&hid=4208 (accessed 05/18/17), 1177.
[67] Molinski, Tom S., Feero, William E., Damsky, Ben L., "Shielding Grids from Solar Storms" IEEE Spectrum, http://spectrum.ieee.org/energy/the-smarter-grid/shielding-grids-from-solar-storms (accessed 05/04/17), 56.
[68] NOAA http://www.swpc.noaa.gov/impacts/electric-power-transmission (accessed 05/18/17); Molinski, Tom S., Feero, William E., Damsky, Ben L., "Shielding Grids from Solar Storms" IEEE Spectrum, http://spectrum.ieee.org/energy/the-smarter-grid/shielding-grids-from-solar-storms (accessed 05/04/17), 58.
[69] Molinski, Tom S., Feero, William E., Damsky, Ben L., "Shielding Grids from Solar Storms" IEEE Spectrum, http://spectrum.ieee.org/energy/the-smarter-grid/shielding-grids-from-solar-storms (accessed 05/04/17), 58.

head required to produce flow that will keep 4 cables cool at steady state operation, for each candidate fluid. The MATLAB code is included below:

```
function pump_distance()
R=1.5;
R_cable=0.170/2;
e_concrete=0.003;
T_i=20;
Cable_Power=70; % W/m
rho_water=992.26;
rho_air=(1.1124-1.0779)/2;
c_a=1007.2;
c_w=4184;
T_req=45;
meu_a=0.0000181;
meu_w=0.00089;
k_a=0.02735;
k_w=0.62856;
% Re_a=rho_air*va*2*R/meu_a
Pr_a=c_a*meu_a/k_a;
% Re_w=rho_water*vw*2*R/meu_w
Pr_w=c_w*meu_w/k_w;
%va_trans=solve(rho_air*v*2*R/meu_a=20000,v);

%T_d_a=((280*d)/(rho_a*pi*R^2*c_a*va)+40);
%T_d_w=((280*d)/(rho_w*pi*R^2*c_w*vw)+40);
%h_a_low=0.3+(0.62*(Re_a)^(0.5)*(Pr_a)^(1/3))/((1+(0.4/Pr_a)^(2/3))^(0.25));
%h_a_high=0.3+((0.62*(Re_a)^(0.5)*(Pr_a)^(1/3))/((1+(0.4/Pr_a)^(2/3))^(0.25)))*(1+(Re_
a/282000)^(0.5));
% for air transition speed is 3.5 m/s (max 70 m/s)
%h_w=0.3+((0.62*(Re_w)^(0.5)*(Pr_w)^(1/3))/((1+(0.4/Pr_w)^(2/3))^(0.25)))*((1+(Re_w/28
2000)^(5/8))^(4/5));
% for water maximum model value is at 0.75 m/s

i=0;
va=linspace(0,3.5,36);
da1=[];
pa1=[];
for i=1:length(va)
    d_max_air_low=(T_req-
((4*2*pi*R_cable)*(k_a*(0.3+(.62*(rho_air*va(1,i)*2*R/meu_a)^(1/2)*(Pr_a)^(1/3))/(1+(0
.4/Pr_a)^(2/3))^(0.25))/(2*R))/Cable_Power)^(-1)-
T_i)*(rho_air*pi*(R^2)*c_a*va(1,i)/280);
    da1(i,1)=va(1,i);
    da1(i,2)=d_max_air_low;

p_req=(((1.8*log((6.9/(rho_air*va(1,i)*2*R/meu_a))+((e_concrete/(2*R))/3.7)^(1.11)))^(
-2))*d_max_air_low*rho_air*(va(1,i))^2)/(2*2*R);
    pa1(i,1)=va(1,i);
    pa1(i,2)=p_req;
end

i=0;
va=linspace(3.5,15,24);
da2=[];
pa2=[];
for i=1:length(va)
    d_max_air_high=((T_req-
((4*2*pi*R_cable)*((k_a*(0.3+((0.62*(rho_air*va(1,i)*2*R/meu_a)^(0.5)*(Pr_a)^(1/3))/((
1+(0.4/Pr_a)^(2/3))^(0.25)))*(1+((rho_air*va(1,i)*2*R/meu_a)/282000)^(0.5)))/(2*R)))/C
able_Power)^(-1))-T_i)*((rho_air*pi*R^2*c_a*va(1,i)/280));
```

```
    da2(i,1)=va(1,i);
    da2(i,2)=d_max_air_high;

p_req=(((1.8*log((6.9/(rho_air*va(1,i)*2*R/meu_a))+((e_concrete/(2*R))/3.7)^(1.11)))^(
-2))*d_max_air_high*rho_air*(va(1,i))^2)/(2*2*R);
    pa2(i,1)=va(1,i);
    pa2(i,2)=p_req;
end

i=0;
va=linspace(15,25,21);
da3=[];
pa3=[];
for i=1:length(va)
    d_max_air_highest=((T_req-
((4*2*pi*R_cable)*((k_a*(0.3+((0.62*(rho_air*va(1,i)*2*R/meu_a)^(0.5)*(Pr_a)^(1/3))/((
1+(0.4/Pr_a)^(2/3))^(0.25)))*(1+((rho_air*va(1,i)*2*R/meu_a)/282000)^(5/8))^(4/5))/(2*
R)))/Cable_Power)^(-1))-T_i)*((rho_air*pi*R^2*c_a*va(1,i)/280));
    da3(i,1)=va(1,i);
    da3(i,2)=d_max_air_highest;

p_req=(((1.8*log((6.9/(rho_air*va(1,i)*2*R/meu_a))+((e_concrete/(2*R))/3.7)^(1.11)))^(
-2))*d_max_air_highest*rho_air*(va(1,i))^2)/(2*2*R);
    pa3(i,1)=va(1,i);
    pa3(i,2)=p_req;
end

i=0;
vw=linspace(0,0.75,16);
dw=[];
pw=[];
for i=1:length(vw)
    d_max_water=((T_req-
((4*2*pi*R_cable)*((k_w*(0.3+((0.62*(rho_water*vw(1,i)*2*R/meu_w)^(0.5)*(Pr_w)^(1/3))/
((1+(0.4/Pr_w)^(2/3))^(0.25)))*((1+((rho_water*vw(1,i)*2*R/meu_w)/282000)^(5/8))^(4/5)
))/(2*R)))/Cable_Power)^(-1))-T_i)*((rho_water*pi*R^2*c_w*vw(1,i)/280));
    dw(i,1)=vw(1,i);
    dw(i,2)=d_max_water;

p_req=(((1.8*log((6.9/(rho_water*vw(1,i)*2*R/meu_w))+((e_concrete/(2*R))/3.7)^(1.11)))
^(-2))*d_max_water*rho_water*(vw(1,i))^2)/(2*2*R);
    pw(i,1)=vw(1,i);
    pw(i,2)=p_req;
end

subplot(2,2,1);
plot(pw(:,1),pw(:,2));
title('Required Pressure Head vs. Fluid Speed (Water)');
xlabel('Water Velocity (m/s)');
ylabel('Required Pressure Head (Pa)');
legend('4E5<Re_D<5E6','Location','northwest');

subplot(2,2,3);
plot(dw(:,1),dw(:,2));
title('Max Pump Separation vs. Fluid Speed (Water)');
xlabel('Water Velocity (m/s)');
ylabel('Maximum Pump Separation (m)');
legend('4E5<Re_D<5E6','Location','northwest');

subplot(2,2,2);
plot(pa1(:,1),pa1(:,2),pa2(:,1),pa2(:,2),pa3(:,1),pa3(:,2));
title('Required Pressure Head vs. Fluid Speed (Air)');
xlabel('Air Velocity (m/s)');
```

```
ylabel('Required Pressure Head (Pa)');
legend('Re_D<2E4','2E4<Re_D<4E5','4E5<Re_D<5E6','Location','northwest');

subplot(2,2,4);
plot(da1(:,1),da1(: ,2),da2(:,1),da2(:,2),da3(:,1),da3(:,2));
title('Max Pump Separation vs. Fluid Speed (Air)');
xlabel('Air Velocity (m/s)');
ylabel('Maximum Pump Separation (m)');
legend('Re_D<2E4','2E4<Re_D<4E5','4E5<Re_D<5E6','Location','northwest');
end
```

(I) The "Solutionary Rail" movement by the Backbone Campaign

The following is a summary of an activist movement's effort to achieve widespread rail electrification in the U.S. This summary is presented for the edification of the reader, who, after reading this paper, may have interest in learning more about the prospect of using railroads as transmission corridors. The following discussion is taken directly from communication with and materials provided by the Backbone Campaign. The following does not represent the strategic intentions of the author or indicate any collaboration between the campaign and the Cable Train project at MIT.

The Backbone Campaign's mission is to "[amplify] the aspirations of 'We the People' with creative strategies and artful activism to manifest a world where life, community, nature, and our obligations to future generations are honored as sacred." Their vision and strategy is the manifestation of a broader social and ethical ethos and centers around the "Solutionary Rail." The Solutionary Rail campaign advocates for the broad electrification and rehabilitation of the United States' railway infrastructure, starting with the Northern Transcon from Seattle to Chicago, owned by BNSF Railway Company, as well as other lines considered part of the Northern Corridor. [70] The campaign's proposed solution suggests the co-location of HVDC, bulk power transmission infrastructure along railroads as a panacea for national transportation. Some of the benefits they claim the Solutionary Rail will bring are:

- Modernized rail systems that have better reliability and capacity, replacing road haulage and passenger transport with a clean form of locomotion.
- Co-located transmission capacity capable of bringing landlocked renewable energy generation from utility, electric coop, or native tribal plants.
- Increased connectivity between rural areas and metropolitan centers, spurring rural development.
- Decreased noise levels and air pollution in trackside communities.
- Easement of highway congestion, resulting in less accidents, road damage, and carbon dioxide emissions.

Broad railway electrification in the United States is a development that has been attempted before. Most notably, the electrification of a large portion of the Chicago, Milwaukee, St. Paul &

[70] Bill Moyer, et al. "Solutionary Rail: A people-powered campaign to electrify America's railroads and open corridors to a clean energy future," Backbone Campaign (Washington: 2016) http://www.solutionaryrail.org/ (accessed 04/15/2018), 6-7.

Pacific line between 1915 and 1920, served as proof for the feasibility of the electrification of steam railways. Today, many of the most advanced and heavily used railway systems in the world are largely electrified – nations including China, France, Germany, Italy, and Russia have upwards of 40% or their rail systems electrified. Because of the increased reliability and speed of these lines, electrified lines often account for a disproportionate amount of actual haulage. There is consensus around the fact that electrified trains offer operating improvements and cost reductions for railway companies – electrified trains are faster, more energy efficient, and require less maintenance. However, electrified rail in the U.S. lags far behind, with only about 1% of railway miles being electrified.[71]

While China and European nations have been prolific in their implementation of electrified railways, the system of private railway ownership in the U.S., combined with the capital-intensive nature of railway electrification, has limited its penetration in America. Railway companies must not only endure interest on borrowed funding, but they must also incur property taxes on improvements made. Any attempt to modify railroads would lead to temporary cost increase and intensified competition from the road-hauling industry, which are free from property tax and a prime beneficiary of public transportation subsidies.[72]

The concept of feeding electrified trains with trackside, bulk power transmission is an interesting one, but has its problems. If this were to be accomplished, HVAC systems would be required because electrified trains could not operate on DC. If HVDC were to be used, intermediate converter stations would be required, which would never be economically feasible. The right of ways required by three-phase HVAC systems may prove to be a limiting factor on railroads. Even if HVAC is used, the constant desire for increased transmission voltages may mean that trains cannot operate at transmission voltages and intermediate substations would be required along the entire length of the electrified railway.

Nevertheless, the Solutionary Rail campaign has done a great deal of thinking on the incentives of various stakeholders – railways companies, utilities, energy consumers, trackside communities, native tribes, and the public at large – as well as the institutional relationships and regulatory environment that may make large capital improvements in the U.S., like an HVDC system built by the Cable Train, possible. With the primary goal of providing low-cost capital and public support that is relatively abundant in European and Asian countries, the campaign proposes the establishment of an interstate, public agency, that is not-for-profit and tax-exempt, to raise funds through the sale of government-backed, tax-free bonds as well as low-cost Transportation Infrastructure Finance and Innovation loans (TIFIA).[73] Transmission would therefore be publicly owned and funded by payments from utilities using the transmission systems and electrified railroads drawing power from the system. This charter would empower such a public agency to navigate regulatory obstacles and stakeholder conflicts, as well as oversee

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[71] Bill Moyer, et al. "Solutionary Rail: A people-powered campaign to electrify America's railroads and open corridors to a clean energy future," Backbone Campaign (Washington: 2016) http://www.solutionaryrail.org/ (accessed 04/15/2018), 16.
[72] Bill Moyer, et al. "Solutionary Rail: A people-powered campaign to electrify America's railroads and open corridors to a clean energy future," Backbone Campaign (Washington: 2016) http://www.solutionaryrail.org/ (accessed 04/15/2018), 53.
[73] Ibid, 57.

railroad infrastructure improvements and incentivize renewable energy generation through Renewable Energy Credits (RECs).[74]

More information on the Solutionary Rail project can be found at:
http://www.solutionaryrail.org/

(J) Alternative Vision for the Delivery of Factory-Made Cable by Train

While the vision of this paper is to prove the feasibility of in-situ cable production using manufacturing capability onboard a moving train, and while the countermeasures and solutions presented here are promising, there may be challenges in the future that prove insurmountable. What is certain is that manufacturing cable onboard a train in theoretically unlimited lengths is many times more complicated than manufacturing in a factory setting. Even if problems arise that undermine the possibility of continuous manufacturing or impose practical limits on cable length, the concept of transmission co-location with railroads is still one that makes gut sense and railways may still be used to delivery extraordinarily long lengths of factory-made cable, by freight train.

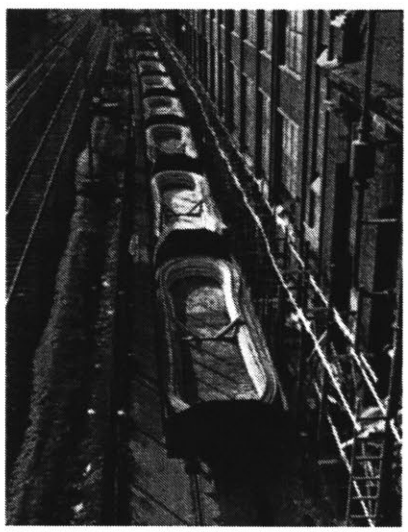

Figure A: A continuous length of submarine cable being shipped to port inside of gondola railcars.[75]

The machines, processes, and logistics to safely move continuous lengths of cable from factory to train, as well as safely dispense cable from railcars into trackside duct banks may be possible with the nonobvious implementation of primitive technology. Figure A shows the precedent for long submarine cable transport, from factory to harbor, by railcar. In the loading of submarine cable from harbor sites to CVLs, speed between 3 and 20 m/min have been

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[74] Ibid, 58-59.

[75] Wor[illegible]yk, Thomas, "Submarine Power Cables: Design, Installation, Repair, Environmental Aspects," Springer Dordrecht Heidelberg (London: 2009) https://link.springer.com/book/10.1007%2F978-3-642-01270-9 (accessed 11/30/2017), 173.

achieved.[76] Still, the challenge of preventing kinking, twisting, buckling, and excessive tension while handling extremely long lengths of cable (tens to hundreds of kilometers) is nontrivial.

Such a solution would still warrant the use of the continuous manufacturing countermeasures – continuous extrusion, horizontal curing, and inline degassing – which are the focus of this paper, in order to produce extremely long cables in a factory setting, without any joints. Achieving continuous cable production in dedicated facilities would eliminate some of the complications intrinsic to in-situ production like the need for clean environments for plastics handling, raw material delivery, servicing of machines, and the need for a thorough quality assurance protocol, requiring specialized machines and personnel, among many others discussed throughout this paper. When compared to in-situ production using the Cable Train, this approach would reduce the time that railroads are out of commission due to installation because cable installation can happen much faster than cable extrusion, which is the rate limiting step in cable manufacturing. Lastly, if a cable does not pass qualification in the field and repair is not an option, a rolling stock-based cable dispensing system could remove cable just as easily as it laid it down, whereas the Cable Train is only able to produce and place cable.

The construction of a continuous, extruded cable factory, comprising the same methods and machines as the theoretical Cable Train, centrally located within a railway system, could achieve higher machine utilization because it avoids downtimes from the transportation and assembly/disassembly of the manufacturing modules.

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[76] Wor[illegible]yk, Thomas, "Submarine Power Cables: Design, Installation, Repair, Environmental Aspects," Springer Dordrecht Heidelberg (London: 2009) https://link.springer.com/book/10.1007%2F978-3-642-01270-9 (accessed 11/30/2017), 174.

(K) Remote Renewable Energy Resources in the U.S.

It is well known that many nations possess the natural resources to meet their energy needs with completely renewable sources. The U.S. has great untapped renewable energy resources and this is especially the case in remote, landlocked regions of the country. It is well-recognized that a robust HVDC grid, with its distinct advantages to AC systems over long distances, will be critical to the efficient transportation of renewable power to populated marketplaces in the future. Below are several figures that have been widely cited and used to illustrate the need for, and potential of, renewable HVDC.

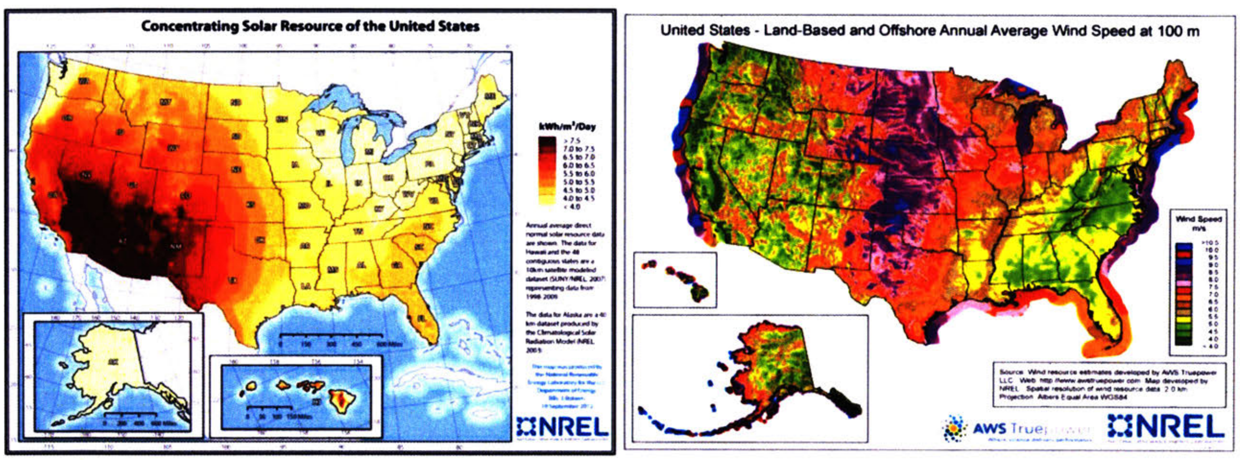

Figure B: (Left) A map of the U.S. showing the distribution of absolute power flux from solar irradiation.[77] (Right) A map of the U.S. showing the distribution of wind resources.

[77] Roberts, Billy J., "Concentrating Solar Resource of the United States," National Renewable Energy Laboratory (September 19, 2013) https://www.nrel.gov/gis/images/eere_csp/national_concentrating_solar_2012-01.jpg (accessed 01/01/18).

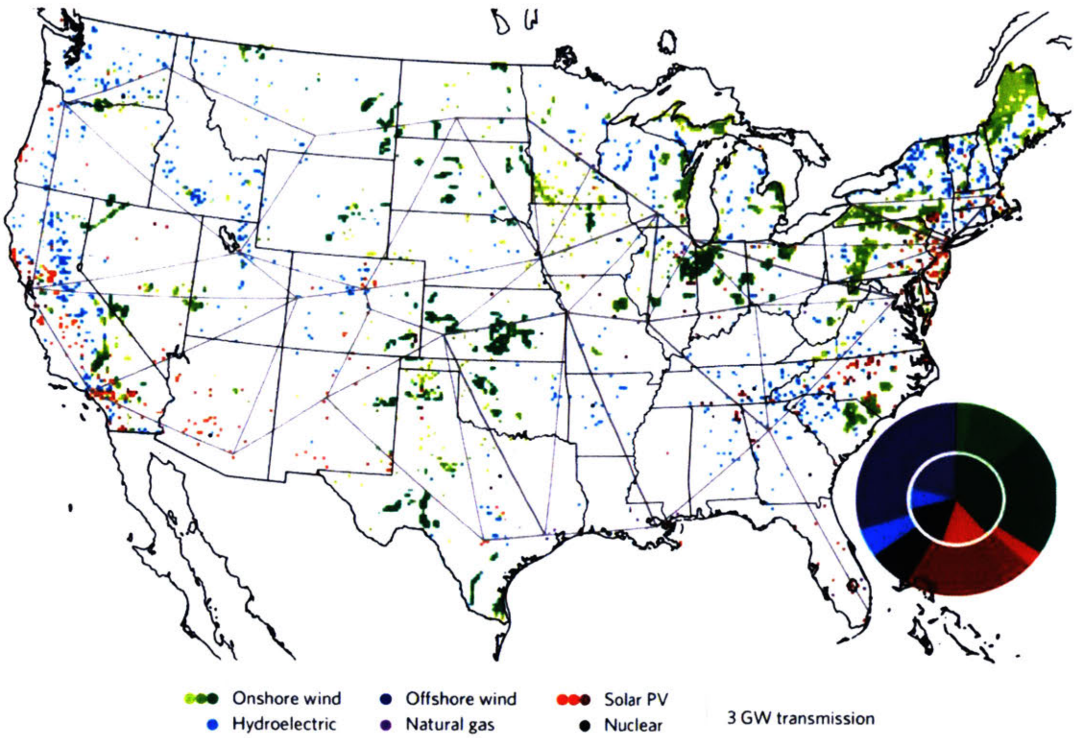

Figure C: An image from a frequently cited publication showing a proposed nationwide HVDC grid and renewable generation portfolio capable of reducing carbon dioxide emissions by 80% relative to 1990 levels using existing technologies.[78]

(L) Degassing Car Design Spreadsheet

A tool was developed to aid the design of the "space-saving inline handling system for roll-to-roll processing" discussed in Section 1.3.3. The spreadsheet with example number is shown below. The tool calculates the optimum number of drums and railcars necessary to achieve a particular degassing time. The spreadsheet also calculates the Von Mises stress in the conductor and insulation due to bending, tension, torsion, and side-wall pressure. Lastly, the spreadsheet recalculates the Von Mises stress at the comb-cable contact under the assumption that discrete combs, as discussed in Section 1.3.3, are used, to make sure that stress is manageable with these implementations. This design spreadsheet, along with finite element simulation, provides all grounds for the soundness of the inline cable handling process described in Section 1.3.3. It can be provided upon request made to the corresponding author.

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[78] Alexander E. MacDonald, et al., "Future cost-competitive electricity systems and their impact on US CO_2 Emissions," Nature Climate Change (January 2016) https://www.nature.com/articles/nclimate2921.pdf (accessed 05/01/2018).

Cable Data and Parameter Input	
Drum/Cable Diameter Factor	22
Cable Insulation OD (m)	0.125
Conductor OD (m)	0.06
Diameter of Drums (m) for Degas	2.75
Diameter of Nuetral Axis of Cable (m)	2.875
Area of Conductor (m^2)	0.002827433
Packing Fraction Circles (Milliken)	0.9069
Single Conductor Strand Diameter (m)	0.003
Number of Layers in Conductor	10
Total Number of Strands (Concentric Stranded)	331
Lay Angle (Degrees)	45
Max Tensile Traction Force on Cable (N)	169646.0033
Clearance Between Cable on Neighboring Drums (m)	0.1
Distance Between Drum Centers (m)	3.1
Clearance to Bottom of the railcar (m)	0
Max Length of Suspended Cable (m)	8.743996984
Weight Per Meter of Cable (N/m)	333.0161188
Poisson's Ratio Copper	0.364

Calculation of Optimum # of Reels per Railcar	CSX Boxcar	CIMC Container
Inner Height (m)	3.3274	2.393
Inner Width (m)	2.896	2.352
Inner Length (m)	15.418	5.898
Drum Diameter (m)	2.75	2.75
Clearance Between Cable on Neighboring Drums (m)	0.1	0.1
Drums Per Car/Container Vertical (#)	1	0
Drums Per Car/Container Horizontal (#)	4	1
Total Drums Per Car/Container (#)	4	0
Clearance Between Drum and Walls (m)	0.4	0.4
Cable Length per Car/Container (m)	625.6843484	0
Degassing Time (hrs)	168	168
Cable Production Speed Goal (m/hour)	80	80
Number of Cars/Containers (#)	22	#DIV/0!
Length of Degassing Section of the Train (m)	339.196	#DIV/0!

Copper		Insulation	
Yield Strength (Pa)	333400000	Yield Strength (Pa)	200000000
Shear Modulus (Pa)	46000000000	Shear Modulus (Pa)	4830000000
E (Pa)	1.1E+11	E (Pa)	1300000000
EI (Pa*m^4)	0.44	EI (Pa*m^4)	14752.47
Radius of Curvature (m)	1.41	Radius of Curvature (m)	1.44
Curvature (/m)	0.71	Curvature (/m)	0.70
I (m^4)	3.98E-12	I (m^4)	1.13E-05
Internal Moment (Pa*m^3)	0.31	Internal Moment (Pa*m^3)	10262.59
Max Bending Stress (Pa)	117229129.66	Max Bending Stress (Pa)	5.65E+07
Density (kg/m^3)	7764	Density (kg/m^3)	1270
Max weight of suspended cable (N)	2911.89	Max weight of suspended cable (N)	2911.89
Loading	84%	Loading	16%
Tensile Stress from dead weight (Pa)	865091.73	Tensile Stress from dead weight (Pa)	49331.04
Total Max Axial Stress (Pa)	118094221.39	Total Max Axial Stress (Pa)	56571070.17
Normal Force Drum to Cable (N/m)	3488.98	Normal Force Drum to Cable (N/m)	3488.98
Delta Deformation of Insulation (m)	1.64E-06	Delta Deformation of Insulation (m)	2.47818E-05
Strain	5.05256E-05	Strain	0.000762517
Contact Patch Area (m^2) per unit length	6.28E-04	Contact Patch Area (m^2) per unit length	0.003519722
Force Constraint	3488.999798	Force Constraint	3489.000418
Side Wall Pressure from Drum (Pa)	5557780.32	Side Wall Pressure from Drum (Pa)	991265.6574
Coefficient of Friction XLPE to Steel	0.2	Coefficient of Friction XLPE to Steel	0.2
Normal Force from Comb (N/m)	697.8769297	Normal Force from Comb (N/m)	697.8769297
Delta Deformation of Insulation (m)	5.34E-07	Delta Deformation of Insulation (m)	8.49E-06
Strain	1.77839E-05	Strain	0.000261314
Contact Patch Area (m^2) unit length	3.58E-04	Contact Patch Area (m^2) unit length	2.06E-03
Force Constraint	700.00	Force Constraint	700.000073
Side Wall Pressure from Comb (Pa)	1.95E+06	Side Wall Pressure from Comb (Pa)	3.39E+05
Torque on Cable @ Cable Center (N*m)	34.89	Torque on Cable @ Cable Center (N*m)	34.89384648
Internal Torque Constraint (N*m)	34.89	Internal Torque Constraint (N*m)	34.89
Max dPhi / dx (Degrees/m) from Rolling	0.000014127	dPhi / dx (Degrees/m)	0.000014127
Max Stress from Twist (Pa)	19495.49468	Max Stress from Twist (Pa)	4264.639461
Max Axial Stress Total (Pa)	118094221.39	Max Axial Stress Total (Pa)	56571070.17
Max Radial Stress Total (Pa)	5557780.32	Max Radial Stress Total (Pa)	991265.66
Max Circumferential Stress Total (Pa)	19495.49468	Max Circumferential Stress Total (Pa)	4264.639461
Safety Factor	2	Safety Factor	2
Von Mises at Danger Point (Pa)	1.63E+08	Von Mises at Danger Point (Pa)	7.93E+07
Good for Static Case?	YES	Good for Static Case?	YES
Von Mises at Comb/Cable Contact (Pa)	165634476.8	Von Mises at Comb/Cable Contact (Pa)	79762129.72
Good for Static Case?	YES	Good for Static Case?	YES

Continuous Comb		Discrete Comb		Discrete Rollers	
Thickness (m)	0.0127	Thickness (m)	0.0127	Radius of the Rollers (m)	0.01405245
Largest Expected Cable OD (Gap) (m)	0.125	Largest Expected Cable OD (m)	0.125	Approximate Largest Expected Cable OD (m)	0.125
Length of Drum	2.2864	Angle (Degrees)	0.873545792	Length of Drums Flange-to-Flange	2.2864
Revolutions	16.51006352	Number of Comb Rows	4	Number of Roller Rows	4
Angle (Degrees)	0.873545792	Circumferential Sep. (m)	2.16	Number of Revolutions	14
Normal Force on Comb (N/m)	697.8769297	Length of Flat Section (m)	0.05	Angle (degrees)	0.97128082
Delta Deformation of Insulation (m)	4.28387E-07	Normal Force on Comb (N/m)	31516.40	Force Acting on Each Roller (N)	1575.86315
Strain	1.37084E-05	Delta Deformation of Insulation (m)	0.000793603	Delta Deformation @ Contact (m)	0.00046231
Contact Patch Area (m^2) per unit length	0.000462809	Strain	0.02441854	Strain	0.01422495
Force Constraint	697.8798181	Contact Patch Area (m^2) unit length	0.000992827	Elliptical Contact Patch Area (m)	8.5216E-05
Side Wall Pressure from Drum (Pa)	1507914.363	Force Constraint	11516.39602	Force Constraint (N)	1575.85991
FEA Result?	Good!	Side Wall Pressure from Comb (Pa)	31744103.03	Pressure on Insulation (Pa)	18492429.2
		Fin Attachment Good? (FEA)	YES	Roller Attachment Good? (FEA)	YES
		Von Mises at Fin-Cable Cont. (Pa)	69452135.51	Von Mises at Roller-Cable Cont. (Pa)	70651246.4
		Safety Factor	2.879681072	Safety Factor	2.8
		Flat Section of Fin Sufficiently Long?	YES	Roller Radius Sufficiently Large?	YES
		Worst Case Precaution - Fin Terminal Radius		Pitch (m)	0.1531049
		Radius at the End of Fin (m)	0.005	Shift Between Bars (m)	0.03827623
		Force from Friction in Jamming (N)	697.7958211	Drum Length (m)	2.2864
		Delta Deformation of Insulation (m)	0.000400702	Drum Length Constraint	2.28640225
		Strain	0.012329298		
		Contact Patch Area (m^2) unit length	4.35361E-05		
		Force Constraint	697.7997896		
		Side Wall Pressure from Comb End (Pa)	16027996.59		
		Von Mises at Fin-Cable Cont. (Pa)	71416414.7		
		Safety Factor	2.800476625		
		Terminal Radius of Fin Sufficiently Large?	YES		

- Pressure on cable for helical comb is evaluated down and to the left (original calculations assumed a helical comb).
- Tribology is yet to be tested.
-Grounding the combs is necessary to eliminate charge build-up from triboelectric effect.
-Comb can be made using spiral bender - used to make auger flights - and welded together.
- Experiments and calculations conducted reveal a limited twisting from cable rolling when entering the first reel (before sliding begins). The roll direction can be chosen such that the twist in the cable is the same direction as the twist in the conductor to prevent unwinding.

1. Use cells to solve for R_min given the number of roller rows desired. Try to minimize both these values to save cost and increase revolutions per drum in the end and keep SF > 2.

Figure D: The table above shows example numbers from a design spreadsheet made to aid in the design of the helical cable combs proposed in the discussion of a "space-saving inline handling system for roll-to-roll processing" in Section 1.3.3. The spreadsheet calculates all Von Mises stresses and re-checks the stresses assuming different types of cable combs. All dynamic variables are shown in red and general data about the cable, the drums, and the containment vessel (railcar or shipping container) are shown in the green highlighted area.

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