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Traction Power Autotransformer Substation Modernization and Switchgear Development

Phase I Final Report

Southeastern Pennsylvania Transportation Authority

July 1997

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16. Abstract

SPD Technologies is developing 12 kV and 24 kV switchgear as part of SEPTA's modernization program to upgrade its traction power supply and distribution system. This report provides a summary of the design and development work performed through Phase I, "Design and Engineering of Power Components". The report describes design requirements for circuit breakers, disconnect switches, bus structure, switchgear and other system components.

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1 square inch (sq in, in²) = 6.5 square centimeters (cm²)
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1 square mile (sq mi, mi²) = 2.6 square kilometers (km²)
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1 cubic foot (cu ft, ft³) = 0.03 cubic meter (m³)
1 cubic yard (cu yd, yd³) = 0.76 cubic meter (m³)

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1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

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1 square meter (m²) = 1.2 square yards (sq yd, yd²)
1 square kilometer (km²) = 0.4 square mile (sq mi, mi²)
1 hectare (he) = 10,000 square meters (m²) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

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1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

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1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m³) = 36 cubic feet (cu ft, ft³)
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CENTIMETERS 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 | 25.40

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For more exact and/or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10 286.

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SECTION 1.0 EXECUTIVE SUMMARY

SPD Technologies was awarded a contract by the Southeastern Pennsylvania Transportation Authority (SEPTA) under research project grant PA-26-7002, sponsored by the Federal Transit Administration. SPD Technologies is developing 12 kV and 24 kV switchgear as part of SEPTA's modernization program to upgrade their traction power supply and distribution system. This report provides a summary of the design and development work performed to date through Phase I, "Design and Engineering of Power Components."

Through an extensive review of existing technologies and hardware, complemented by additional design and 3-D computer modeling and analyses, SPD has developed a conceptual switchgear layout for each voltage class. The design is fully compliant with the performance requirements and size constraints defined in **Reference 1** and is also in accordance with the relevant IEEE, ANSI, NEC and NEMA design standards and codes. The effort through Phase I has focused on the design of the basic switchgear components including the circuit breakers, disconnect switches, ground switches, bus structure and cubicle enclosures. Using a building block approach, these standard component designs were integrated to develop the five basic cubicle types for each voltage class. Ultimately, these cubicle types can be combined, in a modular fashion, to satisfy the particular switchgear layout requirements for Wayne Junction as well as for each of the outlying substations on the SEPTA regional rail system.

To achieve the baseline designs that comply with the stringent system performance requirements of indoor, metal-clad switchgear with challenging voltage withstand ratings, SPD successfully addressed several key technical issues. The issues were resolved through the prudent use of existing technologies in creative new ways. Temperature rise concerns were addressed through the analysis and proper sizing of the main current-carrying members. Electrostatic stress management was achieved through the extensive use of 3-D modeling and analysis, and prudent design practices in concert with the careful selection of geometry and materials. Overall switchgear size was minimized through the effective use of leading edge

insulating bushing technology, optimized cubicle design layout and creative design of the bus and enclosure structures.

As a result, the present design requires 20 to 38 percent less floor space and 28 percent less height than was originally anticipated. The immediate benefit is reduced material cost of the switchgear. Moreover, the size and thus the cost of the substation buildings to house the switchgear will be less. Finally, the compact design reduces the complexity, risk and attendant cost of shipping and handling the switchgear after manufacturing.

This report presents a detailed description of the design and a summary of the substantiating analytical results. The design features the following:

- Vacuum interruption technology for high voltage circuit protection
- Single-bottle configurations for the circuit breakers
- An operating mechanism based on a proven durable design
- Common parts and equipment where possible for standardization
- "2-Tier" cubicle arrangements for efficient use of space and thermal management
- Capacitively graded bushings for compact electrical insulation of conductors
- Versatile, multifunctional junction couplers
- Modular cubicle frame design
- State-of-the-art microprocessor-based controls (design to be completed in Phase II)

SPD Technologies will continue to develop the switchgear and associated power components and control system through Phase II of the contract. The emphasis will be on the detailed design and documentation to support the procurement, fabrication and subsequent verification of the prototype switchgear through qualification testing.

SECTION 2.0 OVERVIEW

2.1 BACKGROUND

As part of a comprehensive modernization program, "SEPTA plans to modernize the traction power supply system by replacing the traction power control facility in Wayne Junction, circuit breakers feeding the new static frequency converters (SFCs) to the overhead (traction) distribution system, and autotransformer substations located throughout the system" as specified in **Reference 1**. SPD Technologies has been awarded a contract to design and develop the power components, the switchgear and the control system under the "Traction Power Autotransformer Substation Modernization and Switchgear Project".

This report summarizes the features of the design and highlights the program development to date. This project includes the mechanical and electrical design and development of the power components and switchgear for two distinct voltage ratings of 12 kV and 24 kV.

The program schedule is shown in **FIGURE 2-1**. The detailed design of the power components and switchgear will continue through the balance of this year as the detailed design of the control system advances as well. **FIGURE 2-1** also shows key program milestones that have been met including the monthly Design Review Meetings (DRM) as well as several field trips to Wayne Junction and other substations. During these review meetings and on-site exchanges, the SPD engineering staff gained valuable insight into the operational, maintenance, and installation aspects of this program. At the same time, SEPTA personnel have had direct input into the evolution of the design and are an integral part of the development process. As the prototype phase begins, on-site exchanges will also be held at SPD's manufacturing facility.

As the program enters the next phase, additional design details will be developed for the operating and protection control systems. Subsequently, all switchgear components and elements will be documented in sufficient detail to facilitate the procurement and fabrication of prototypes. These prototypes will be used to verify form, fit and function of the equipment to the SEPTA requirements. This program will culminate in the validation of the design by

conducting qualification tests on the prototype units. Potential enhancements and improvements to the design will be noted as the testing and evaluation proceeds. They may then be incorporated into the documentation and drawing packages.

2.2 APPROACH

The design approach taken to date has been an iterative one. The design team started with the program requirements and developed a conceptual design with enough detail to employ 3-D computer aided design (CAD). Some design features and functions are then verified by computer analysis and visual inspection of the resulting designs and drawings. When warranted by the complexity of the design or technical risk, requirements are verified by performing the appropriate engineering analyses. The design and analysis iteration process continues until a compliant solution is found. The analysis results are reviewed monthly with SEPTA to solicit feedback and to ensure compliance with their specifications and expectations. This report captures the design as it stands at the completion of Phase I of the program.

The conceptual design was developed by uniquely applying proven technologies and materials to the specific requirements of this project, while minimizing development risks. As a result, some elements are off-the-shelf with minor modifications, while others are extrapolations of proven designs. In an effort to continually improve the design and to minimize cost, solicitations from alternate suppliers are continually being made. As each new element or approach was assimilated into the design, SPD's CAD capability afforded the design team the opportunity to check form, fit and function with the switchgear. Furthermore, elemental or material testing was helpful in selecting candidate parts and materials such as insulators or insulation material. Ultimately, a complete and compliant design concept was developed.

The first step in a development effort is to clearly define the requirements. SPD compiled the requirements with applicable standards and codes including ANSI, IEEE, NEC and NEMA as specified by **Reference 1**. From these requirements and an understanding of available

technology, a conceptual design was developed and analyses were conducted. Several key technical challenges were identified:

- Electrostatic stress management of the switchgear and power component designs due to the relatively high Basic Impulse Levels (BIL)
- Thermal stress management of the bus structure design due to steady state current as well as dynamic load requirements
- Mechanical durability of the circuit breakers due to the endurance rating of 20,000 mechanical operations
- Transportability using normal shipping and material handling methods with minimum disassembly due to the relatively large switchgear

Several design approach opportunities were also recognized as a result of the magnitude of this development effort:

- Compact switchgear design has a positive impact on building size requirements and ease of transportation
- Modular component and switchgear design provides maximum commonality between the five basic cubicle types needed throughout the SEPTA railway system
- Commonality of elements and hardware between the voltage classes reduces initial procurement costs and spares management costs
- Microprocessor-based controls ensure proper systems protections under a wide range of conditions and modes.

These themes permeate the design as described in the sections that follow. A conscientious effort to incorporate commonality and modularity has resulted in a versatile switchgear design that is cost effective and fully compliant with all of the performance requirements.

SPD has utilized two key subcontractors to support the design effort. SPD contracted Piedmont Dielectrics Corporation, with over thirty years of design and manufacturing

experience, to aid in the design of the bushing elements. SPD also contracted IAP Research, Incorporated, to complement the design and analysis in the areas of thermal, electrostatic stress and electromagnetic field management. Both subcontractors have been an integral part of the development effort.

In addition to these two subcontractors, several other companies with widespread industry recognition and expertise have been consulted for the design of various items. Each company has contributed to the design and development to ensure that a robust, practical and producible design solution was achieved. SPD has incorporated each company's experience in various areas of the design including the selection of the insulation materials, the configuration of key junction and bus elements, and the adaptation of the operating mechanism.

2.3 TECHNICAL DISCUSSION

Starting with the key technical challenges noted previously, the top-level performance requirements presented in **TABLE 2-1**, and through an extensive development effort, SPD has achieved a compliant, comprehensive design. The designs of the power components feature the following:

- Vacuum interruption technology for high voltage circuit protection
- Single vacuum interrupter configuration for circuit breakers in both voltage classes
- Operating mechanism based on a heritage SPD design
- Common truck arrangement for circuit breakers and disconnect switches

The levels of required operating voltage resulted in the utilization of vacuum interruption technology for the main circuit protection element. To minimize the size of the circuit breakers and to increase reliability by reducing complexity, considerable design effort went into achieving a single-bottle configuration for each voltage class. A thorough assessment of the circuit breaker requirements, especially the high impulse voltages in concert with the demanding mechanical endurance rating of 20,000 cycles, prompted SPD to base the design of the operating mechanism on a proven design previously qualified to over 20,000 operations. Finally, for ease of manufacture and reduction of parts count, commonality between the truck designs was used wherever feasible.

The switchgear design features the following:

- A "2-Tier" cubicle arrangement
- Round conductors sized for steady state current and thermal conditions
- Capacitively graded bushings for both disconnect and fixed conductors
- A versatile, multi-functional junction coupler for multiple connections
- A modular frame design for efficient fabrication and assembly
- State-of-the-art microprocessor-based controls (to be defined in Phase II)

A preliminary analysis revealed that the temperature rise in the bus compartment was a key technical issue. **FIGURE 2-2** shows the duty cycle for the current loading on the switchgear using a design maximum of 200% of nominal current. The results prompted a significant change in the design philosophy of the switchgear layout from the original "3-Tier" configuration to a thermally superior, more streamlined "2-Tier" arrangement. **FIGURE 2-3** shows a side-by-side comparison of the Transfer Circuit Breaker cubicle for the two arrangements. The "2-Tier" configuration shown on the right has two basic compartments providing access to at least one outside wall in each compartment.

The thermal advantage of the "2-Tier" design is that the surrounding ambient air directly cools the bus compartment, instead of being trapped inside the middle compartment of the "3-Tier" layout. An additional benefit was better utilization of space, resulting in significantly less unused space and less depth required to house all of the equipment while simultaneously meeting the BIL requirement. Taking the optimization one step further, each cubicle arrangement was further tailored to the respective components housed inside, reducing the height and width where warranted to minimize the amount of unused space.

In addition to optimizing the overall switchgear arrangement, significant design effort was put into optimizing the individual elements. Round conductors are used instead of flat bus, which dramatically improves electrostatic stress management. Similarly, capacitively graded bushings are utilized to achieve the necessary insulation of the main current path elements as they pass through the walls of the metal-clad structure. The bus structure itself is a build-up of individually mounted, capacitively graded fixed bushings concatenated end to end for optimal electrostatic field stress management. The bushings form a continuous current path through the use of a junction coupler design that is configurable to handle 2, 3 and 4-way electrical bus connections.

A pictorial summary of the evolution of the switchgear size and configuration for the 24 kV line-up is indicated in **FIGURE 2-4**, with the current switchgear layout shown in the bottom right hand corner. The culmination of the design effort is a compact design that requires 20 to

40 percent less floor space than was originally anticipated along with a 28 percent reduction in overall height of the switchgear enclosures. The immediate benefit of the smaller size is the reduced procurement cost of the line-ups. Moreover, the size and cost of the buildings or structures needed to house the switchgear are also reduced as a result of this compact design. Furthermore, the smaller height reduces the complexity, risk and attendant cost which will be incurred in shipping the product to the various substations during the production phase of the program.

While the initial focus is on the Wayne Junction substation, SPD and SEPTA recognize that the switchgear and power component designs developed for this program will become the building blocks to be used in the upgrades of the entire SEPTA railway system. SPD's design addresses technical challenges head on and provides an ambitious use of materials and technology to aid SEPTA in the modernization of their distribution system.

The balance of this report discusses the design in more detail and is structured to follow the program work breakdown structure. The power components (circuit breakers and switches) are presented first and the bus structures and the switchgear sections follow. Each section starts with a recapitulation of the key applicable design requirements, and presents the design approach, features and highlights. At appropriate points in the discussion, the related analyses are summarized. Please note that the analysis and results presented herein are a summary of the numerous iterations required to achieve the design solution presented. For clarity and completeness, the body of the report concludes with summaries of the key system-level assessments: the shipping and handling assessment and the overall thermal and electrostatic analyses.

The list of requirements presented near the beginning of each section also provides a means of continually checking the compliance of the design with SEPTA's requirements. The SPD design complies with all of the technical and performance requirements. Each section covers these findings in more detail. This report presents a summary of the design and the analysis results to date. More details as well as the ultimate verification of this conceptual design will be demonstrated by the successful completion of the design tests planned as part of Phase II.

SECTION 3.0 CIRCUIT BREAKERS

3.1 REQUIREMENTS REVIEW

The scope of work for the design of the circuit breakers includes the development of 25-Hz, 1-phase components rated for 1,200 amps and 2,000 amps nominal continuous current. The first component is a 24 kV feeder circuit breaker, with a 12 kA interrupting current capability, 105 kV nominal frequency withstand, and 250 kV BIL withstand capability. An additional requirement for this circuit breaker is an 8 kA interruption at 36 kV. The second component is a 12 kV trolley circuit breaker, with 25 kA interrupting current capabilities, 60 kV nominal frequency withstand and 150 kV BIL withstand voltage capabilities.

The requirements for the design of the vacuum circuit breakers were compiled from **Reference 1** and applicable industry standards including ANSI, IEEE, NEMA and NEC. In addition, standard industry practices have been used to guide the design to ensure safety and reliability. **TABLE 3-1** lists the key applicable requirements considered in the design of the circuit breakers.

3.2 TECHNICAL DISCUSSION

3.2.1 General Arrangements

Initial market research indicated that none of the circuit breakers available satisfy the key program requirements including the BIL rating, endurance rating and dimensional restrictions. This necessitated the development of vacuum circuit breakers for these applications.

One circuit breaker design satisfies both current ratings for the 24 kV applications, and another circuit breaker design satisfies both current ratings for the 12 kV applications. Commonality between the two circuit breaker designs is maintained wherever possible. These differences are described under the appropriate detailed design sections that follow.

The major technical design challenge is the high BIL levels. 250 kV BIL ratings are typically found in outdoor switchgear, where space allows for large clearance distances. On the other hand, indoor, metal-clad switchgear requires that components and cubicles be compact.

SPD's design goals include:

- Robust, simple design
- Commonality of parts
- Minimum maintenance
- Ease of installing and removing components
- Minimum number of operating and/or maintenance tools
- Adaptability of one basic design to cover all circuit breakers
- Utilization of proven technology wherever reasonable (for reliability)
- Utilization of domestic suppliers wherever possible

FIGURE 3-1 shows the general arrangement and overall size of both the 12 kV and 24 kV vacuum circuit breakers. Projected overall weight of each is approximately 140 kilograms.

The circuit breaker can be removed from the cubicle using a center-mounted leadscrew withdrawal mechanism. There are four indexed positions possible during complete rack in and rack out: connected, test, disconnected and withdrawn. A description of the circuit breaker operations that can be performed in each position is shown in **TABLE 3-4**. Welded steel trucks with guide wheels that engage rails on the cubicle are used to locate and align the breakers within the cubicle. See section 3.2.7 for a more detailed description of the trucks.

The current path through the circuit breaker is as follows. The disconnect bushings, mounted on the compartment walls, are automatically engaged by multi-fingered, tulip-style primary disconnects when the circuit breaker is racked in to the connected position. These primary disconnects are attached to insulated, copper primary conductors which carry the current to and from the vacuum interrupter. Flexible conductors carry the current from the lower

primary conductor assembly to the movable electrode of the vacuum interrupter. Current travels through the closed vacuum interrupter to the fixed electrode, which is connected to the upper primary conductor with a solid copper conductor. Detailed descriptions of the primary disconnects and the primary conductors are included in the sections 3.2.2 and 3.2.3, respectively.

Secondary disconnects automatically engage when the circuit breaker is being racked into the connected or test positions, providing control current for electrical operation of the breaker. Circuit breaker ground contact is made with a ground contact shoe that engages a copper strip attached to the ground bus. The ground contact shoe utilizes conventional "first in, last out" (FILO) sequence for electrical safety. As the circuit breaker is racked in, the ground contact shoe is the first secondary contact to engage ensuring proper system grounding prior to connecting control power. Similarly, as the circuit breaker is racked out, the ground contact shoe is the last secondary contact to disengage.

General arrangement of the circuit breaker includes the operating mechanism, vacuum interrupter, and support structures. The operating mechanism is fastened to the truck and operates the vacuum interrupter through a wipe mechanism. The operating mechanism frame supports a closing spring charging motor, a shunt trip coil, and a close coil. See section 3.2.5 for a detailed description of the operating mechanism. The vacuum interrupter, described in section 3.2.4 is bolted to the upper heat sink/support housing and is restrained in the horizontal plane by a pilot hole in the lower support housing. Each heat sink/support housing is mounted to an insulator that is bolted to the vertical frame of the truck. The upper and lower heat sink/support housings are mechanically coupled through non-conductive support struts. Supporting structures are described in section 3.2.6.

The circuit breakers feature mechanical interlock mechanisms that prevent accidental closing/opening operations as described in section 3.2.8. These interlock mechanisms are attached to the truck, and connect through linkages to the operating mechanism. They consist of roller-type cam followers, which are mounted on pivoted levers, and activated by linear cams

mounted in the cubicle. Manual tripping operations may be performed by pushing the mechanical trip button mounted outside the cubicle.

The vacuum circuit breaker design utilizes proven technology wherever possible, including a single bottle configuration, a center leadscrew, a welded steel truck, and tulip-style primary disconnects. This results in improved safety and reliability.

3.2.2 Primary Disconnects

The function of the primary disconnects is to provide a low-resistance contact between the bus structure and the vacuum circuit breakers. In order to operate within acceptable temperature limits, the primary disconnects must have ample contact area between the conductor and fingers and they much have a sufficient amount of conducting material. Furthermore, the contact surfaces must be capable of withstanding the required life cycle with a negligible amount of loss in performance due to wear. The primary disconnects must be able to engage the disconnect bushings while accommodating an ample amount of misalignment between the conductors. This misalignment could be introduced by tolerance buildups, play within the moving components, or wear. Also, to avoid arcing, the primary disconnects must remain connected while conducting rated short circuit current.

The design of the primary disconnects is based on a proven SPD product. As seen in **FIGURE 3-2**, the assembly is composed of 17 primary disconnect fingers, a primary disconnect washer, a support stud, and retaining pieces. The primary disconnect fingers are made of silver-plated copper and the other components are plated steel. The assembly allows for a high degree of misalignment in all directions by utilizing the tulip formation, and spherical mating surfaces between the support stud and the primary disconnect washer. This allows the assembly to swivel on top of the conductor. Not shown in **FIGURE 3-2** are the garter springs that wrap around each end of the fingers to provide the contact pressure needed to withstand short-circuit blow-off forces.

Analysis of the primary disconnect configuration was performed to determine how many primary disconnect fingers and garter springs were necessary to maintain contact during short circuit events. During a short circuit event, blow-off forces push the primary disconnect fingers away from the conductor in a radial direction. The blow-off force is approximately proportional to the square of the current. The amount of current passing through each finger is equal to the total current divided by the number of fingers. Therefore, by increasing the number of fingers, less current passes through each finger, and there is subsequently a large decrease in the blow-off force per finger (for example, doubling the quantity of fingers reduces the blow-off forces by a factor of four). It is assumed that radial force from the garter springs is applied equally to all of the fingers. The force on each finger is equal to the total radial force divided by the quantity of fingers.

FIGURE 3-3 shows the results of the primary disconnect blow-off force analysis. The force per finger, on the y-axis, is plotted as a function of the number of fingers, on the x-axis. The dashed lines plotted along the graph indicate the predicted spring force applied to each finger by the garter spring(s). The solid line indicates the blow-off force that occurs at peak short circuit current. The graph shows that the blow-off force decays more quickly than the spring force per finger as the quantity of fingers is increased. The results indicate that a primary disconnect with one garter spring per side and 17 primary disconnect fingers adequately withstands the calculated blow-off forces, indicated by the intersection point of the two curves. An additional spring, identical to the first, is provided for redundancy, in the event that one spring is damaged or experiences excessive wear. The primary disconnect analysis was performed for the worst case short circuit current of the 12 kV circuit breaker. The same disconnects are then used on the 24 kV circuit breaker that has a lower short circuit rating.

3.2.3 Primary Conductors

The key function of the vacuum circuit breaker primary conductors is to provide a current carrying path from the primary disconnect to the vacuum circuit breaker bottle. The primary conductor must also have an ample amount of conducting material to minimize losses from electrical resistance and to provide adequate heat dissipation at the maximum steady state current.

FIGURE 3-4 shows the circuit breaker conductor assembly. The conductor is made of a 50.8-mm diameter copper bar. One end of the conductor is internally threaded to mount the stud support of the primary disconnect assembly. A mounting bracket is brazed onto the other end and fastened to the heat sink. The conductors for both the 150 kV and 250 kV BIL configurations are rated for 2,000 amps and are insulated to their required voltage rating using Raychem heat shrink insulation. In addition to the Raychem insulation, the 250 kV BIL configuration also utilizes Lexan tubing to achieve the increased BIL rating.

3.2.4 Vacuum Interrupters

TABLE 3-1 and **TABLE 3-2** show the requirements for the vacuum circuit breakers including the requirements for the vacuum interrupters. Cutler-Hammer/Westinghouse was selected from an array of manufacturers to provide the vacuum interrupters. Cutler-Hammer is a domestic supplier of vacuum interrupters that are reliable, compact, and cost effective. One vacuum interrupter will satisfy both current ratings for the 12 kV (150 kV BIL) applications, and another vacuum interrupter will satisfy both current ratings for the 24 kV (250 kV BIL) applications. The overall size and stroke of the two bottles are similar, therefore minimum differences between the two operating mechanisms and circuit breaker configurations are required. Both bottles use an axial magnetic contact design that is utilized in approximately 10,000 vacuum interrupters currently in service.

FIGURE 3-5 and **FIGURE 3-6** show the manufacturer's specification and outline drawing for the 12 kV vacuum interrupter, and **FIGURE 3-7** and **FIGURE 3-8** show the manufacturer's specification and outline drawing for the 24 kV vacuum interrupter. Note that all of the specifications, including the rated frequency of 25 Hz, BIL ratings of 150 kV and 250 kV respectively, and short circuit ratings of 25 kA and 12 kA respectively, all comply with SEPTA requirements. The mechanical life rating of 30,000 operations and electrical life of 10,000 continuous current switching operations also comply with SEPTA requirements.

3.2.5 Operating Mechanism

The design of the operating mechanism began with extensive industry research and trade studies, to review and compare the available vacuum interrupter operating mechanism designs and technology. Also considered was SPD's substantial experience in the design of high-endurance circuit breaker operating mechanisms. As a result, the design of the SEPTA vacuum circuit breaker operating mechanism, shown in **FIGURE 3-9**, is based on a heritage SPD mechanism which has been qualified for over 20,000 operations. The wipe mechanism is similar to industry standard designs, with consideration given to technical input from the bottle manufacturer. Parts are sized to be consistent with vacuum circuit breaker loading, and commercial off-the-shelf products will be procured when possible. Commonality between the 12 kV mechanism and 24 kV mechanism is maintained wherever feasible. The only significant difference is expected to be the length of the operating rod, due to the difference in required BIL clearance distances.

The operating mechanism design meets all requirements as indicated in **TABLE 3-1**. The mechanism is a spring-charged, stored energy type mechanism, consisting of all the necessary equipment required for circuit breaker operation. "Operation" includes tripping (opening) and closing of the circuit breaker main contacts, as well as charging of the closing springs. Provisions are included to perform all operations manually as well as electrically in the appropriate circuit breaker positions as described in **TABLE 3-4**. The mechanism has a mechanical switching capability of 20,000 operations, to include a continuous current switching capability of 10,000 operations. The mechanism is mechanically and electrically trip free. The wipe mechanism is the portion of the operating mechanism that supplies the appropriate contact pressure and transfers the closing and opening energy into vertical motion of the vacuum interrupter contact. The 12 kV wipe mechanism is designed to close and latch against short circuit currents of 25 kA. The 24 kV wipe mechanism is designed to close and latch against short circuit currents of 12 kA (at 24 kV) as well as 8 kA (at 36 kV).

The general arrangement of the operating mechanism, shown in **FIGURE 3-9**, is based on a heritage SPD mechanism. Parts have been scaled to approximately 70% of their original height and depth to be consistent with vacuum circuit breaker loading. The overall width of the

mechanism frame structure will remain approximately the same in order to facilitate assembly and accommodate the use of standard bearing sizes. The operating linkage is supported by a frame structure, which is bolted near the front of the circuit breaker truck in eight locations, and offset from the circuit breaker centerline. A jackshaft extends to the center of the breaker where the wipe mechanism linkage is attached. The wipe mechanism linkage extends directly below the vacuum interrupter, where a bellcrank pivot joint is located. The bellcrank pivot transforms the linear motion provided by the jackshaft to the vertical motion required by the vacuum interrupter. The bellcrank pivot is supported by a mounting bracket that is bolted to the circuit breaker truck. The vertical portion of the wipe mechanism is a non-conductive operating rod that is long enough to accommodate the BIL clearance distance required. Candidate materials for the operating rod include red-glass polyester, G-10, or equivalent. Interface to the vacuum interrupter moving contact is accomplished inside the lower support structure with a threaded coupling rod. A bearing mounted in the support structure minimizes misalignment between the vacuum interrupter contacts. The close solenoid and shunt trip solenoid are mounted on one side of the operating linkage frame, and the charging motor is flange-mounted on the opposite side.

The operating mechanism also includes the following features: an electrical charging motor, a shunt trip solenoid, a closing solenoid, an opening buffer, a closing spring charge indicator, an open / close status indicator, a contact erosion indicator, an anti-pump mechanism, and an anti-rebound latch. Electrical signals for an operations counter and open/close indicating lights are provided through auxiliary switches. Interfaces to the vacuum interrupter, truck and withdrawal mechanism interlocks are also provided.

The mechanism is designed to operate the following vacuum interrupters per the supplier's specifications: Cutler-Hammer #WL-35632P (12 kV) and Cutler-Hammer #WL-35561P (24 kV). There will be minor differences between the mechanism that operates the 12 kV bottle and the one that operates the 24 kV bottle, driven by the respective differences in the bottle manufacturer's specifications. The bottle parameters which most directly impact the design of the operating mechanism are the stroke distance and minimum required contact force, indicated for the two bottles in **FIGURE 3-5** and **FIGURE 3-7**. Since the two bottles have

similar stroke distances, only a minor modification in the location of the jackshaft interface with the wipe mechanism is necessary. Furthermore, designing the wipe spring to provide the maximum of the two values of required contact force could accommodate this difference with the same wipe spring assembly. The similarity between the two bottles, allowing the use of substantially similar operating mechanisms, is a distinct advantage of using the above Cutler-Hammer vacuum interrupters. The mechanism could also be easily modified in the future for use with any other bottle with similar design parameters.

Closing operations are performed using a closing spring assembly, which provides the energy necessary to close the vacuum interrupter at the manufacturer-specified speed, as well as charge the opening and wipe springs. During a closing operation, as detailed in **FIGURE 3-10 and FIGURE 3-13**, the interrupter contacts touch near the end of the operating mechanism stroke, at which point contact force is provided by a single, preloaded wipe spring. The remainder of the operating mechanism stroke is used to further compress the wipe spring to provide sufficient contact pressure at maximum allowable contact erosion. The level of contact pressure, specified by the vacuum interrupter manufacturer, is required to withstand short circuit blow off forces, and to minimize contact resistance. Energy stored in the compressed wipe spring is used to assist the opening stroke.

Shunt trip/opening operations, detailed in **FIGURE 3-11**, are performed using an opening spring assembly, which together with the wipe spring provides the energy necessary to open the vacuum interrupter contacts at the manufacturer-specified speed. The opening system is provided with a buffer, or damping mechanism, to decelerate the contacts and limit overtravel and rebound per the vacuum bottle manufacturer's recommendations. An anti-rebound latch is also provided to further limit rebound of the jackshaft and to prevent a restrike of the interrupter contacts.

Electrical charging of the closing spring, detailed in **FIGURE 3-12**, is provided by a parallel shaft permanent magnet DC gear motor. An offset roller on the motor output shaft rotates the charge lever back and forth. This action drives the charging linkage up and down, which indexes the ratchet wheel. The motor automatically charges the springs, immediately upon

closing spring discharge, as long as control power is available. Conceptual charging motor parameters and specifications are listed in **TABLE 3-3**. The electrical charging cycle is completed in 12 seconds or less, at voltages from 100-136 VDC. A charging crank handle is provided for manual charging of the closing springs.

Analysis of the operating mechanism is performed using 3-dimensional computer models and state-of-the-art software for the dynamic simulation and analysis of mechanical systems. The analyses are iterative processes, in which results are compared to system requirements, and the designs and models are modified and reanalyzed as necessary. Both the trip/close model and the charging model are complete and running. Wipe spring, opening spring, and closing spring gradients have been determined, and verified by contact pressure, opening speed and closing speed measurements, respectively. Requirements for the charging motor torque and speed have been determined. Analysis iterations continue as the details of the design are finalized.

A dynamic model of the tripping and closing systems, shown in **FIGURE 3-13**, simulates both a closing and opening stroke, and calculates forces and motion behavior of the entire mechanism. The results are used to determine contact stroke, opening and closing speed, contact pressure, rebound and overtravel, stresses in parts, loads in pins and bearings, and forces necessary for tripping and closing. A sample time-history plot of the contact stroke through one complete close-open cycle is shown in **FIGURE 3-14**. The y-axis represents the travel of the moving contact with 0 mm representing the contacts in the open state. As indicated on the plot, closing speed and opening speed are within the ranges specified by the bottle manufacturer. Overtravel of the opening stroke is controlled by a damper, and is also within the manufacturer-specified limit. A sample plot of contact force is shown in **FIGURE 3-15**. At least eighty percent of the total required contact force is available as soon as the contacts touch, as recommended by the bottle manufacturer. The additional force induced by the external atmospheric pressure is included in this plot.

A quasi-static model of the charging system, shown in **FIGURE 3-16**, simulates a complete electrical or manual charging cycle. Closing spring gradients determined from the trip/close model, described above, are used in the charging model to determine charging motor torque requirements, stresses in parts, and loads in pins and bearings. A sample plot of the force on the motor roller is shown in **FIGURE 3-17**. The eleven peaks shown in the plot represent the intermittent contact force between the offset motor roller and the charging lever and they indicate that eleven revolutions of the motor output shaft are required to completely charge the springs. This corresponds to a minimum motor output speed of 55 revolutions per minute to comply with the 12-second charging time requirement. The maximum value of each peak load decreases at the end of the charging cycle as the mechanism linkage goes over-center and mechanical advantage increases. Slight dips in the peaks are a result of the ratcheting action of the mechanism.

3.2.6 Support Structures

Support structures include the upper and lower insulators, the upper and lower heat sink/support housings (including flexible and rigid conductors), and the insulating struts, all of which can be seen in **FIGURE 3-1**. The insulators bolt to the vertical frame of the truck and support the heat sink/support housings, which in turn support the primary conductors and the vacuum interrupter. Non-conductive struts connect the upper and lower heat sink/support housings so that they share the mechanical loads transmitted through the vacuum interrupter during opening and closing operations. The heat sink/support housings are insulated with heat shrink insulation.

The insulators are commercially available off-the-shelf items that meet NEMA SG6 requirements. They are made of Polykeram, a material similar in properties to porcelain and epoxy, but less expensive and easier to manufacture. Polykeram has replaced porcelain and cycloaliphatic epoxy in many modern applications. The insulator is sized for the 150 kV BIL rating, and commonality of parts is achieved for both voltage classes by using the same insulator in conjunction with Raychem insulation for the 250 kV BIL applications. This is standard industry practice. **FIGURE 3-18** shows the insulator and its properties.

Two design options for the heat sink / support housing are being evaluated for performance, producibility and cost effectiveness. The first option, shown in **FIGURE 3-19**, utilizes an aluminum "bowl" as the mechanical structure and heat sink. The second option, shown in **FIGURE 3-20** uses steel or aluminum square tubing as the support structure. Both upper heat sink/support housings bolt to the top of the fixed electrode of the vacuum interrupter. A rigid, copper conductor is used inside each upper heat sink/support housing to connect the primary conductor to the fixed electrode of the vacuum interrupter. One size of the rigid connector is used for all applications. Both lower heat sink/support housings have pilot holes in the top surface to locate the bottom of the vacuum interrupter by trapping the outside diameter of the vacuum interrupter bushing. Both lower heat sink/support housings have provisions for a bushing in the lower surface to guide the operating rod of the wipe mechanism and minimize misalignment of the vacuum interrupter contacts. Current and heat are conducted from the movable electrode of the vacuum interrupter, through the flexible conductors and the copper plate mounted inside the heat sink/support housing, into the primary conductors.

Flexible laminated shunts, shown in **FIGURE 3-19**, are used inside each lower heat sink/support housing to connect the primary conductor to the movable electrode of the vacuum interrupter. A series of thin copper laminations is formed, stacked and welded together at each end forming a one-piece flexible shunt. Slots may be incorporated into the laminations to reduce the effective spring force of the assembly and improve heat dissipation. Two of these shunts are required to conduct 2,000 amps, and they are located symmetrically to the right and left of the centerline of the heat sink/support housing. Advantages of the flexible shunt design are its compact size, high reliability, cost effectiveness, and stability during a short circuit event. Similar flexible laminated shunts have been used in military applications and have been demonstrated at an endurance rating of 25,000 cycles.

3.2.7 Trucks

The function of the vacuum circuit breaker truck is to provide a mounting structure for the circuit breaker assembly, and the mobility to move the circuit breaker in and out of the cubicle. The truck must be strong and stiff enough to withstand the loads incurred during insertion of the circuit breaker into the cubicle, the loads during closing and opening operations, and short circuit forces.

FIGURE 3-21 shows the circuit breaker truck assembly. The truck consists of a vertical frame, a base, and wheels. The vertical frame is constructed of formed 11-gauge sheet steel with c-channel stiffeners welded to the front. The vertical frame is welded to the truck base, which consists of a 3.2-mm thick plate welded between two rectangular tubes (76.2 mm high x 50.8 mm wide x 3.2 mm thick). The base provides stiffness along with provisions to mount the wheels and a manual withdrawal handle. The truck base is common for both the 12 kV and 24 kV vacuum circuit breakers, however the height of the vertical frame is different due to different spacing between conductors.

Steel wheels provide mobility inside and out of the cubicle. The wheels on the left side of the truck have two raised surfaces that form a v-groove to constrain the truck's movement from side to side when riding on the rails inside the cubicle. The wheels on the right side have one raised surface and do not constrain the side to side movement of the truck, eliminating the need to manufacture the truck and cubicle to tight tolerances. The raised surfaces serve as the rolling surfaces of the wheel when the truck is outside of the cubicle. More detail on the wheels and rails is included in section 6.2.4. The truck wheel base and track are 559 and 562 mm respectively.

3.2.8 Operation and Control Provisions

Operation and control provisions for the vacuum circuit breakers include the withdrawal mechanism, rails, interlocks, secondary disconnects, and interfaces between the circuit breaker and switchgear.

The withdrawal mechanism consists of a center-mounted leadscrew with bearings and a floating nut plate mounted inside the cubicle. The nut plate is attached to the circuit breaker with a spring-loaded latch and handle, as shown in **FIGURE 3-21**. Withdrawal (or racking-out) of the circuit breaker is accomplished by inserting the manual withdrawal tool through the opening in the front of the cubicle, engaging the hexagonal nosepiece of the leadscrew, and turning the handle clockwise. Insertion of the withdrawal tool automatically trips the circuit breaker. Turning the handle counterclockwise racks the circuit breaker into the cubicle. For more detail on the withdrawal mechanism, see section 6.2.4.

The mechanical interlocks, shown in **FIGURE 3-22**, are comprised of roller cam followers mounted on pivoted levers. The levers are connected to the trip and close latches of the operating mechanism through mechanical linkages. Linear cams mounted in the cubicle activate the cam followers during rack-out and rack-in to prevent accidental trip and close operations. See section 6.2.4 for more detail on the mechanical interlocks.

There are four indexed positions of the circuit breaker: connected, test, disconnected, and withdrawn. **TABLE 3-4** indicates the four positions and summarizes which operations (tripping, closing and charging) are possible in each position. Racking the breaker into the connected position automatically opens the protective metal shutters mounted within the cubicle, and engages the primary and secondary disconnects. All electrical and mechanical operations are possible in the connected position. Insertion of the manual withdrawal tool is prevented when the circuit breaker is closed in the indexed connected position. The breaker must be tripped by manual or electrical means before the manual withdrawal tool can be inserted. This prevents accidental tripping of a closed or in-service breaker.

Racking the circuit breaker into the indexed test position automatically trips the breaker, disengages the primary disconnects, closes the metal shutters, and engages the secondary disconnects. With the circuit breaker in the test position, adequate clearance between the "live" primary disconnect and the component is ensured so that all electrical and mechanical tests can be performed safely. The circuit breaker is held "trip free" between indexed withdrawal positions preventing the contacts from closing.

Racking the circuit breaker into the disconnected position automatically trips the breaker, discharges the closing springs, and disengages the secondary disconnects. No electricity is available for operations in this position, but manual charging of the closing springs is possible with the cubicle door open. The interlock mechanism holds the breaker "trip free" which prevents the contacts from closing in the disconnected position.

Racking the circuit breaker out from the disconnected position automatically trips a closed breaker, discharges the closing springs, and places the circuit breaker in the withdrawn position. No electricity is available through either the primary or secondary disconnects, but secondary power and control may be obtained through the use of a secondary test cable. No mechanical interlocks are activated in the withdrawn position, so manual operation of the circuit breaker is possible.

To ensure operation of the circuit breakers at the appropriate current and voltage levels, provisions have been added to the circuit breaker trucks and cubicles such that a cubicle will only accept a circuit breaker with the appropriate rating. A series of "keying" plates is attached to the individual trucks with mating plates attached to the corresponding cubicles.

3.2.9 Compliance to Applicable Specifications and/or Practices

TABLE 3-1 indicates the compliance of SPD's vacuum circuit breaker design with the key design requirements. The vacuum circuit breaker designs comply with all applicable SEPTA and industry standards.

SECTION 4.0 DISCONNECT SWITCHES

4.1 REQUIREMENTS REVIEW

The scope of work for the design of the disconnect switches includes the development of two types of 25 Hz, 1-phase 1,200 amp / 2,000 amp continuous current components. The first is a 24 kV no-load break disconnect switch, with a 105 kV nominal frequency withstand voltage, and 250 kV BIL withstand voltage capability. The second is a 12 kV no load break disconnect switch, with a 60 kV nominal frequency withstand voltage, and 150 kV BIL withstand voltage capability.

The requirements for the design of the disconnect switches were compiled from **Reference 1** and applicable industry standards including ANSI, IEEE, NEMA and NEC. In addition, standard industry practices have been used to guide the design to ensure safety and reliability. **TABLE 4-1** lists the key applicable requirements considered in the design of the disconnect switches.

4.2 TECHNICAL DISCUSSION

4.2.1 General Arrangements

Initial market research indicated that none of the disconnect switches available satisfy the key requirements of the SEPTA project. The high BIL rating and the corresponding clearance distance required around all conductive components, combined with the dimensional restrictions, make the use of a knife-type disconnect switch impractical.

Drawout-type disconnect switches were chosen because of their smaller size and their similarity to the vacuum circuit breakers. Parts common to the disconnect switches and circuit breakers include the trucks, withdrawal mechanisms, disconnect bushings and tulip-type primary disconnects.

One type of disconnect switch is used for all applications with minor differences, including the height of the truck uprights, the length of the center part of the conductor, and the type of insulation. Motor-operated switches include a motor mounted inside the cubicle.

The major technical design challenge is the high BIL levels. Attention to electrostatic issues including insulation and elimination of sharp corners is necessary. The conceptual design of disconnect switches is simple, cost effective and reliable.

SPD's design goals for the disconnect switches include:

- Robust, simple design
- Commonality of parts (especially sharing parts with vacuum circuit breaker)
- Minimum maintenance
- Ease of installing and removing switches
- Minimum number of operating and/or maintenance tools
- Adaptability of one basic design to cover all disconnect switches, including motor operated switches
- Utilization of proven technology wherever possible (for reliability)
- Utilization of domestic suppliers wherever possible

FIGURE 4-1 shows the general arrangement of the four types of disconnect switches. Switches for the 24 kV applications are the same as the switches for the 12 kV applications with additional insulation to meet the 250 kV BIL requirement. The disconnect switch trucks are similar to the vacuum circuit breaker trucks, utilizing a center-mounted leadscrew and guide wheels. Insulators, primary conductors, and insulation are also of the same types as those used on the circuit breakers. The conductor clamps are off-the-shelf items, shown in **FIGURE 4-1** and **FIGURE 4-7**. The projected overall weight of the largest switch is 95 kilograms.

Two concepts for the ground switch are currently being investigated, and are shown in **FIGURE 4-2** and **FIGURE 4-3**. These switches are used during maintenance operations to remove any residual charge the switchgear circuit may have. SPD has developed a design that incorporates knife blade-type switches in the switchgear cubicles. The switches are actuated with the same tool that withdraws the manually operated power components. Using a gearbox with a 4:1 gear ratio, one full 360° rotation closes the switch. The switch contacts are silver-plated and the live portion of the switch is fully insulated to be consistent with the switchgear BIL levels. The switch concepts presented are being evaluated for electrostatic properties, and their final configuration may change before prototype fabrication begins.

4.2.2 Primary Disconnects

The function of the primary disconnects is to provide a low-resistance contact between the bus structure and the disconnect switches. The primary disconnects for the disconnect switches are the same tulip assemblies that are used for the circuit breakers. See section 3.2.2 for a complete description.

4.2.3 Primary Conductors

The function of the disconnect switch primary conductor is to provide a conducting medium for the primary current path. The primary conductor must also have sufficient conducting material to minimize losses from electrical resistance and to provide adequate heat dissipation at the maximum steady state current.

FIGURE 4-4 shows the disconnect switch primary conductor assemblies. The conductor bars are made from 50.8-mm diameter copper bars. The primary conductor for the 12 kV small switch is composed of two identical copper bars, each with a 90-degree bend. The 24 kV disconnect switch primary conductor assemblies utilize a straight conductor bar of various lengths clamped between the two 90-degree conductors to be consistent with the required contact spacing. The conductors are clamped together using the conductor support clamp shown in **FIGURE 4-7**. The ends of the conductor are internally threaded to mount the stud support of the primary disconnect assembly. The conductors are rated for 2,000 amps and are insulated to be consistent with their voltage rating.

4.2.4 Trucks

The function of the disconnect switch truck is to provide a mounting structure for the disconnect switch assembly, and the mobility to open and close the primary disconnect switch. The truck must be strong and stiff enough to withstand the loads incurred during insertion of the disconnect switch into the cubicle.

FIGURE 4-5 shows the disconnect switch truck assembly. The assembly is substantially similar to the circuit breaker truck, and utilizes four configurations to satisfy all SEPTA applications. Each configuration has a different overall height, driven by the height of the primary conductor, shown in **FIGURE 4-1**. The truck base and track are common among all of the disconnect switches and circuit breakers. The steel wheels on the disconnect switch trucks are also the same as those used on the circuit breaker trucks.

Analysis of the truck was required to verify that it has adequate stiffness and strength. The largest operating load on the truck occurs during insertion of the component into the cubicle. To ensure full engagement of the primary disconnects, neither contact could deflect more than 6.4 mm. A maximum design value of 3.2 mm was used to include a margin for safety. Test results on primary disconnects indicate that a maximum load of 72.6 kilograms-force is required to fully insert the conductor into the primary disconnect. A finite element analysis was performed on each of the disconnect switch trucks simulating the maximum insertion loads that each truck would see during normal operation. The 24 kV disconnect switch experienced the greatest deflection of 2.7 mm, which is less than the maximum design value. The results of the analysis also showed that the yield strength of the truck exceeded the maximum operational stresses by a factor of three. The analysis results showing the maximum displacements and maximum stresses for the various truck configurations are presented in **FIGURES 4-6A** through **4-6D**. The stress distribution imparted on the truck during insertion into the cubicle is depicted on the right side of each figure. The stresses are highest in the areas around the insulators. An exaggeration of the deflections of the truck is depicted on the left side of each figure. The top primary disconnect undergoes a larger deflection than the lower one because the truck is stiffer at the base. These results demonstrate that the primary conductor and truck base experience negligible deformation relative to the vertical frame. The

vertical frame deforms because of the large loads being transmitted down the middle of the flat rectangular plate. To reduce these deformations, c-channel stiffeners are placed across the frame behind the insulator. These features, while adding negligible weight to the assembly, distribute the loads more evenly, resulting in an 800% improvement in the overall stiffness.

4.2.5 Operation and Control Provisions

The state of the disconnect switches can be changed either manually or electrically. Manual operation is similar to the racking operation of the circuit breakers. The manually operated switches are actuated by inserting the withdrawal tool through the opening in the cubicle, engaging the hexagonal nosepiece of the leadscrew, and turning the handle. Clockwise rotation moves the disconnect switch to the disconnected position, and counterclockwise rotation moves the switch into the connected position. The mechanical position indicator indicates the position of the disconnect switch. Position is also indicated electrically by position-indicating switches that are installed in the cubicle and activated by tabs on the truck. In the connected position, the primary disconnects are automatically engaged, and the protective metal shutters are opened. In the disconnected position, primary conductors are disengaged, the metal shutters are automatically closed, and adequate clearance between the "live" primary disconnects and the component is provided.

Motor-operated switches are activated either remotely, or from the front of the cubicle. Electricity is delivered to the motor, and power is transmitted through a flexible shaft behind the leadscrew. Power is stopped automatically when the appropriate position-indicating switch is activated. A manual override feature allows for manual operation of the switch should there ever be a problem in which the motor system does not operate the switch (due to unavailability of control power or a motor failure). To ensure insertion of the correct disconnect switch into a cubicle, a series of "keying" plates is attached to the individual trucks with mating plates attached to the corresponding cubicles.

4.2.6 Compliance to Applicable Specifications and/or Practices

TABLE 4-1 indicates the compliance of SPD's disconnect switch design with the key design requirements. The disconnect switch designs comply with all applicable SEPTA and industry standards.

SECTION 5.0 BUS STRUCTURE

5.1 REQUIREMENTS REVIEW

The key requirements for SPD's design of the bus structure were compiled by combining the requirements found in **Reference 1** with applicable industry standards including ANSI, IEEE, NEMA and NEC. In addition, standard industry practices have been used to guide the design to ensure safety and reliability. The key requirements are as follows:

- Operates at 1,200 amps / 2,000 amps, 24 kV/12 kV and 25 Hz nominally
- Insulated to withstand either 150 kV or 250 kV BIL
- Insulated to withstand 25 Hz nominal frequency voltages of 60 kV or 105 kV
- Compact design with provisions incorporated to permit future expansion
- Fabricated from high conductivity copper alloy with silver plated contact areas

5.2 TECHNICAL DISCUSSION

5.2.1 General Arrangements

During Phase I of this project, SPD overcame many significant technical challenges to develop a bus structure arrangement that meets all of the project's stated design goals. The stringent requirements for indoor, metal-clad equipment at the stated BIL ratings dictated that SPD look for design solutions other than those typically used in the industry. For example, in order to pass live conductors through grounded compartment walls, while maintaining very high levels of insulation to ground (for safety), SPD used the concept of capacitively graded layers embedded in epoxy insulation. Using this well-proven approach that is usually applied to outdoor entrance bushings, the fixed and disconnect wall bushings were developed and analyzed. A detailed description of the analyses performed and the results obtained are presented in section 8.0. Subsequently, a method of coupling these elements was developed

that not only took into account the current carrying and thermal characteristics of the system but also the electrostatic characteristics. SPD then performed an exhaustive industry survey to determine the type of insulation required for the interconnecting bus structure and the corresponding spacing to ground. Using these building blocks, SPD developed the bus structure arrangement depicted in **FIGURE 5-1**. All five cubicle types required by **Reference 1** are depicted. The key feature of the arrangement is that the bus runs (main, test and transfer) are not continuous copper bars. Instead, they are a modular build-up of common components. This benefits the project in many ways, but most significantly, in the areas of product cost and ease of future expansion.

The bus structure arrangement is a modular build up of five basic elements: fixed wall bushings, disconnect wall bushings, junction couplers, interconnecting bus structure, and heat-shrinkable insulation. A typical 3-way branch circuit, utilizing a spherical junction coupler to connect the bushings together, is depicted in **FIGURE 5-2**. An insulated junction coupler connects the fixed wall bushings to form the required bus run. At the junction coupler, power is "tapped" off and fed to an individual power component through a disconnect wall bushing. The spherical coupler represents the optimal shape from an electrostatic and thermal management perspective; however this concept may prove to be cost-prohibitive. **FIGURE 5-3** presents a more cost effective and compact approach that SPD is also considering.

5.2.2 Disconnect Wall Bushings

SPD, working with Piedmont Dielectric (PDC), developed the primary disconnect wall bushing concept presented in **FIGURE 5-4**. This bushing is shown in the operating condition, with the primary conductor of the power component engaged. These bushings are capacitively graded to manage the electric field stresses in very a compact envelope. The layers are precisely spaced within the epoxy, to reduce the voltage potential gradually from the high voltage at the internal conductor surface to the grounded outer surface of the bushing where current transformers are located. In order to meet the 250 kV BIL rating, the power component primary conductor has additional insulation applied.

The manufacturing process of these bushings is meticulously controlled and extensive testing is performed during fabrication to ensure the integrity of the capacitative layers. If warranted, the integrity of the individual bushings can be checked even after the initial field installation of the switchgear. These bushings have been utilized for over 20 years in the field, and have demonstrated a very high reliability rate over the design operating conditions. They have never suffered a catastrophic failure. In some cases, a degraded condition might occur whereby one of the embedded capacitive layers is compromised, as shown qualitatively in **FIGURE 5-7**. SPD analyzed this condition and showed that the field potential is simply redistributed over the remaining layers. Though the total dielectric capability is slightly reduced, the bushing still performs the main function of insulating the bus structure from the metal-clad enclosure.

The bushings to be used on the 12 kV switchgear are 55.9 cm long, 16.5 cm in diameter, weigh 38 kg, and are rated for either 1,200 amps or 2,000 amps continuous and 150 kV BIL. This is significantly smaller than a similarly rated molded type of bus insulator, resulting in a smaller overall switchgear cubicle. Similarly, the 24 kV bushings are 74.3 cm long, 21.6 cm in diameter, weigh 45 kg and are rated for either 1,200 amps or 2,000 amps continuous and 250 kV BIL. The main current carrying portion of these bushings is a circular copper conductor that is mounted in the center of the epoxy. This conductor has silver plating on the contact areas where the power component "tulips" engage and where the junction coupler engages. The 1,200-amp bushings use a tubular conductor that has an internal diameter of 22.8 mm and an external diameter of 50.8 mm, while the 2,000-amp bushings use a solid 50.8-mm diameter conductor in order to limit the temperature rise of the element to a maximum of 50°C.

The bushing is bolted firmly in place inside the cubicle enclosure through a four-hole pattern in an aluminum mounting flange that is part of the bushing. When the bushing is not in service, a grounded metal shutter automatically moves in front of the bushing's power component opening to provide a measure of safety for SEPTA maintenance personnel. This shutter is shown in **FIGURE 5-5**.

PDC has been manufacturing this type of wall bushing rated up to 150 kV BIL successfully for many years. Based on the analyses and correlation studies done to date, SPD is very confident that these new designs will meet or exceed SEPTA's expectations.

5.2.3 Fixed Wall Bushings

In concert with the development of the disconnect wall bushings, SPD developed the fixed wall bushings presented in **FIGURE 5-6.** These bushings are also capacitively graded to manage the electric field stresses. The layers are precisely spaced within the epoxy, to reduce the voltage potential from the internal conductor surface to an aluminum mounting flange where the bushing mounts directly to the cubicle wall. This allows a live conductor to be passed through a grounded barrier in a minimal amount of space.

The bushings to be used on the 12 kV switchgear are 48.3 cm long, 9.2 cm in diameter, weigh 18 kg, and are rated for either 1,200 amps or 2,000 amps continuous and 150 kV BIL. The 24 kV bushings are 50.8 cm long, 10.2 cm in diameter, weigh 20 kg, and are rated for either 1,200 amps or 2,000 amps continuous and 250 kV BIL. The main current-carrying portion of these bushings is a solid 50.8-mm diameter copper conductor that is embedded in the center of the epoxy. The conductor has silver plating on both ends where the junction couplers engage. The bushing is bolted firmly in place through a four-hole pattern in an aluminum mounting flange that is part of the bushing.

5.2.4 Junction Couplers

To connect the bushings together electrically, thermally and mechanically, SPD addressed the issue of a junction coupler, and developed several candidate concepts. The first concept is a spherical junction coupler, depicted in **FIGURE 5-8**. The spherical coupler represents the optimum shape for uniform electric field generation, thermal convection and radiation and structural rigidity. This concept is a 4.5-kg, three-piece "split-clamp" design, with the dimensions as shown, that would accept up to four mutually perpendicular conductors. It is an investment casting made from a high-conductivity copper alloy with silver-plated contact areas. Through an iterative design and analysis process assisted by the latest CAD software packages, SPD developed a second, more compact design solution for the junction coupler that is presented in **FIGURE 5-9A** and **FIGURE 5-9B**. These couplers more closely resemble the "split-clamp" designs commercially available. They are also copper castings with silver plated contact areas. SPD took advantage of several features, including external radii and bulk mass, to develop a concept that is comparable to the ideal sphere with regards to strength, thermal and electrostatic properties. A qualitative comparison between the two concepts is presented as **TABLE 5-2**. Cost, logistics and overall switchgear sizing are the major design parameters that SPD is considering in the final selection process.

5.2.5 Conductors and Insulation

The placement of the bus runs, and the required connections between them, along with the metal-clad requirement that each bus run be isolated in its own compartment, drove the overall sizing of the cubicles. Once this sizing was established, SPD developed the additional interconnecting bus structure required to facilitate the switchgear functionality. The conductors used for the interconnecting bus structure are solid 50.8-mm diameter copper rods that are silver-plated where they engage a junction coupler. Round conductors are used to provide uniformity of the electrostatic fields generated around the conductors. The diameter of the conductors, like that used in the bushing designs, is sized to keep the insulation operating temperatures below 90°C which corresponds to the temperature rise limit specified by the insulation manufacturers.

The insulation applied to the interconnecting bus structure and the junction couplers is 3.175-mm thick Raychem heat-shrinkable sleeve. The Raychem insulation material properties are presented in **FIGURE 5-10**. This material is widely used as insulation in the high-voltage industry, and is well suited to this application.

5.2.6 Compliance to Applicable Specifications and/or Practices

SPD has developed a unique bus structure for 12 kV and 24 kV metal-clad switchgear that results in a significantly smaller overall switchgear size than is currently available in the industry. A compliance assessment and summary of the key technical requirements and goals for the bus structure are presented in **TABLE 5-1**.

SECTION 6.0 SWITCHGEAR

6.1 REQUIREMENTS REVIEW

The requirements for SPD's design of the 12 kV and 24 kV medium voltage switchgear were compiled by combining the requirements found in **Reference 1** with the applicable industry standards including ANSI, IEEE, NEMA and NEC. In addition, standard industry practices have been used to guide the design to ensure safety and reliability. **TABLE 6-1** lists the key applicable requirements considered in the design of the switchgear.

6.2 TECHNICAL DISCUSSION

6.2.1 General Arrangements by Cubicle Type

Reference 1 defines the basic cubicle types and their respective functionality required to meet all of the design goals. The five basic types defined by SEPTA are:

- 12 kV or 24 kV Main Bus Incomer cubicle
- 12 kV Trolley Circuit Breaker or 24 kV Feeder Circuit Breaker cubicles
- 12 kV or 24 kV Transfer Circuit Breaker cubicle
- 12 kV or 24 kV Fault Test cubicle
- 12 kV or 24 kV Bus-Tie cubicle

In the 12 kV switchgear, the Main Bus Incomer (BI) cubicle is where power fed from the Philadelphia Electric Company (PECO) through SEPTA's main power substation enters the switchgear. In this cubicle, the power comes in through a takeoff structure on the rear of the cubicle and connects to the main bus through a manually operated disconnect switch. The arrangement of this cubicle is presented as **FIGURE 6-1**. This cubicle also features a Main Bus Grounding Switch to ground the main bus during maintenance operations, and a potential

transformer to monitor the voltage of the incoming power. The corresponding 24 kV BI cubicle, a general layout of which is presented as **FIGURE 6-6,** is arranged and functions identically to the 12 kV BI cubicle, only at different voltage and BIL levels.

The 12 kV Trolley Circuit Breaker (TR) cubicle feeds the traction power to the overhead catenary lines that feed SEPTA's trains. As shown in **FIGURE 6-2**, this cubicle is made up of two cubicles, placed side-by-side, that are extensively interconnected. This cubicle contains the following features:

- A 1,200-amp circuit breaker that feeds the traction power system
- A grounding switch to isolate an individual trolley circuit during maintenance operations
- A test bus disconnect switch to connect an individual trolley circuit to the fault test equipment located in the Fault Test (FT) cubicle
- A transfer bus disconnect switch that enables an individual circuit to be fed from the circuit breaker in the Transfer Circuit Breaker (TB) cubicle while that particular trolley circuit breaker is out of service.

The corresponding 24 kV Feeder Circuit Breaker (FD) cubicle depicted in **FIGURE 6-7** is arranged in the same way. The only difference between the two, other than voltage and BIL ratings, is that the FD cubicle feeds "feeder" circuits in SEPTA's system, while the 12 kV TR cubicles feed trolley circuits.

The 12 kV Transfer Circuit Breaker (TB) cubicle has a 1,200-amp circuit breaker, used to feed power when any individual trolley circuit breaker is out of service, and a transfer bus disconnect switch to connect the breaker to the trolley circuit to be fed. A layout of this cubicle type is presented as **FIGURE 6-3**. The corresponding 24 kV TB cubicle depicted in **FIGURE 6-8** is arranged identically to the 12 kV cubicle. The only difference, other than voltage and BIL ratings, is that the 24 kV cubicle feeds "feeder" circuits in SEPTA's system in the event a feeder circuit breaker is out of service, whereas the 12 kV TB cubicle feeds trolley circuits.

The 12 kV Fault Test (FT) cubicle features the equipment used to measure faults in the traction power system circuits. The cubicle has two disconnect switches that connect the equipment to the various circuits in the system. Additionally, a potential transformer is located in this cubicle to monitor the voltages in the system. An arrangement of this cubicle type is presented as **FIGURE 6-4**. The corresponding 24 kV cubicle is presented as **FIGURE 6-9**.

The 12 kV and 24 kV Bus-Tie (BT) cubicles are actually two cubicle frames side-by-side. One side houses a 2,000-amp Bus-Tie circuit breaker that is used to connect the different sections of the switchgear line-up. The other side contains interconnecting bus bars that complete the connection. The 12 kV cubicle arrangement is presented as **FIGURE 6-5** and the 24 kV arrangement is shown in **FIGURE 6-10**.

6.2.2 Wayne Junction Line-Up Arrangements

Through an extensive review of existing technologies and hardware, complimented by 3-D computer modeling and analysis techniques, SPD developed the 12 kV and 24 kV switchgear line-ups presented in **FIGURE 6-11** and **FIGURE 6-12**. These line-ups are a modular combination of the five cubicle types described in the previous section, and are fully compliant with the performance and size requirements defined in **Reference 1**. In fact, the overall line-up footprint depicted is smaller than that allocated by the SEPTA specification. The 12 kV line-up footprint is approximately 20 percent smaller than allocated, while the 24 kV footprint is 40 percent smaller. These reductions benefit SEPTA by reducing the construction costs of the new substation buildings needed to house the equipment. The 12 kV and 24 kV switchgear line-up arrangements for the outlying substations can be found in Appendix C.

6.2.3 Switchgear Enclosures

FIGURE 6-13 depicts the general arrangement of a 12 kV switchgear cubicle enclosure, incorporating all of the features SEPTA requires in **Reference 1**. For ease of manufacture and handling during the manufacturing process, the cubicle is a combination of two smaller compartments (upper and lower) that are bolted together. It has a welded angular steel frame

with 11-gauge side panels. These side panels are welded to the frame, and have mounting provisions for the fixed wall bushings that form the three major bus runs. The floor pans, located on the bottom of the lower compartment, are 7-gauge steel panels that are welded in place. Separating the bus compartments and power component compartments of the cubicle are 11-gauge panels that feature captive hardware to permit easy removal during maintenance operations. The front door panels provide hinged-door access to the power components. They have provisions for padlocking and also serve as instrumentation and relay panels. Additionally, the front doors provide sliding-door access to the power component withdrawal mechanisms, to enable an operator to manually change the position of any power component or ground switch with the cubicle door closed. The top panels are also 11-gauge steel panels, however they are perforated to allow ventilation for thermal management. Not shown in this figure, is a "cap" that will go over the panels to prevent foreign objects including dirt, dust, and debris from entering the top of the cubicle. Each bus compartment is accessible by removing six ¼-turn, captive fasteners in an individual rear panel. The front and rear doors and panels also feature ventilation louvers for thermal management. There will be screens behind these louvers to prevent penetration into the cubicle. **Reference 1** specifies that dry-type, replaceable air filters be installed behind these louvers, however after further investigation, SPD and SEPTA decided that they were undesirable. The filters would restrict airflow through the cubicle as well as provide an additional maintenance burden on SEPTA's operational staff.

Another key feature of the enclosures is that the guide rails that the power components roll on are permanently mounted inside the cubicle compartment. This helps to maintain proper alignment of the power component upon insertion or withdrawal over the expected service life of the equipment. An example of the corresponding 24 kV cubicle arrangement is presented as **FIGURE 6-14**.

SPD performed a variety of static and dynamic structural analyses to verify that the cubicles could withstand the operational and transportation loads. **TABLE 6-2** is a summary of the type of analyses that were performed, and **FIGURE 6-15** presents sample results of these analyses.

6.2.4 Operation and Control Provisions

The power components ride on guide rails when moving between the indexed positions in the cubicle. The key design challenge was to maintain the proper alignment between the disconnect bushings and the primary conductors on the disconnect switches or circuit breakers. The worst case power component was the 24 kV Test Bus Disconnect Switch, which has a center-to-center distance between the conductors of about 132 cm. This distance magnifies any misalignment from the racking mechanism on the bottom of the component to the top conductor, so it is critical to ensure that the switch does not "tip" during insertion into the cubicle. To minimize this possibility, SPD is using the concept of captured wheels, depicted in **FIGURE 6-16**. The wheels on the left side of the circuit breaker have machined v-grooves on either side of the surface that contacts the guide rails. These grooves restrain the wheels, within a predetermined tolerance zone, along the horizontal axis perpendicular to the travel of the power component. The modified C-channel rail restrains the wheel along the vertical axis of the power component. One side of the power component is therefore restrained in all axes except the translational axis of motion desired, which is parallel to the axis of the withdrawal mechanism. The other pair of wheels only restrains the power component in the vertical axis. This allows the relaxation of the tolerance on the width of the cubicle, while providing smooth motion of the power component along the axis of travel.

FIGURE 6-17 shows the general withdrawal mechanism arrangement. A steel leadscrew with ball bearings on each end is centered in the switchgear cubicle. The bearings are pressed into steel bearing blocks that are bolted to the cubicle through a support frame that is not shown. The leadscrew nut is pressed into a steel draw block that traverses along the axis of the leadscrew as it is rotated. The power component attaches to the draw block by means of a spring loaded latch and handle. The leadscrew terminates with a hexagonal steel nosepiece at its front. The manual withdrawal tool engages this nosepiece when manually racking the power component between its indexed positions, as described in section 3.2.8. For the power components that are not manually racked into position, a DC motor is attached to the rear of the leadscrew through a flexible shaft. This will enable them to be moved remotely by an operator through the SCADA system.

A steel position index lever has linear cam surfaces on its upper edges nearest the leadscrew that is pivoted at its rear edge around a shoulder bolt. There is a spring at the front edge of the index lever that pulls it into the draw block. The draw block actuates the lever as it traverses. A pointer on the position index lever indicates the component position on a position indicator that is visible on the cubicle front door. On disconnect switch cubicles, the position indicator shows either "connected" or "disconnected" positions. On vacuum circuit breaker cubicles, the position indicator shows "connected", "test", "disconnected" and "withdrawn" positions.

FIGURE 6-18 shows the circuit breaker interlock mechanism arrangement. A c-shaped steel piece has an automatic trip cam on its left leg, a padlock tab on the front, and a spring discharge cam on its right leg. It is free to slide front to back and is spring loaded in the front position. It is activated each time the manual withdrawal tool is inserted into the cubicle access hole, which in turn automatically trips a closed breaker by activating the trip interlock cam followers and levers. The circuit breaker may be locked in any position by placing a padlock through both padlock tabs and the corresponding hole in the cubicle. The manual trip cam is also free to slide front to back and is spring loaded in the front position. The manual trip button is pushed to activate the cam, which trips a closed breaker, in either the connected or test positions (the only positions that allow a breaker to be closed).

FIGURE 6-19 shows the proposed placement of the secondary disconnects. The distance between the test and connected positions inside the cubicle is about 30.5 cm for the 24 kV switchgear and about 20 cm for the 12 kV switchgear. The longest standard sliding disconnect on the market today is about 10 cm long. SPD therefore uses two disconnects inside the cubicle, placed in the two distinct indexed positions in which secondary control power is required. This way, a longer, more expensive, custom disconnect does not have to be developed and procured.

Phase II of this project involves the design and specification of the Operation and Control System for this program. To accommodate the hardware that will be required for this effort, SPD specified and solicited concepts from potential suppliers for current transformers (CTs) and potential transformers (PTs). These items represent the largest-sized items to be

incorporated during Phase II. **FIGURE 6-20** presents the CT concepts that Piedmont Dielectric and SPD are investigating, and **FIGURE 6-21** presents the PT concepts that GEC Alsthom and SPD are investigating. These instruments will be rated in accordance with **Reference 1** and their designs refined as the design and specification of the operating and control system progresses.

6.2.5 Auxiliary Equipment

Very few pieces of auxiliary equipment are necessary to operate the switchgear. SPD's concept of a power component handling fixture is presented in **FIGURE 6-22**. This fixture assists SEPTA's operational personnel in moving the power components into or out of the cubicles for maintenance. The concept is a standard portable lift fixture, modified by replacing the supplied lifting forks with guide rails, identical to the cubicle guide rails. This allows for the power components to ride on the fixture as if they were in the cubicles. With the power component installed and locked on the fixture, the fixture is raised to the correct height with a manual crank handle. The fixture then engages the stationary cubicle rail to permit the power component to be rolled into the cubicle. The same operation in reverse is used to withdraw the component. The heaviest component is about 140 kg, and the highest the fixture has to raise this component is about 2.1 meters. The fixture features an integral ladder that assists the operator in reaching the upper compartments. The fixture conforms to all of the requirements of ANSI/SIA A92.6, "Self-Propelled Elevating Work Platforms".

A manual withdrawal tool, shown in **FIGURE 6-23**, is used to rack the circuit breakers and manually operated switches between indexed positions. This tool also provides a means of manually racking any of the motorized switches into position in the event that secondary control power is lost.

A secondary test cable, defined in **Reference 1**, is depicted in **FIGURE 6-24**. This cable enables the operator to test all of the functions of a circuit breaker outside of the cubicle compartment. It will be about 3.7 m long and have multiple-pin connectors at each end. One

end will plug into a receptacle inside the cubicle that is wired to SEPTA's SCADA system. The other end will plug into a receptacle on the side of the circuit breaker.

A manual charging lever is used to manually charge the closing springs on the circuit breakers. The tool is inserted into the front of the mechanism and to engage a protrusion on the charging lever. Cranking the tool up and down actuates the charging system in the same way as the electrical charging motor. This tool can only be used when the cubicle door is open.

6.2.6 Compliance to Applicable Specifications and/or Practices

SPD has developed a concept for the 12 kV and 24 kV metal-clad switchgear that results in a significantly smaller overall switchgear size than is currently available in the industry. A compliance assessment and summary of the key technical requirements and goals for the bus structure are presented in **TABLE 6-1**.

SECTION 7.0 SHIPPING/TRANSPORTATION ASSESSMENT

7.1 APPROACH

Prior to final installation of the switchgear equipment at any SEPTA substation site, each line-up must be completely assembled and tested as a full line-up, per **Reference 1**. Therefore, working with local rigging companies, a comprehensive plan was developed to address the transportation issues involved with this project. The proposed plan addresses the disassembly, transportation, handling and re-assembly of the switchgear line-ups and is depicted graphically in **FIGURE 7-1** for SEPTA's Wayne Junction substation.

Because of the size of the equipment being transported, the transportation plan involves separating the line-ups into "transport modules" by segmenting the line-ups at the Bus-Tie cubicles. The modules can then be loaded onto tractor-trailers and transported by road to their respective substation sites. The modules can then be unloaded from the trailers, moved into position inside the newly constructed substation buildings and reconnected at the Bus-Tie cubicles. Currently, an estimated thirty-one shipments will be required to transport the switchgear. **TABLE 7-1** presents the data used to determine this number. This number does not take into account the additional shipments needed to transport the power components that will be delivered separately. Early in the project, it was determined that shipping the power components separate from the switchgear cubicles represented the least amount of risk.

Separating the line-ups at the Bus-Tie cubicles minimizes the number of connections that have to be re-made and re-tested as part of the installation and verification testing. Also, the resulting modules are small enough and light enough (since the power components will be withdrawn and transported separately) to be handled and transported without the use of specialized equipment or personnel. The transport weights, shown in **TABLE 7-1**, are well within the limits of standard flatbed trailers, and the worst case estimated shipping envelopes, shown in **FIGURE 7-2**, are within the legal limits for over-the-road transport.

The most critical cost and safety issues pertaining to the shipment is the loading and unloading of the equipment. Three methods of loading and unloading the equipment that can be employed with no adverse impact to cost or schedule. The various options were rated against each other and the results of this comparison are presented in **FIGURE 7-3**. Any of the three methods may be employed depending upon the environmental conditions that exist at each substation site.

Since the substation buildings may only be partially complete when the switchgear equipment arrives, a method of handling the equipment was required that could accommodate many different environmental conditions including unpaved driveways, excessive mud, and construction equipment. To accomplish this, commercially available machinery movers will be used. These movers are well suited to safely handle equipment of this size and shape in many environmental conditions, and can be supplied by the rigging company as part of the overall shipping cost.

7.2 SURVEYS AND RESULTS

Site visits (surveys) were conducted jointly by SPD and SEPTA to evaluate the present environmental conditions at each site, and determine if any of the sites presented significant challenges with regards to access and working space. The findings of the surveys are presented in **TABLE 7-2**. Based on these observations, the access to some of the substation sites will require SEPTA's attention during the substation building construction phase. Additionally, this investigation ruled out the use of rail transport of the switchgear, because unloading of the equipment would require the use of overhead cranes above the rail cars. Overhead cranes would require more clearance than is available under the catenary lines that supply traction power to the trains. Additionally, the overhead clearance along the rail lines is insufficient along some routes due to tunnels, overpasses and power lines that traverse the rails.

Over-the-road planning was investigated by commissioning a local rigging company to conduct route surveys. These route surveys include detailed routing plans from SPD's manufacturing facility to each of SEPTA's substation sites. Currently, only the survey to SEPTA's Norristown substation site has been completed. This site was completed first since it is one of the farthest outlying locations, and it represents significant on-site challenges. The resulting route plan is presented in **FIGURE 7-4**. The route plan demonstrates the equipment's transportability by tractor-trailer. The route ensures that the equipment can safely pass under or over bridges, under neighborhood power and cable television lines, under or around traffic lights and around tight corners and bends in the roadways. To overcome the site access issues uncovered during the surveys, the proposed route utilizes a parking lot adjacent to the substation to provide the access and unloading space required.

With proper site preparation, all of the substation sites are accessible by tractor-trailer, and the switchgear equipment can be transported successfully and safely.

SECTION 8.0 KEY SYSTEM ANALYSES

The switchgear for this project is specialized electrical equipment that distributes current at specified electrical potentials. The heat generated by the electric currents and the electric stresses created by the differences in electrical potentials makes both thermal management and electrostatic field stress management critical issues. System-level thermal and electrostatic analyses were performed with CAD modeling packages utilizing finite element analysis methods. IAP Research Inc, subcontracted by SPD Technologies, performed each analysis on the critical elements for the worst-case operating and service conditions.

8.1 THERMAL ANALYSIS

The key requirements that govern the thermal characteristics of the switchgear and associated power components are related to the nature of the electrical currents that flow though the system. This electrical current is 1,200 amps or 2,000 amps continuous, with harmonic content and current overloads in accordance with **Reference 1**. Items 10 and 11 of **TABLE 8-1** indicate the specified continuous current ratings and **TABLE 8-2** presents the harmonic content of the current. **FIGURE 2-1**, previously presented, shows the overload duty cycle for each of the three static frequency converters that feed the equipment. The switchgear equipment is designed to operate over the specified temperature range of -30°C to +40°C with thermal management being achieved through natural means only.

The crosshatched sections in **FIGURE 8-1** identify the critical compartments used for evaluating thermal management properties of the equipment. These compartments feature comparatively high current densities, due to the number of current carrying elements contained within them and their rated currents. These compartment properties, with the compounding effect of applying electrical insulation on the power components, required SPD to find creative ways to achieve the desired thermal management.

To determine any quasi-static effects of the current overloads that might be encountered in service, the time constant of a typical element or power component was computed by performing a finite difference analysis for the overload conditions. This analysis indicated that the time required for the operating temperatures of the elements to reach a steady state was greater than the predicted duration of the overload. As a result, the thermal modeling and analyses were performed using the nominal current for each element. Thermal analyses were performed for both stand-alone elements under rated continuous current conditions and string elements under rated continuous current conditions. In the analysis of the string condition, which is closer to the actual application, conductive heat transfer is accounted for by connecting the elements before simulating current flow. Additionally, to assess the performance of the junctions, the string analyses were performed with the junction couplers both thermally isolated and thermally connected.

TABLE 8-3 presents the allowable temperatures for the different elements of the switchgear and the corresponding insulation class per ANSI standards. The temperature rise predictions for the wall bushings at both 1,200 amps and 2,000 amps are plotted in **FIGURE 8-2**, while **FIGURE 8-3** represents the temperature rise predictions for conductor insulation. Three conditions were analyzed and are represented by the three bars on **FIGURES 8-2** and **8-3**. The first bar represents the temperature rise prediction for the element in a stand-alone condition. The second and third bars represent the predictions for each element as part of a string of elements between two physical disconnect points in the circuit. The second bar corresponds to a thermally isolated junction and the third bar corresponds to a thermally connected junction. The horizontal line on the plot represents the maximum allowable temperature rise. It can be seen that the bus structure as a system operates at temperatures below the maximum allowable per applicable industry standards and manufacturer recommendations. Thus, the thermal characteristics of the switchgear design comply with the requirements of **Reference 1**.

8.2 ELECTROSTATIC ANALYSIS

The switchgear equipment and associated power components are required to operate nominally at 12 kV or 24 kV, with 60 kV or 105 kV normal frequency withstand and 150 kV or 250 kV full wave impulse voltages in accordance with **Reference 1**.

When an electrical potential is applied between live components, or from a live component to a grounded component, electrical stresses are created in the insulating material and the air gap surrounding the components. The level of electrical stress in the insulating material depends on factors such as the geometry of the conducting components, the dielectric property of the insulating material, and the humidity and barometric pressure of the air between the components. Electrical stresses beyond the capacity of the insulating material and the air gap can cause a variety of breakdown phenomena such as audible corona, visual corona or flashover. The occurrence of any of these phenomena could result in the undesirable tripping or closing of a circuit breaker or damage to the equipment. SPD has adopted design guidelines that include sufficient safety margins to ensure that these phenomena do not occur. The maximum allowable electrical stress is determined to be 3.5 mV/m. Electrical stress levels were determined for the insulating materials, and verified using simulations on engineering models based on existing physical test data from field-proven components and standard industry practices.

Based on the resulting design guidelines, each element, component and compartment was sized and geometrically configured to minimize the clearance distances between the power components and the grounded enclosures through careful electric field stress management. Finite element models were used to analyze the electrical stresses in the critical areas. **FIGURE 8-4** shows an electrostatic field plot, in the horizontal plane, for a live 24 kV disconnect wall bushing with the circuit breaker primary conductor disengaged and the grounded shutter in the closed position. Each contour line represents an equi-stress line in the electrostatic field. The maximum stress occurs at the tip of the disconnect bushing, but the

stress level is well below the established design guideline. This plot is representative of all the circuit breaker and disconnect switch compartments when the power component is not in operation. From this type of plot, the stress levels in the compartment were evaluated and the compartment and components were sized accordingly. **FIGURE 8-5** shows the electrostatic field plot for a typical bus compartment. Using this figure, the stresses generated around a spherical junction coupler were evaluated to size the compartment. **FIGURE 8-6** shows a similar plot for an alternate junction coupler connection. This design was evaluated because it represents the worst-case junction coupler from an electrostatic standpoint. By varying the radius of curvature of the junction coupler, the electrical stress level is brought within acceptable limits.

Comparing the plots with empirical data demonstrates that the cubicle compartments have sufficient margin from an electrostatic field stress management perspective. Using this approach, the following compartment configurations were also analyzed:

- Disconnect bushing, circuit breaker side – connected
- Disconnect bushing, circuit breaker side – disconnected (shutter in place)
- Disconnect bushing, bus side
- Wall bushing, bus side
- Junction coupler, bus side

SPD has sized and configured these compartments to minimize the clearance distances between the power components and the grounded enclosures, resulting in a space-optimized switchgear design. It can be seen from the electrostatic analyses that all of the power components exhibit electrostatic field stresses within the established limits. Thus, the electrostatic characteristics of the switchgear design comply with the requirements of **Reference 1**.

SECTION 9.0 CONCLUSION / SUMMARY

Through extensive design and analysis, SPD has developed 12 kV, 150 kV BIL and 24 kV, 250 kV BIL switchgear design concepts that are fully compliant to the performance requirements and size constraints defined in **Reference 1** and the related industry standards.

The resulting switchgear line-up occupies less floor space and less overall height than what is allocated in **Reference 1**, providing the benefits of lower procurement cost, reduced size and cost of the substation buildings, and reduced shipping cost. The switchgear is modular in design, consisting of five basic cubicle types. These modular cubicles can be configured in any combination necessary for a particular substation, and can easily accommodate future growth. The design concept utilizes common elements and standardized components as much as possible to reduce overall cost and improve reliability. Industry standards and practices, proven technologies, and advanced design and analysis techniques have been utilized to develop the state of the art equipment required to meet SEPTA's modernization goals. Existing technologies have been creatively applied to meet the stringent demands of indoor, metal-clad switchgear with challenging voltage withstand and thermal management requirements.

The development of the power components and the attendant switchgear in Phase I progressed as scheduled. **TABLE 9-1** summarizes the design status of the major components of the switchgear under development.

SECTION 10.0 REFERENCES

1. Technical Specification for 12kV and 24kV Switchgear"; Report 9 of 10, Volume 1of 1; LTK Engineering Services; Final Submission July 1993.

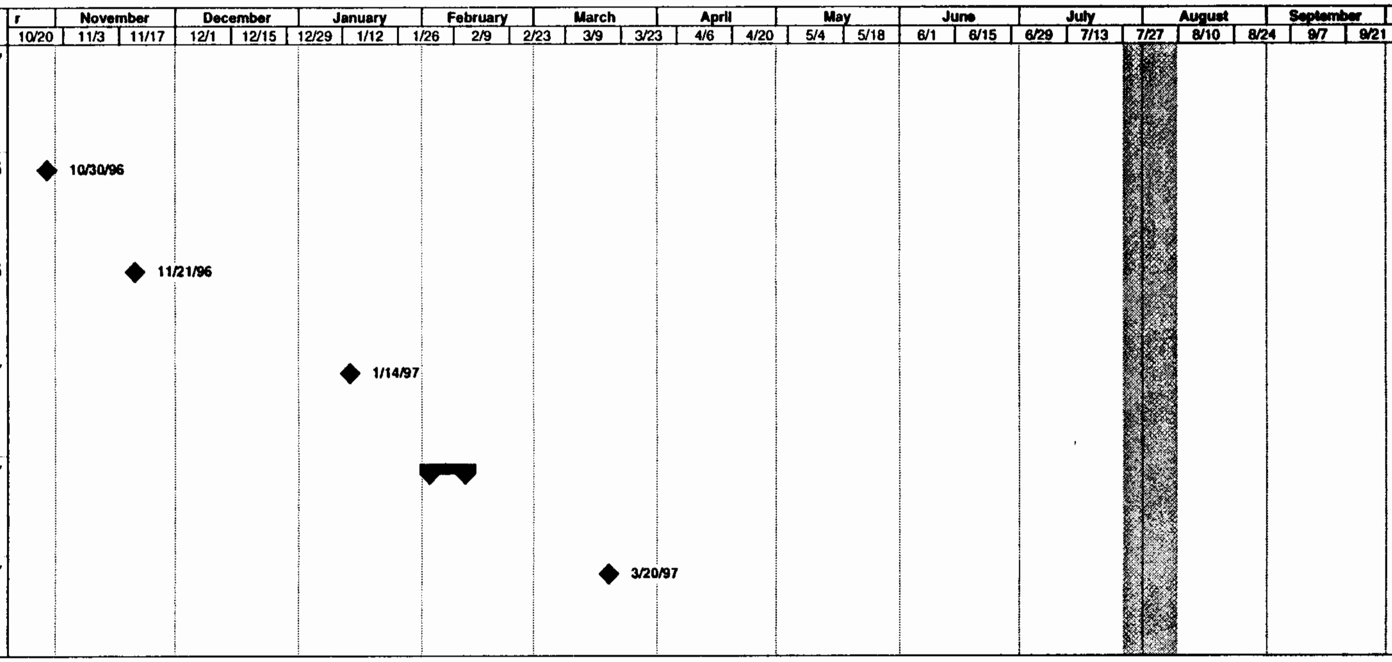
Appendices

Appendix A

Figures

SEPTA Program Schedule 12kV & 24kV Switchgear Phase 1

Task Name	Duration	Start	Finish
TASK 0 Program Milestones	**92d**	**10/30/96**	**3/20/97**
TASK 0.1 Contract Award	1d	10/30/96	10/30/96
TASK 0.2 Post Award Meeting	1d	11/21/96	11/21/96
TASK 0.3 Wayne Junction Visit	1d	1/14/97	1/14/97
TASK 0.4 Substation Site Surveys	7d	2/3/97	2/11/97
TASK 0.5 Center City Tunnel Visit	1d	3/20/97	3/20/97



Project: SEPTA Program Phase 1
Date: 12/4/97
FR Sch Ph I Oct30.MPP

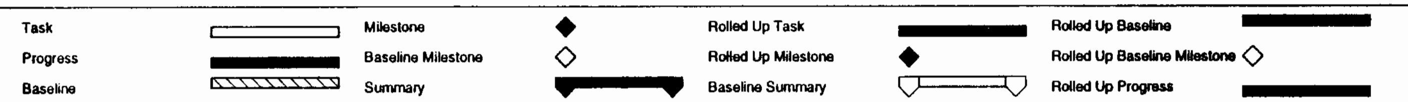
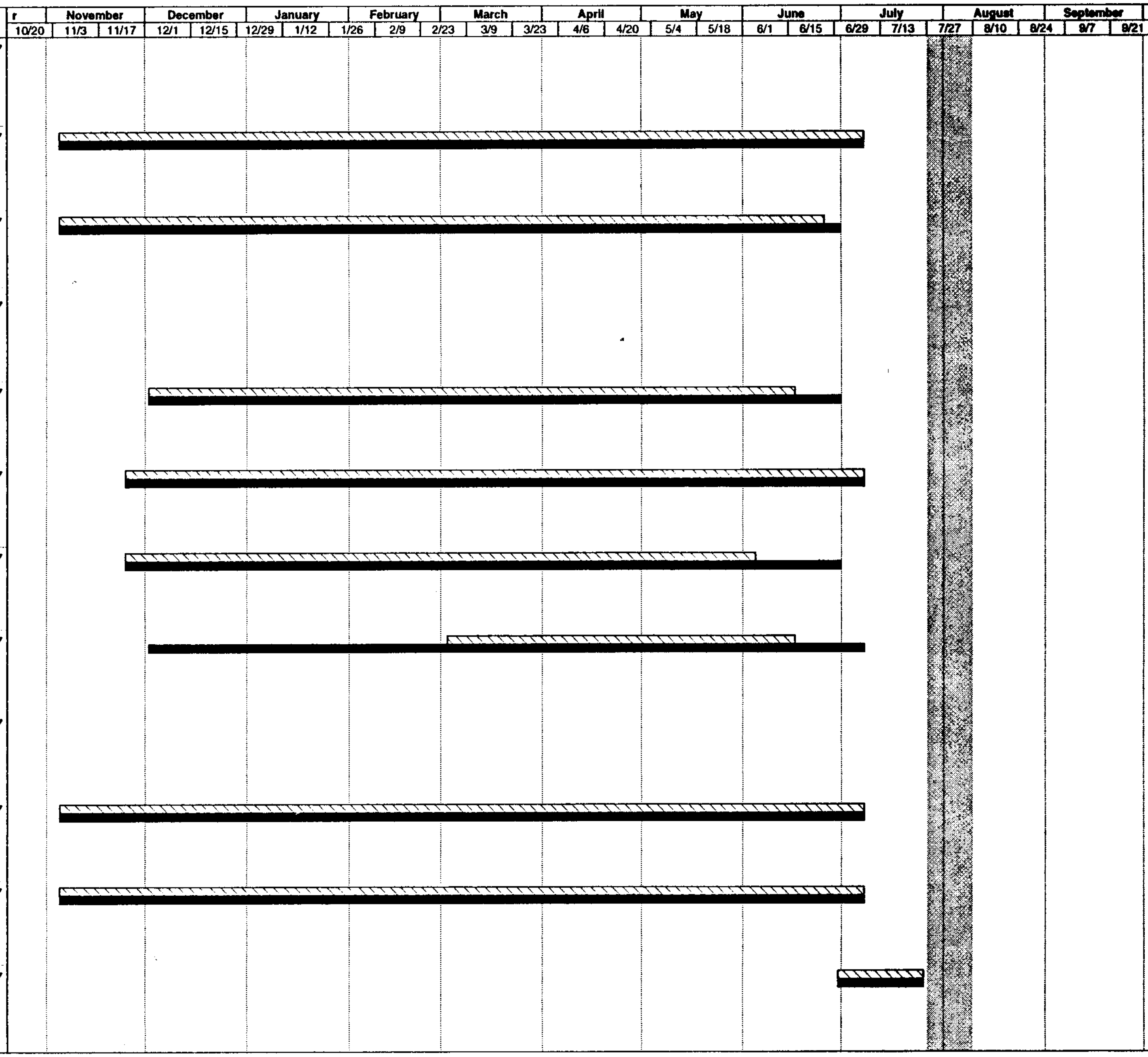


Figure 2-1.1 Project Schedule

SEPTA Program Schedule 12kV & 24kV Switchgear Phase 1

Task Name	Duration	Start	Finish
TASK 1.0 Design Circuit Breakers	**162d**	**11/5/96**	**7/7/97**
1.1 24kV-CB	162d	11/5/96	7/7/97
1.2 12kV-CB	158d	11/5/96	6/30/97
TASK 2.0 Design Disconnect Switches	**148d**	**11/25/96**	**7/7/97**
2.1 24kV Transfer	141d	12/2/96	6/30/97
2.2 12kV Transfer	148d	11/25/96	7/7/97
2.3 24kV Test	144d	11/25/96	6/30/97
2.4 12kV Test	145d	12/2/96	7/7/97
TASK 3.0 Design Switchgear	**162d**	**11/5/96**	**7/7/97**
3.1 24kV Cubicle	162d	11/5/96	7/7/97
3.2 12kV Cubicle	162d	11/5/96	7/7/97
TASK 4.0 Final Report Phase	**19d**	**6/30/97**	**7/25/97**



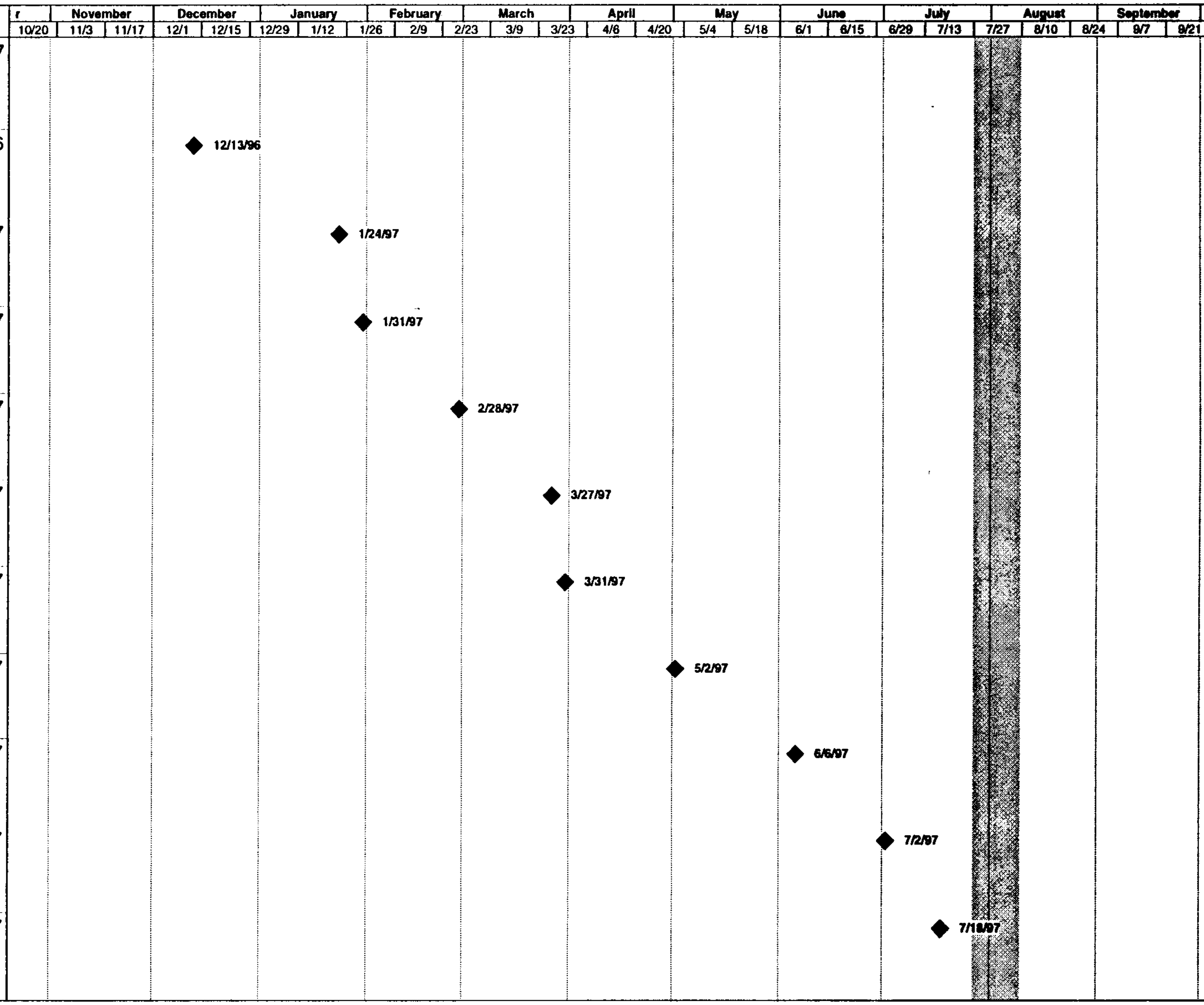
Project: SEPTA Program Phase 1
Date: 12/4/97
FR Sch Ph I Oct30.MPP

Task	Milestone	Rolled Up Task	Rolled Up Baseline
Progress	Baseline Milestone	Rolled Up Milestone	Rolled Up Baseline Milestone
Baseline	Summary	Baseline Summary	Rolled Up Progress

Figure 2-1.2 Project Schedule

SEPTA Program Schedule 12kV & 24kV Switchgear Phase 1

Task Name	Duration	Start	Finish
TASK 5.0 Progress Meetings & Quarterly Reports	**145d**	**12/13/96**	**7/18/97**
Design Review Meeting #1	1d	12/13/96	12/13/96
Design Review Meeting #2	1d	1/24/97	1/24/97
Quarterly Report #1	1d	1/31/97	1/31/97
Design Review Meeting #3	1d	2/28/97	2/28/97
Design Review Meeting #4	1d	3/27/97	3/27/97
Quarterly Report #2	1d	3/31/97	3/31/97
Design Review Meeting #5	1d	5/2/97	5/2/97
Design Review Meeting #6	1d	6/6/97	6/6/97
Design Review Meeting #7	1d	7/2/97	7/2/97
Phase I Final Report	1d	7/18/97	7/18/97



Project: SEPTA Program Phase 1
Date: 12/4/97
FR Sch Ph I Oct30.MPP

Task	Milestone	Rolled Up Task	Rolled Up Baseline
Progress	Baseline Milestone	Rolled Up Milestone	Rolled Up Baseline Milestone
Baseline	Summary	Baseline Summary	Rolled Up Progress

Figure 2-1.3 Project Schedule

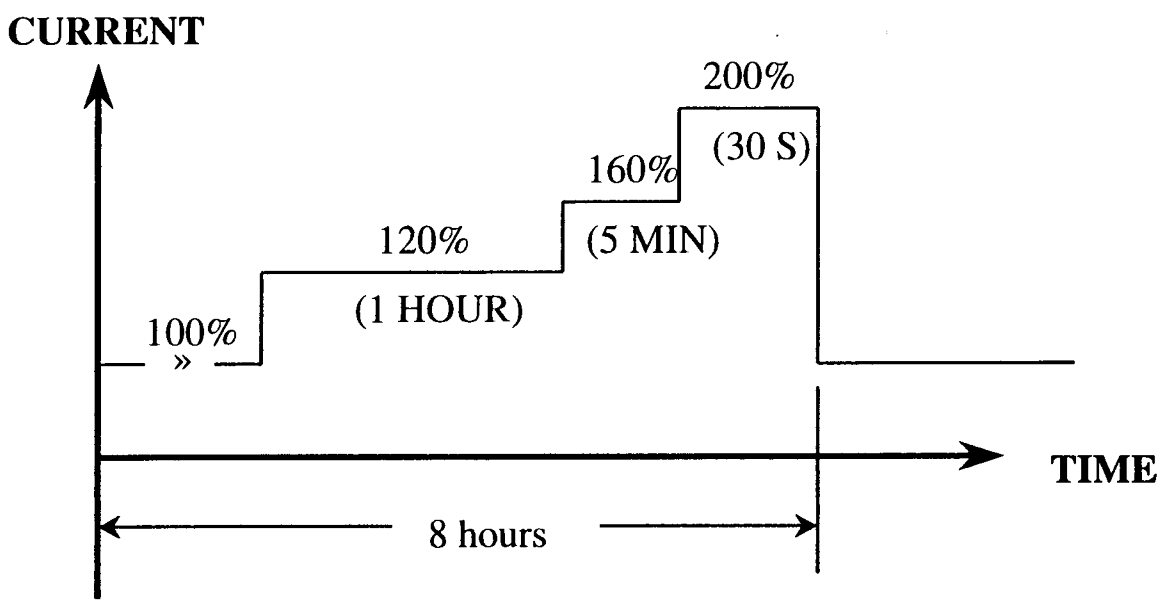
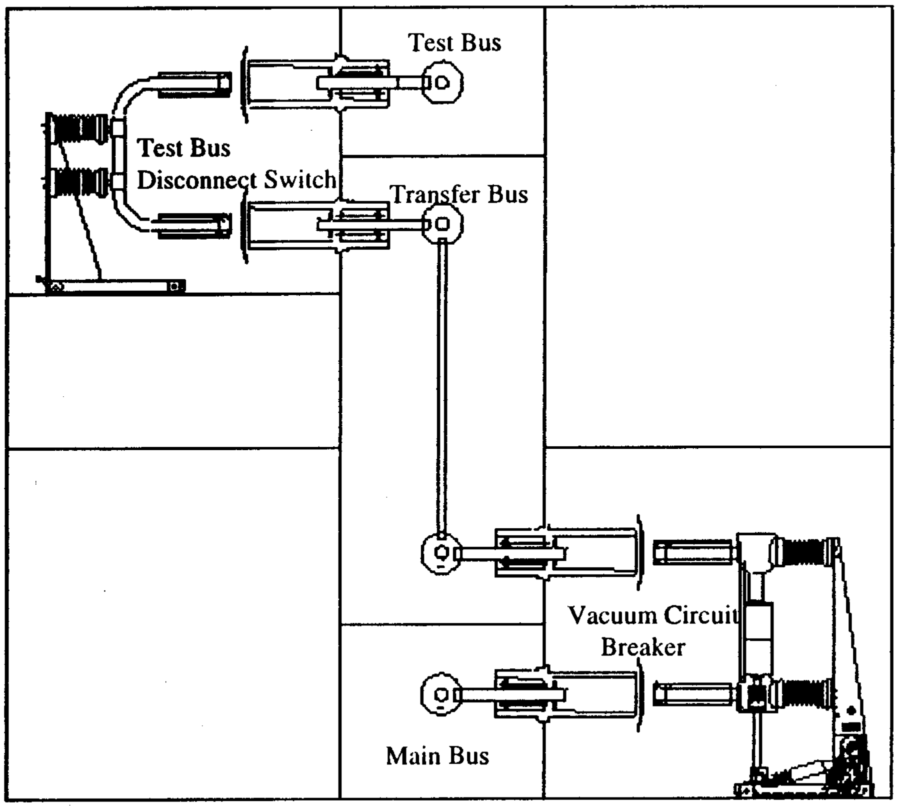
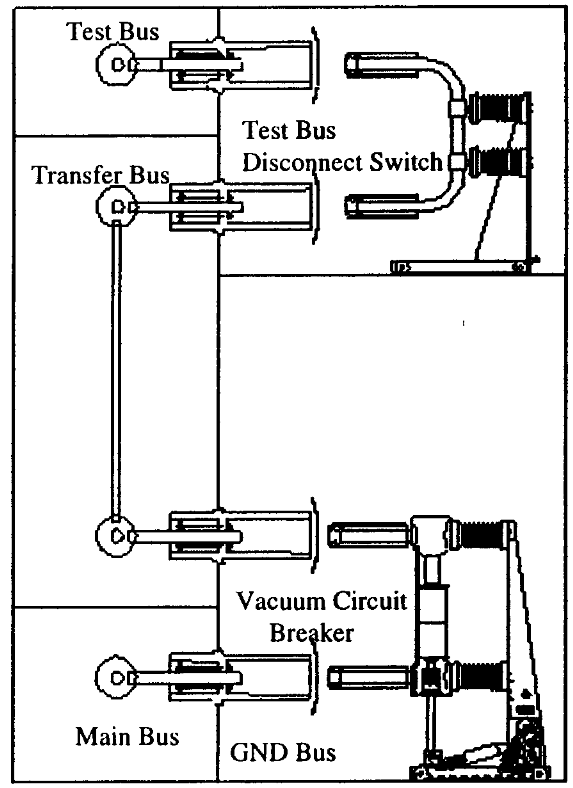


Figure 2-2: Static Frequency Converter Duty Cycle (time history)

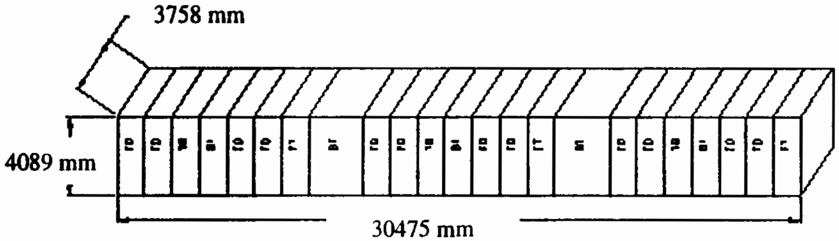


3-Tier

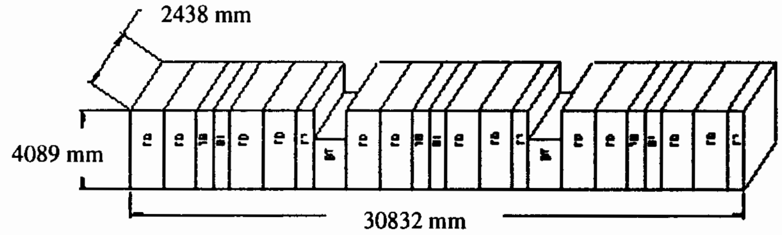


2-Tier

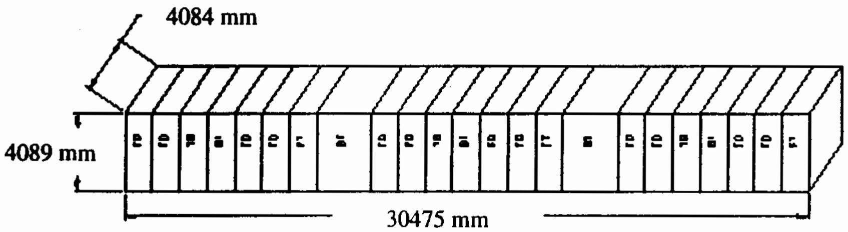
Figure 2-3: "3-Tier" vs. " 2-Tier" Cubicle Arrangement



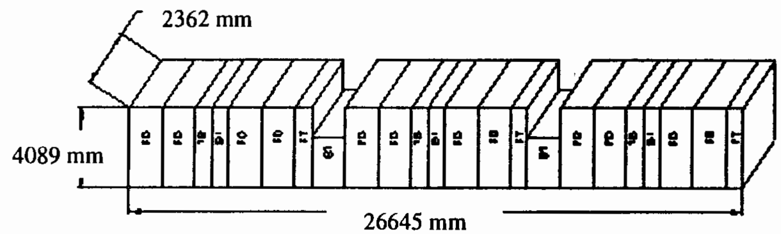
LINE-UP PER SEPTA/LTK SPECIFICATION
FOOTPRINT ESTIMATE: 114.5 m^2



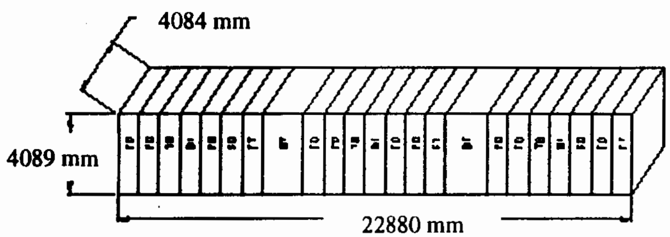
LINE-UP DESIGN III (2-TIER)
FOOTPRINT ESTIMATE: 74.8 m^2 (65 % OF SPECIFIED FOOTPRINT)



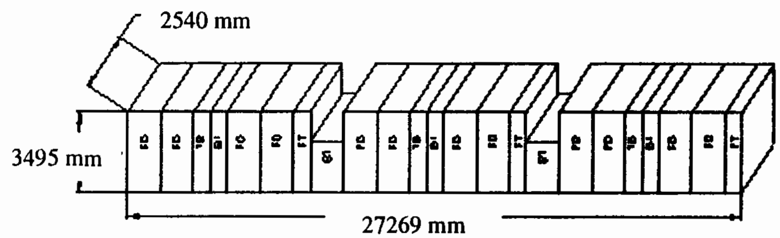
LINE-UP DESIGN I (3-TIER)
FOOTPRINT ESTIMATE: 141.4 m^2 (124 % OF SPECIFIED FOOTPRINT)



LINE-UP DESIGN IV (2-TIER)
FOOTPRINT ESTIMATE: 63 m^2 (55 % OF SPECIFIED FOOTPRINT)



LINE-UP DESIGN II (2-TIER)
FOOTPRINT ESTIMATE: 106.1 m^2 (93 % OF SPECIFIED FOOTPRINT)



LINE-UP DESIGN V (2-TIER)
FOOTPRINT ESTIMATE: 68 m^2 (60 % OF SPECIFIED FOOTPRINT)

Figure 2-4: 24 kV Line-up Evolution

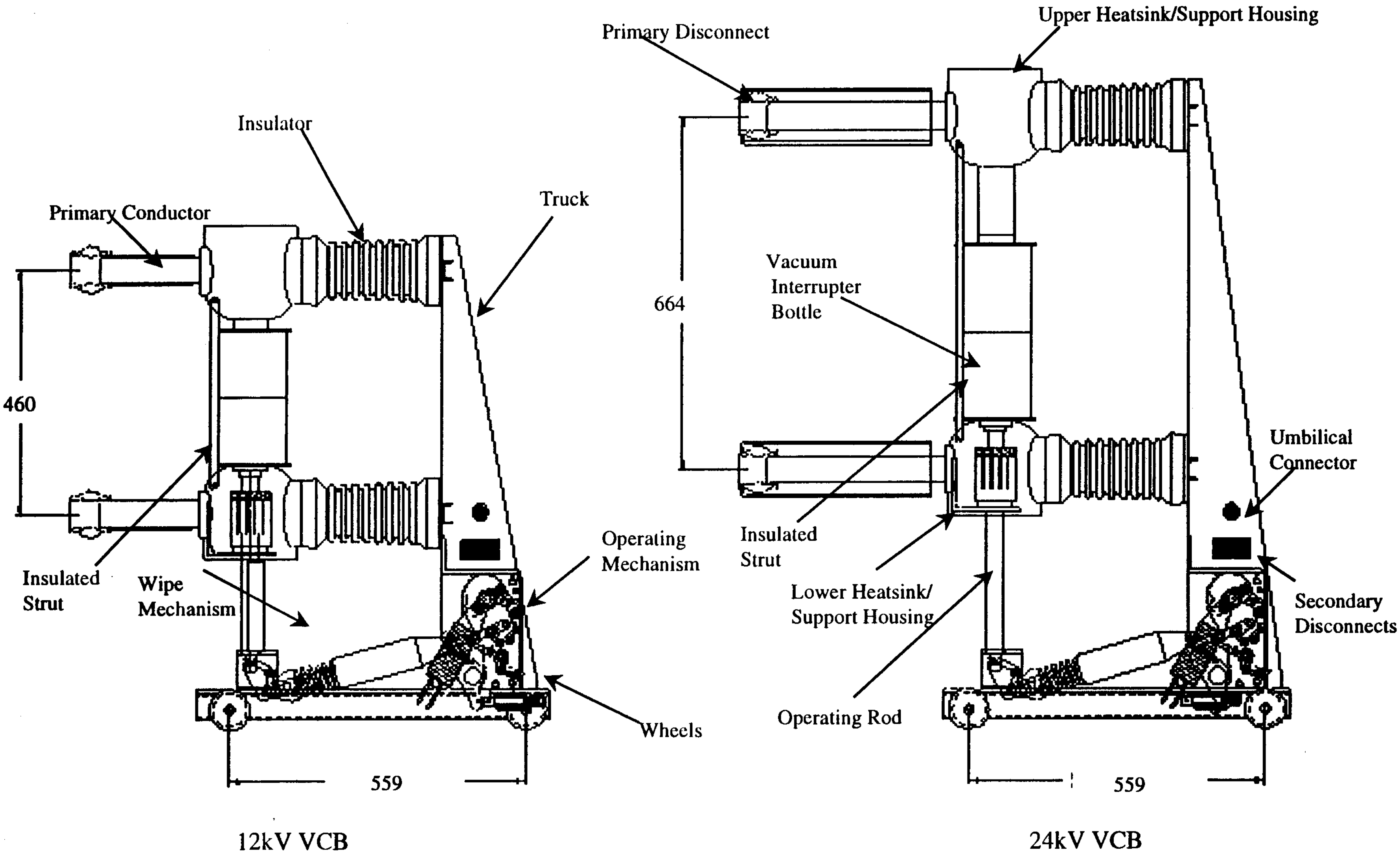


Figure 3-1: Vacuum Circuit Breaker General Arrangement

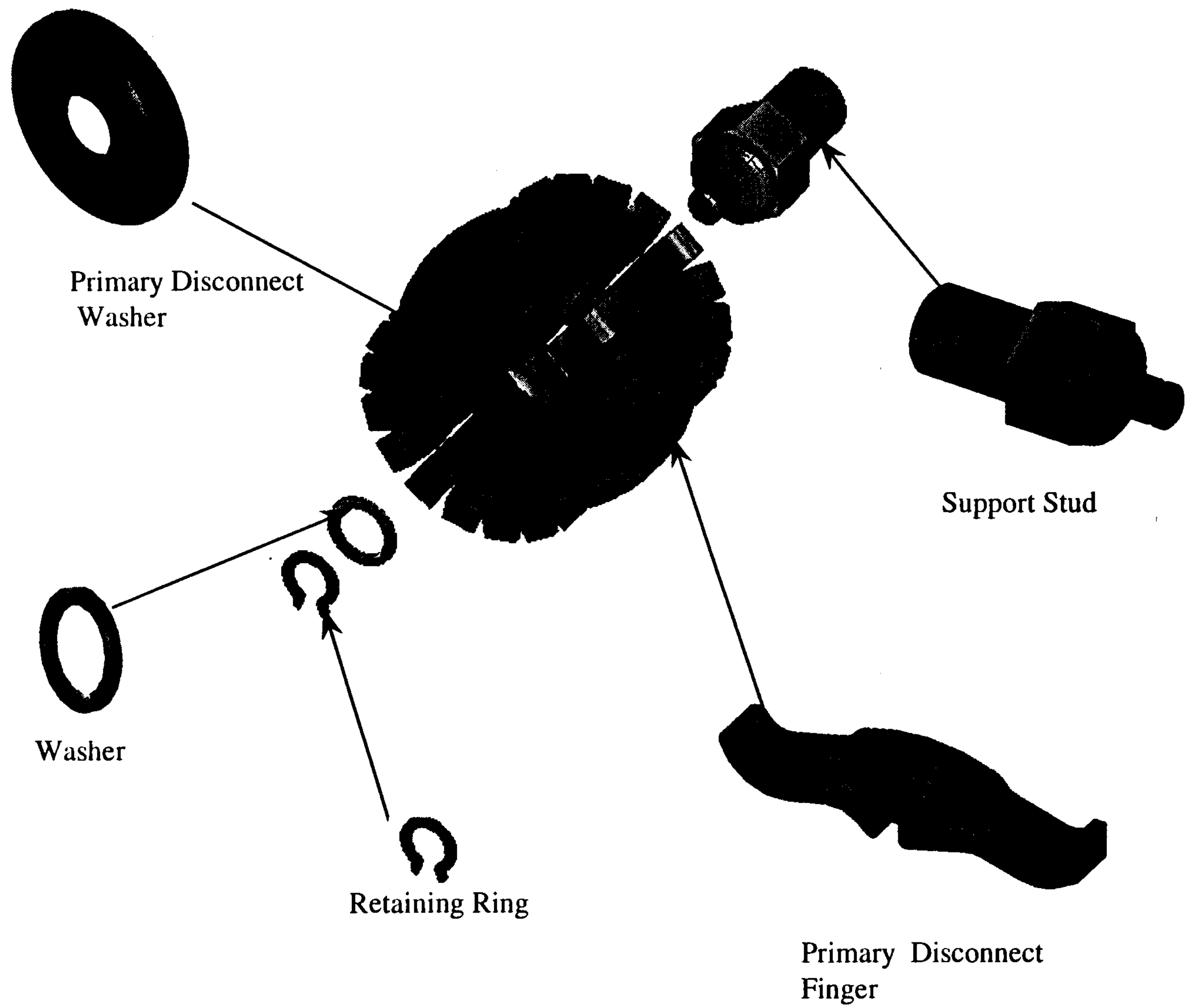


Figure 3-2: Primary Disconnect Assembly

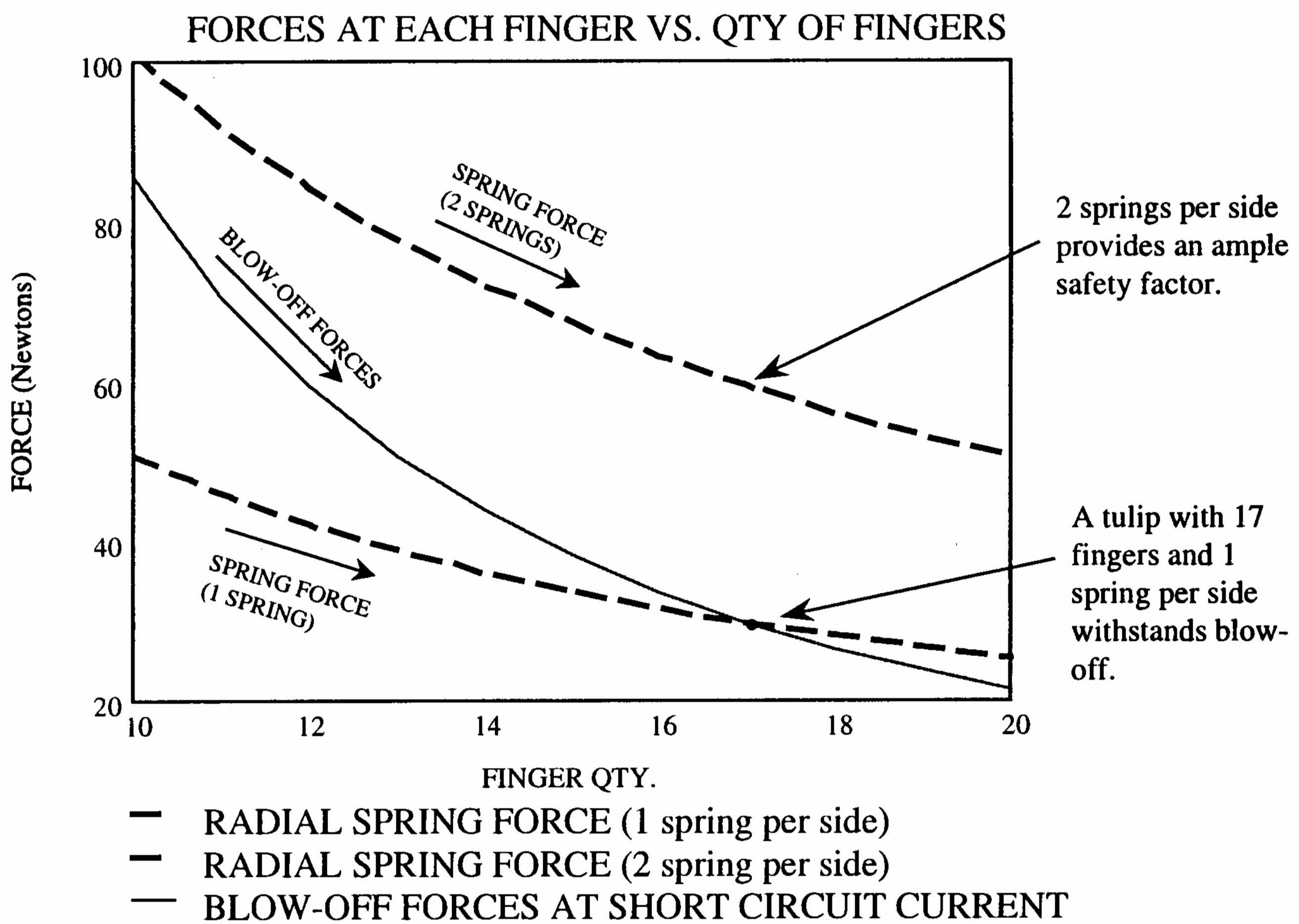


Figure 3-3: Primary Disconnect Blow-off Force Analysis Results

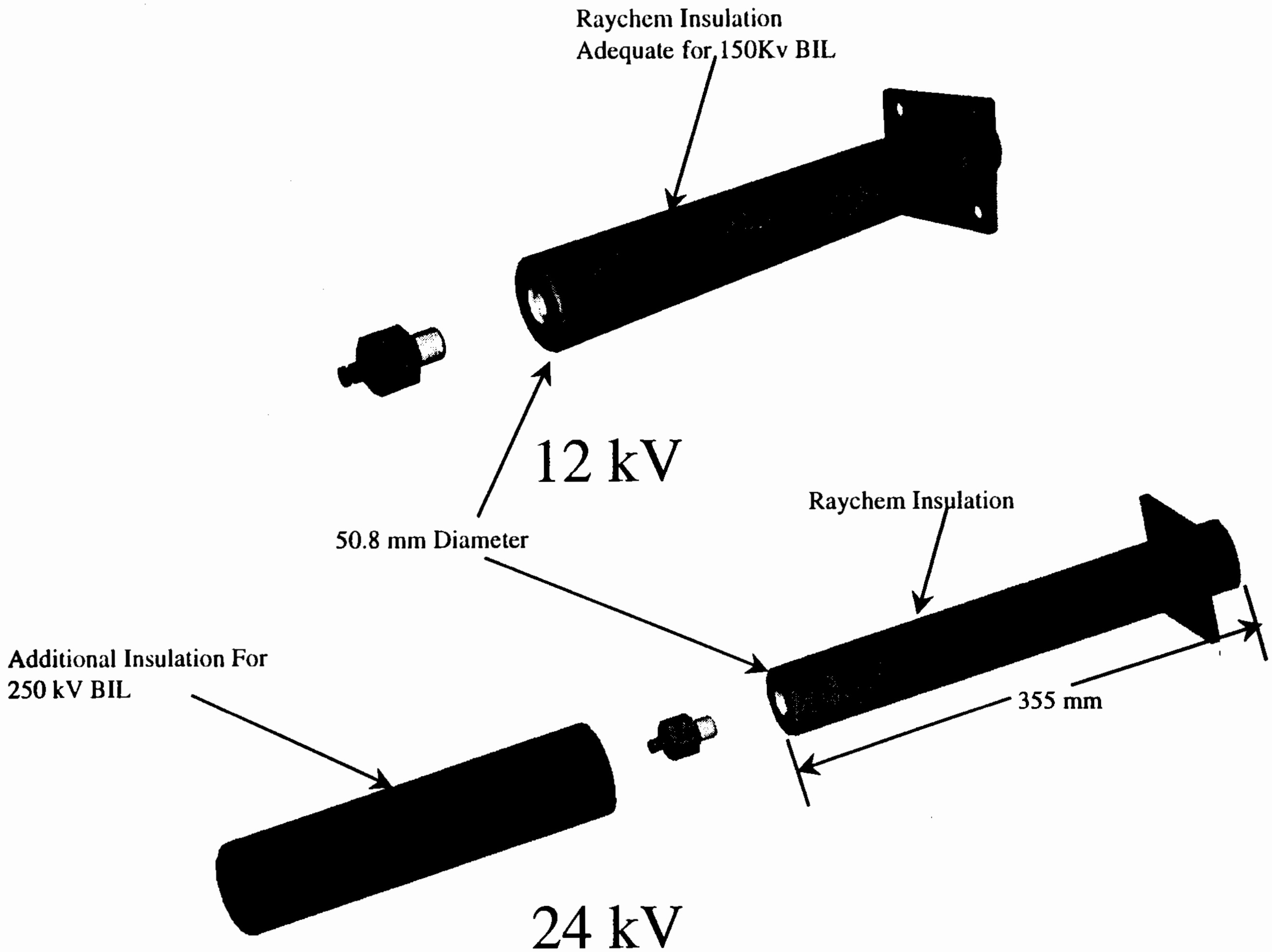


Figure 3-4: Circuit Breaker Conductor Assemblies

Cutler-Hammer
200 Westinghouse Circle,
Horseheads, NY, USA 14845

Date: 5 May 1997 Page: 3
Specification No: 150-35632P
Superseded Date:

PROPRIETARY INFORMATION

Westinghouse
Vacuum Interrupter

Vacuum Interrupter for Railway (Wayside) Applications Type: WL-35632P

ELECTRICAL RATINGS, Single Phase Rating Symmetrical Basis			
Rated Frequency	25		Hertz
Rated Maximum Line-to-Rail Return Voltage	13	rms	kilovolts
Rated Voltage Range Factor K	1.0		
Rated Power Frequency Withstand Voltage	60	rms	kilovolts
Rated Full Wave Impulse Withstand Voltage	150	crest	kilovolts
Rated Continuous Current (Note 2)	2000	rms	amperes
Contact Resistance:			
● Rated Continuous Current	< 25		μ Ω
Rated Short Circuit Current (Symmetrical)	25	rms	kA
Asymmetry Ratio S, Maximum	1.2		
Momentary, Close-and-Latch (Peak):			
● Required Minimum Added Force (2.5 x Isym, rms)	62.5	peak	kA
2-Sec. Short-Time Carrying Capability	25	rms	kA
MECHANICAL DATA			
Interrupter Weight	8.7		kilograms
Moving Part Weight	2.1		kilograms
Contact Force from Atmospheric Pressure	16.8		kilograms
MECHANICAL REQUIREMENTS			
Contact Stroke	17-20		millimeters
Opening Speed, Average to 75% of Rated Stroke	1.5-2.0		meters per second
Overtravel During Opening, Max	2		millimeters
Closing Speed, Average of Last 33% of Rated Stroke	0.7-1.0		meters per second
Contact Bounce Duration, Max	0.002		second
Minimum Added Force for Momentary	200		kilograms
LIFE			
Continuous Current Switching	10,000		operations
Mechanical Life:			
● Required Contact Stroke (20 mm)	30,000		operations
Contact Erosion Limit	3		millimeters

NOTE 1: THESE RATINGS MUST BE FULLY VERIFIED BY CUSTOMER TEST.

NOTE 2: THIS RATING WILL REQUIRE APPROPRIATE THERMAL COOLING CONSIDERATION IN THE BREAKER DESIGN.

	Rev.	EC Number	Drawn	Checked	Approved	Date
150-35632P.PG3	-	10693	MAS			

Figure 3-5: 12kV Vacuum Interrupter Bottle Manufacture's Specifications

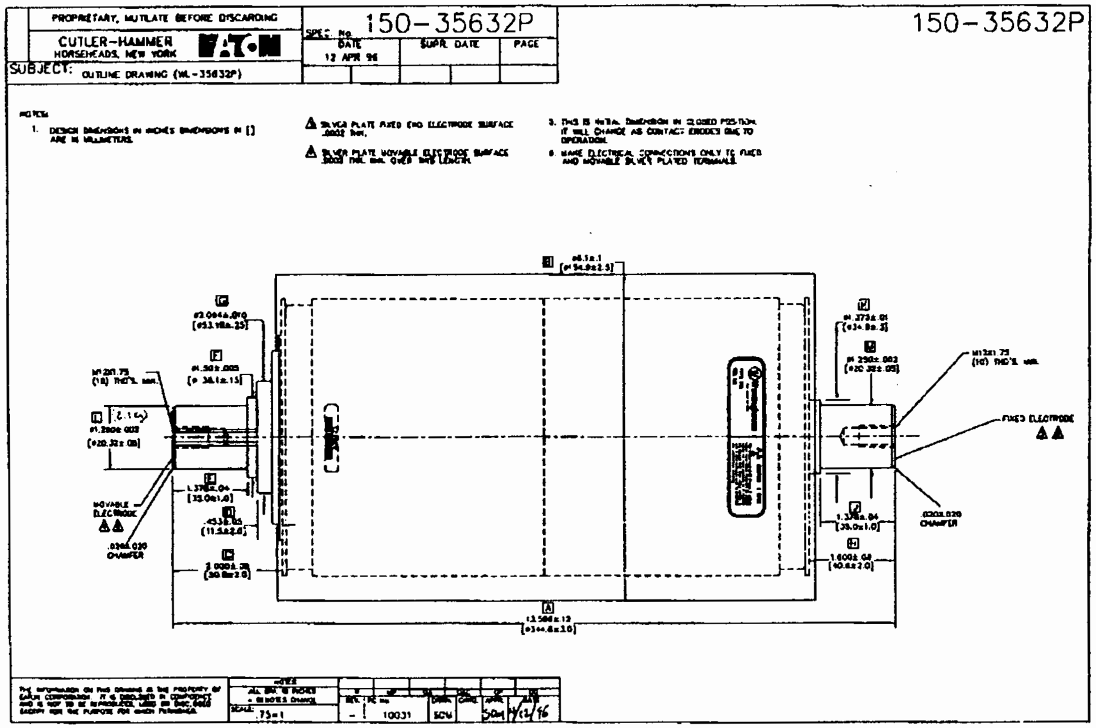


Figure 3-6: 12kV Vacuum Interrupter Bottle Manufacture's Outline Drawing

Cutler-Hammer
200 Westinghouse Circle,
Horseheads, NY, USA 14845

Date: 2 July 1997 Page: 2
Specification No: 150-35561P
Superseded Date:

PROPRIETARY INFORMATION

Westinghouse
Vacuum Interrupter

Vacuum Interrupter for Railway Applications Type: WL-35561P

ELECTRICAL RATINGS, Single-Phase Rating Symmetrical Basis			
Rated Frequency	50/60		Hertz
Rated Maximum Line-to-Line Voltage	38	rms	kilovolts
Rated Power Frequency Withstand Voltage	85	rms	kilovolts
Rated Impulse Withstand Voltage (Note 3)	250	crest	kilovolts
Rated Normal Current	2000	rms	amperes
Contact Resistance	< 25		μ Ω
Rated Short Circuit Current (Symmetrical) (Note 1)	25	rms	kA
Rated Short-Circuit Breaking Current-Percentage d.c.	50		
Rated Short-Circuit Making Current			
• Required Added Force	62.5	peak	kA
Rated Duration of Short-Circuit	3		Seconds
MECHANICAL DATA			
Interrupter Weight	11.5		kilograms
Moving Part Weight	2.9		kilograms
Contact Force from Atmospheric Pressure	16.8		kilograms force
MECHANICAL REQUIREMENTS			
Contact Stroke	22-24		millimeter
Opening Speed, Average to 75% of Rated Stroke	1.6-2.0		meter/second
Overtravel During Opening, Max	3		millimeter
Closing Speed, Average of Last 33% of Rated Stroke	0.7-1.0		meter/second
Contact Bounce Duration, Max	0.002		second
Added Force for Short-Circuit Making Current (Minimum)	200		kilogram force
LIFE			
Mechanical Life:			
• Required Contact Stroke	30,000		operations
Contact Erosion Limit	3		millimeter

NOTE 1: THIS DEVICE HAS BEEN PREQUALIFIED BY TESTS ON A SYNTHETIC CIRCUIT. SYNTHETIC TESTING IS A NORMAL PRELIMINARY PREDICTING HIGH SUCCESS PROBABILITY IN FULL SHORT CIRCUIT LABORATORY CERTIFICATION TESTS.

NOTE 2: THESE RATINGS MUST BE FULLY VERIFIED BY CUSTOMER TEST.

NOTE 3: THESE BIL LEVELS HAVE BEEN ACHIEVED ON PROTOTYPE INTERRUPTERS IN THE LABORATORY. CUSTOMER QUALIFICATION OF THIS INTERRUPTER IN A CIRCUIT BREAKER MECHANISM AND HOUSING IS REQUIRED.

	Rev.	P.C. Number	Drawn	Checked	Approved	Date
150-35561P.PG2	A	10784	MAS		SDM	7/2/97

Figure 3-7: 24kV Vacuum Interrupter Bottle Manufacture's Specifications

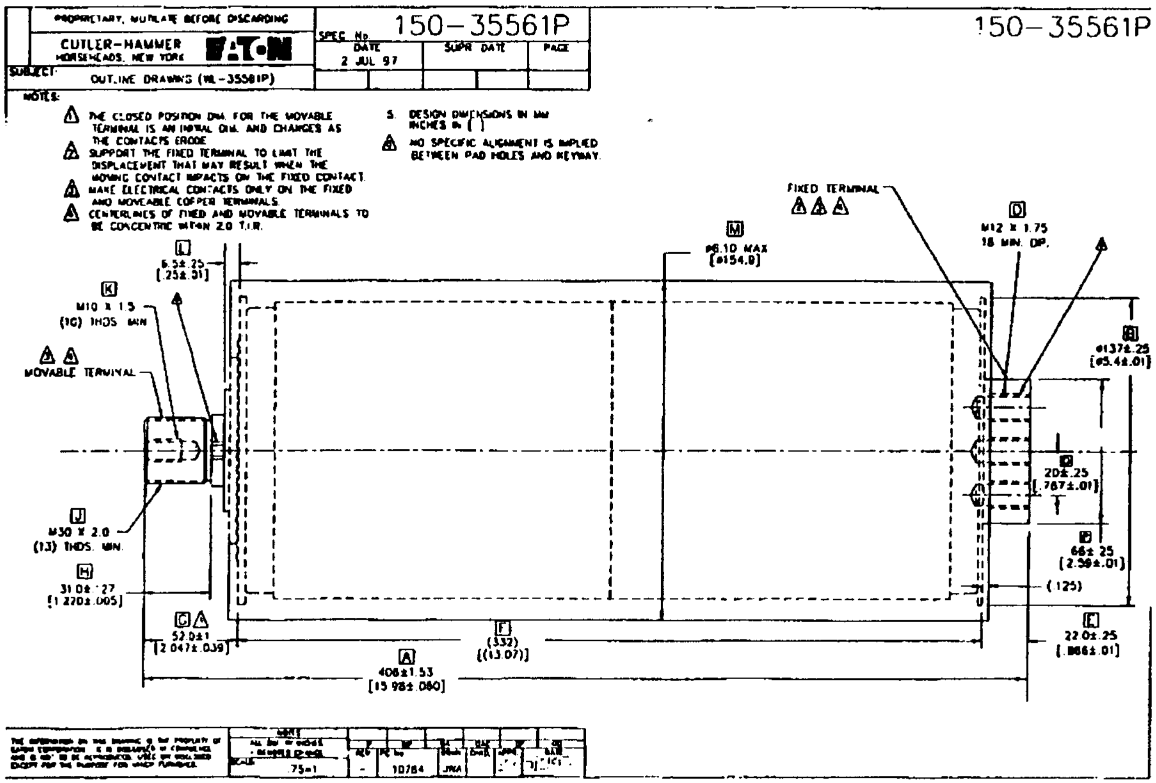


Figure 3-8: 24kV Vacuum Interrupter Bottle Manufacture's Outline Drawing

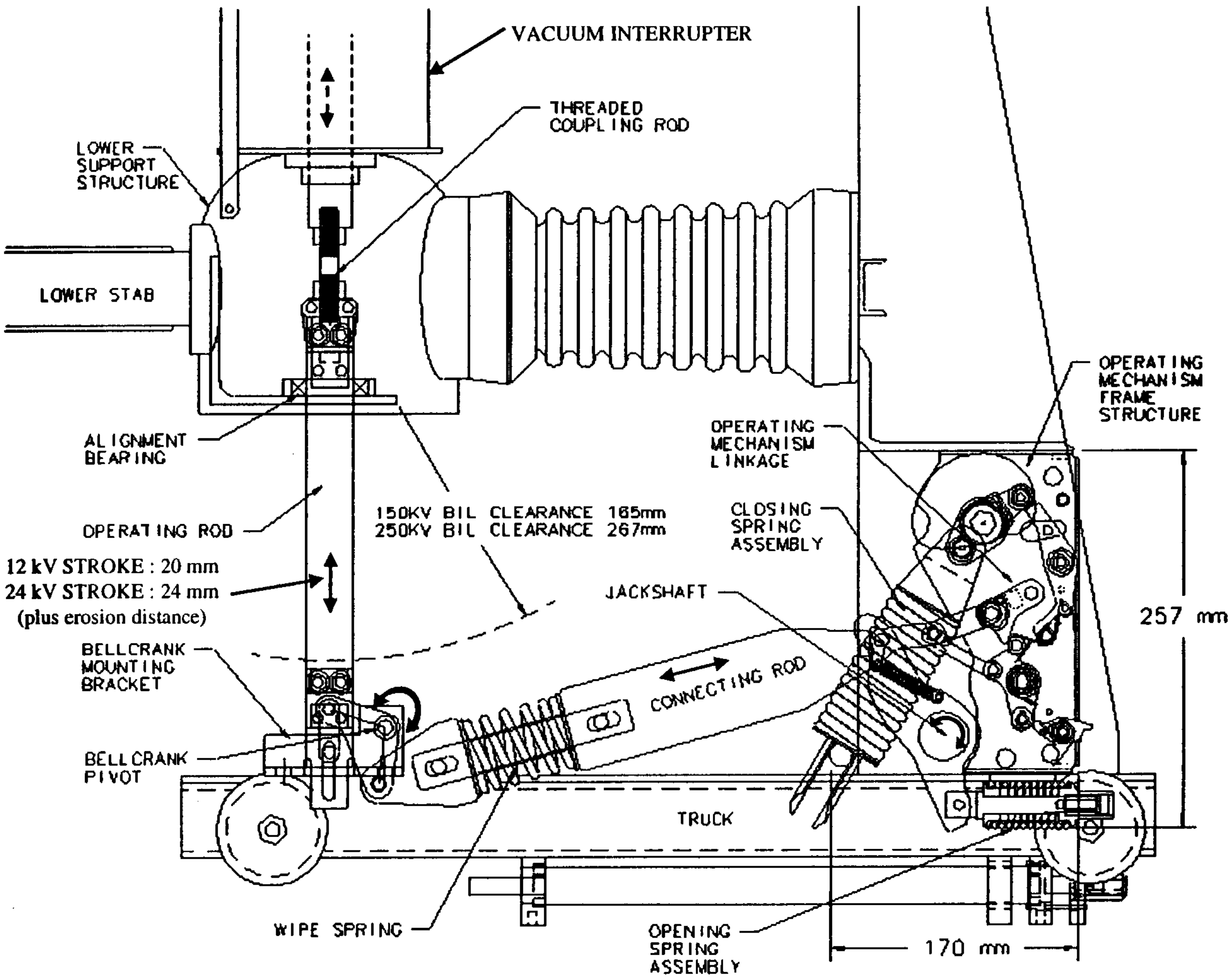


Figure 3-9: Operating Mechanism Layout

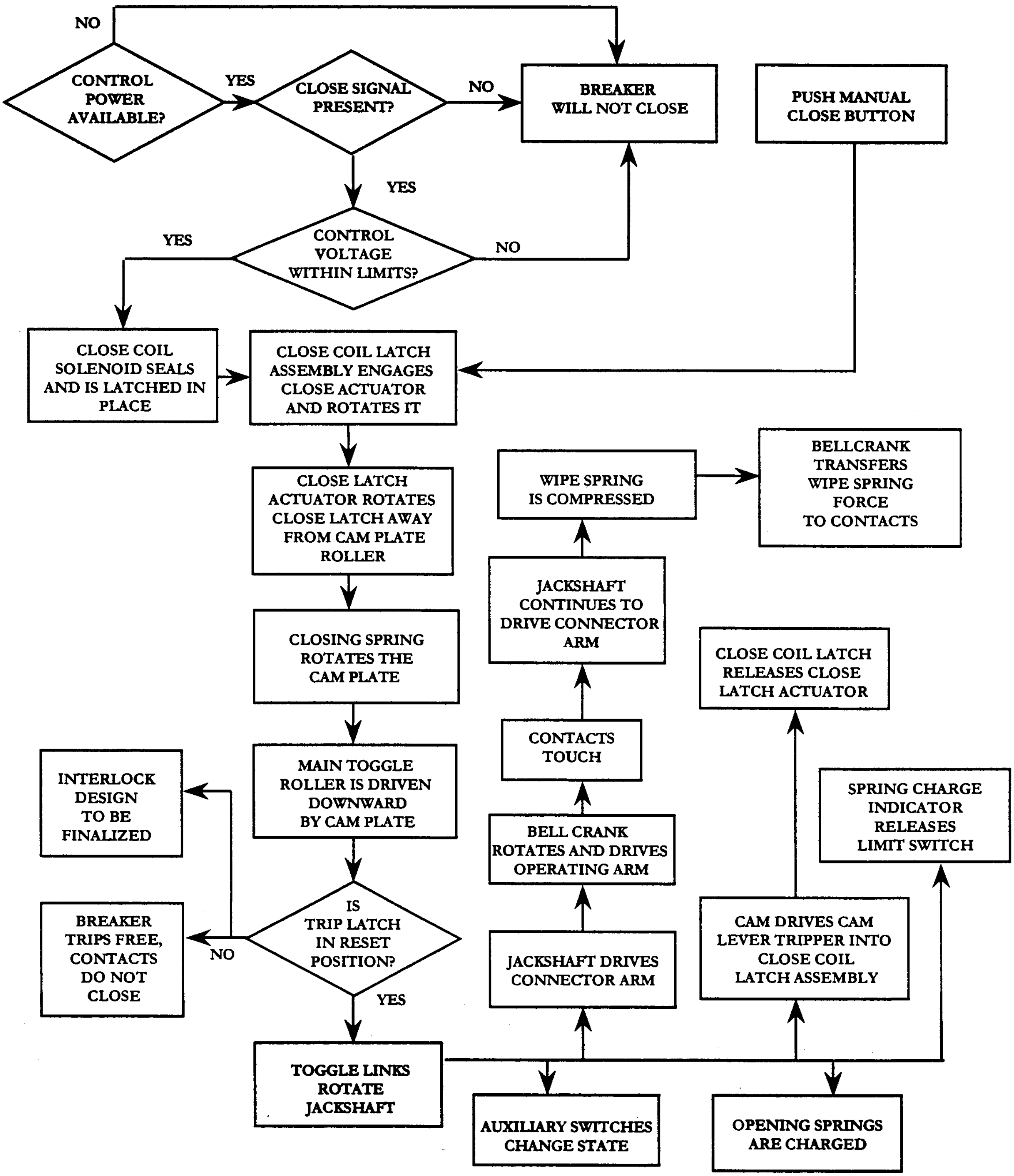


Figure 3-10: Operating Mechanism Closing System Flow Chart

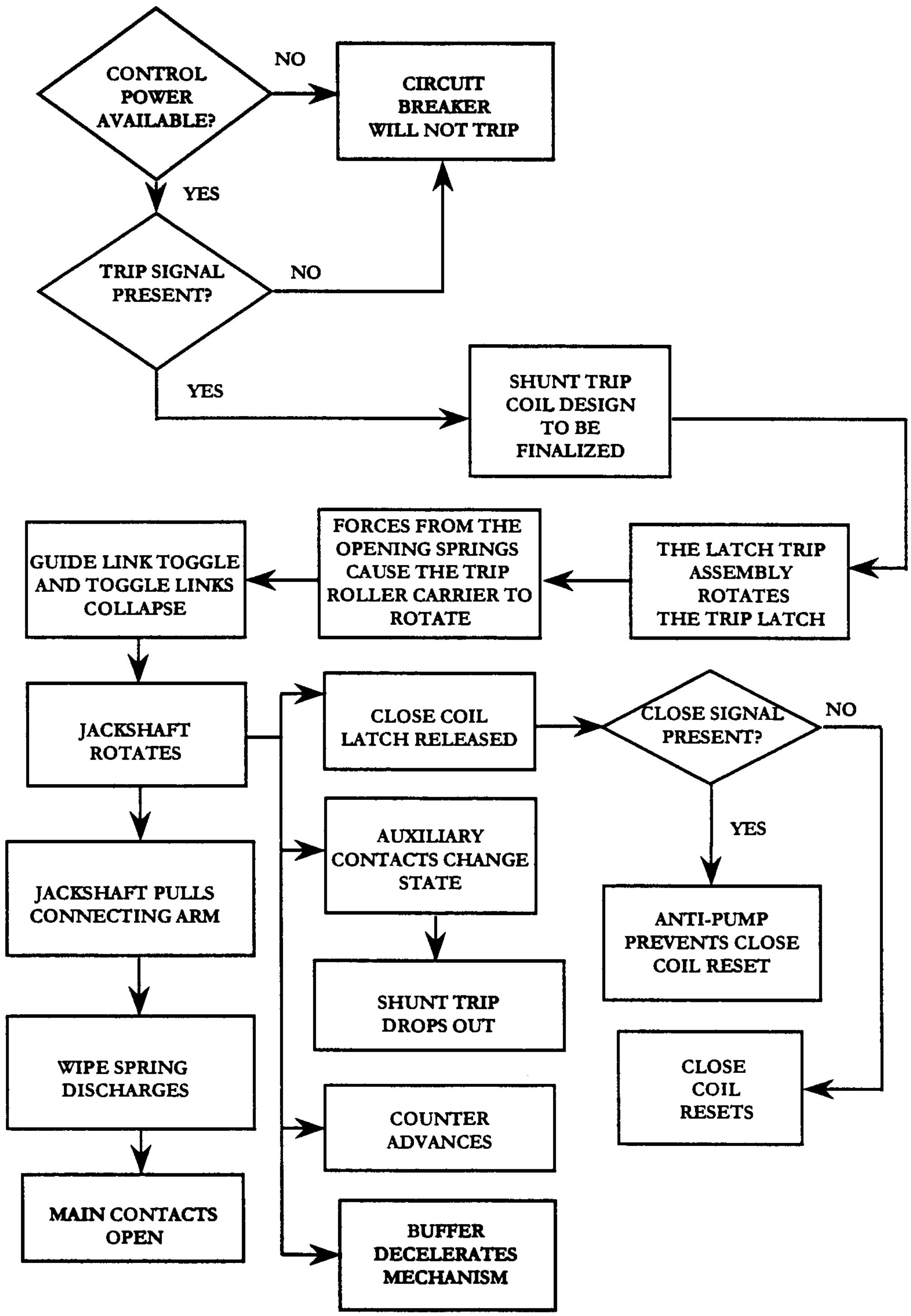


Figure 3-11: Operating Mechanism Shunt Trip System Flow Chart

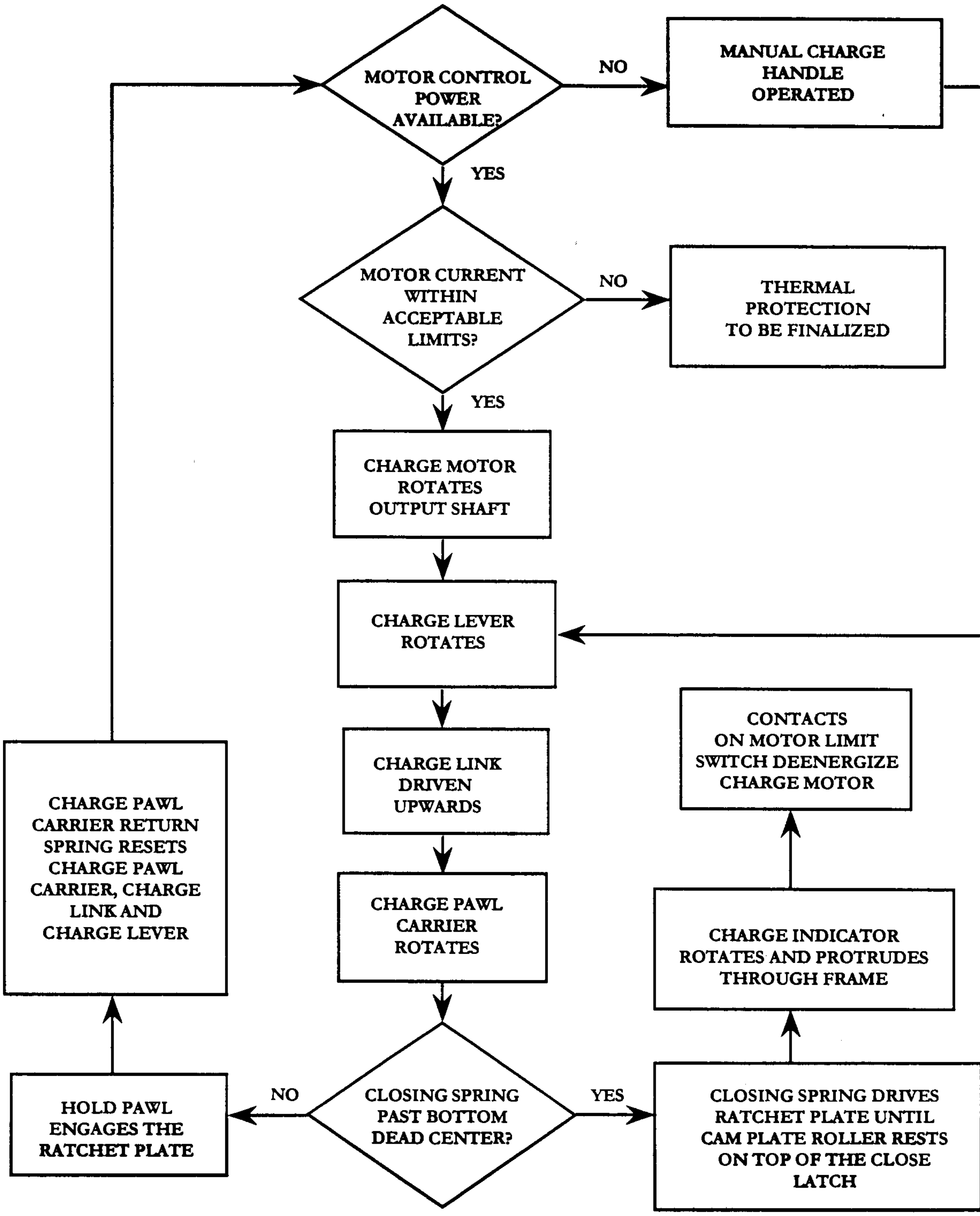


Figure 3-12: Operating Mechanism Charging System Flow Chart

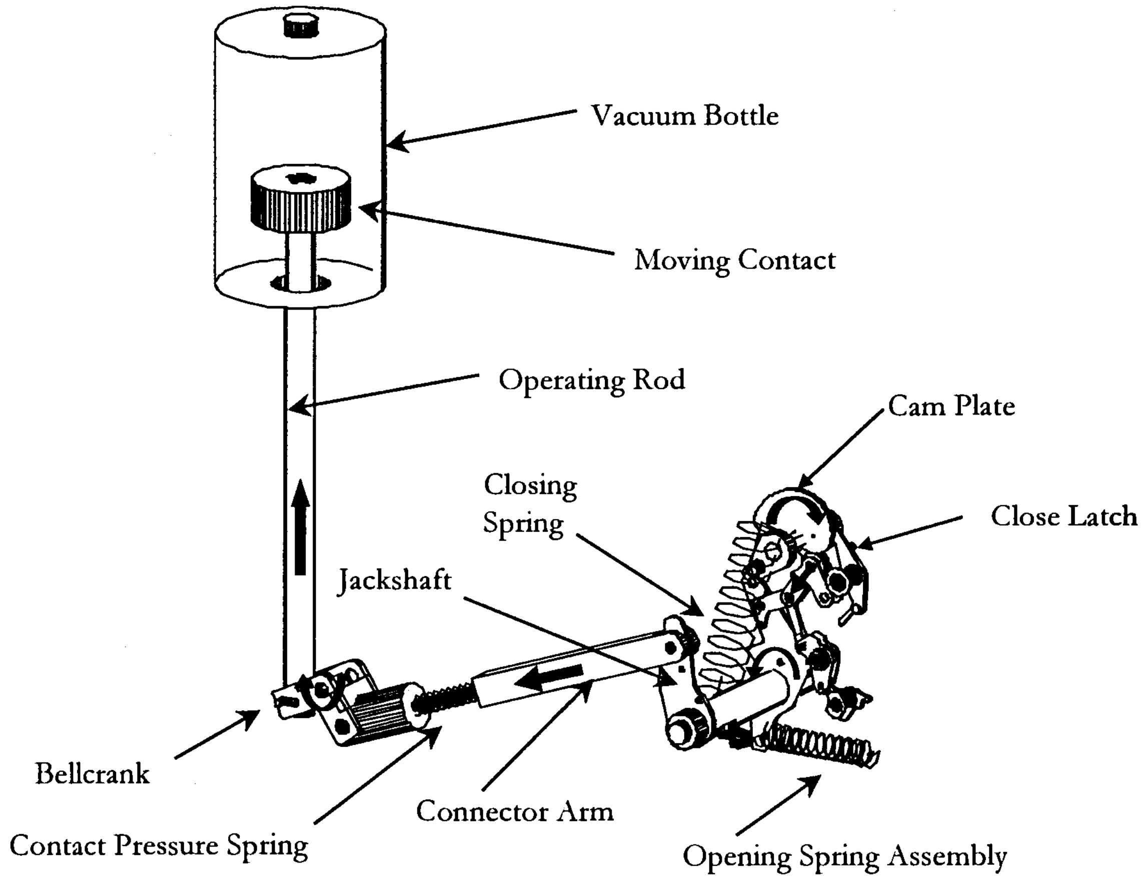


Figure 3-13: Trip / Close Mechanism Analysis Model

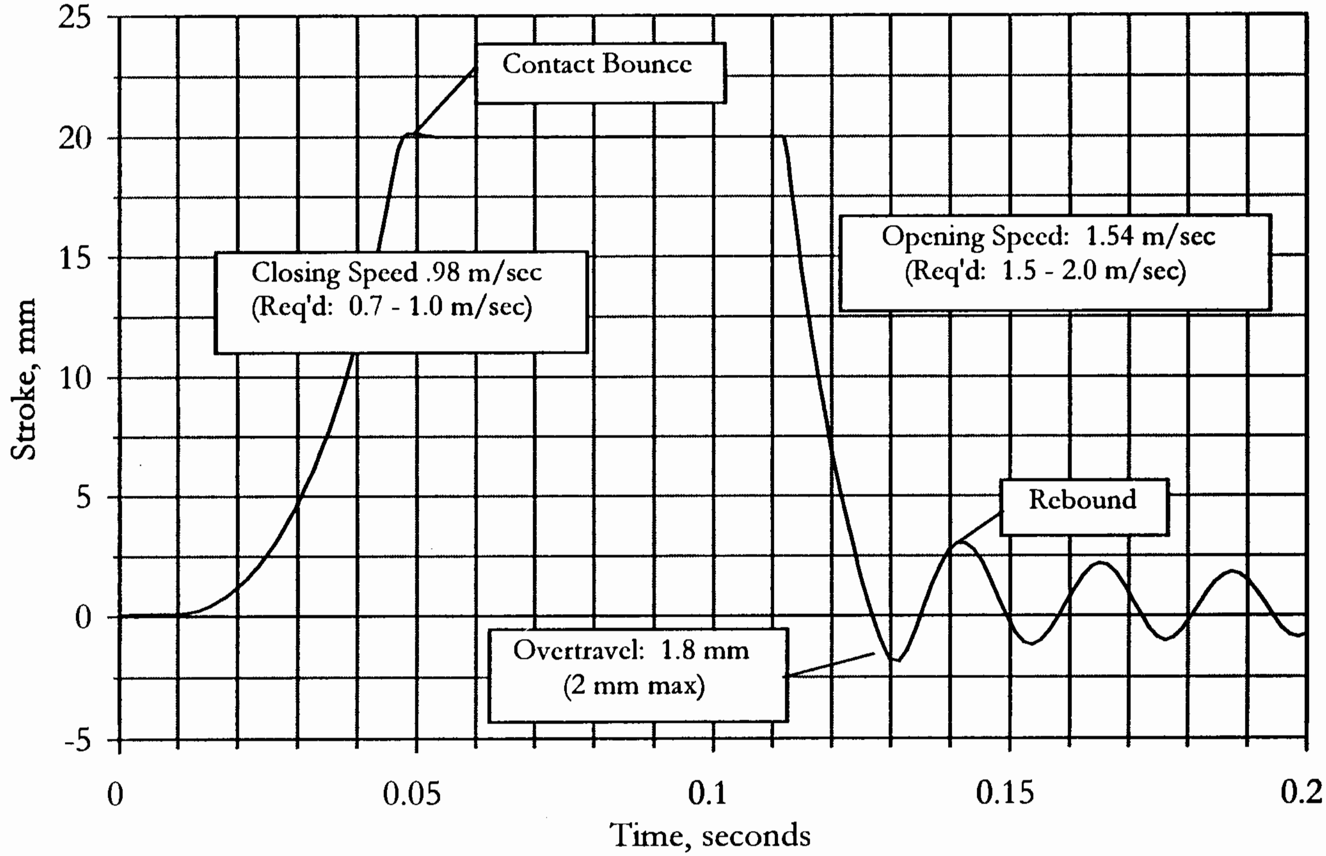


Figure 3-14: Vacuum Interrupter Contact Stroke Plot

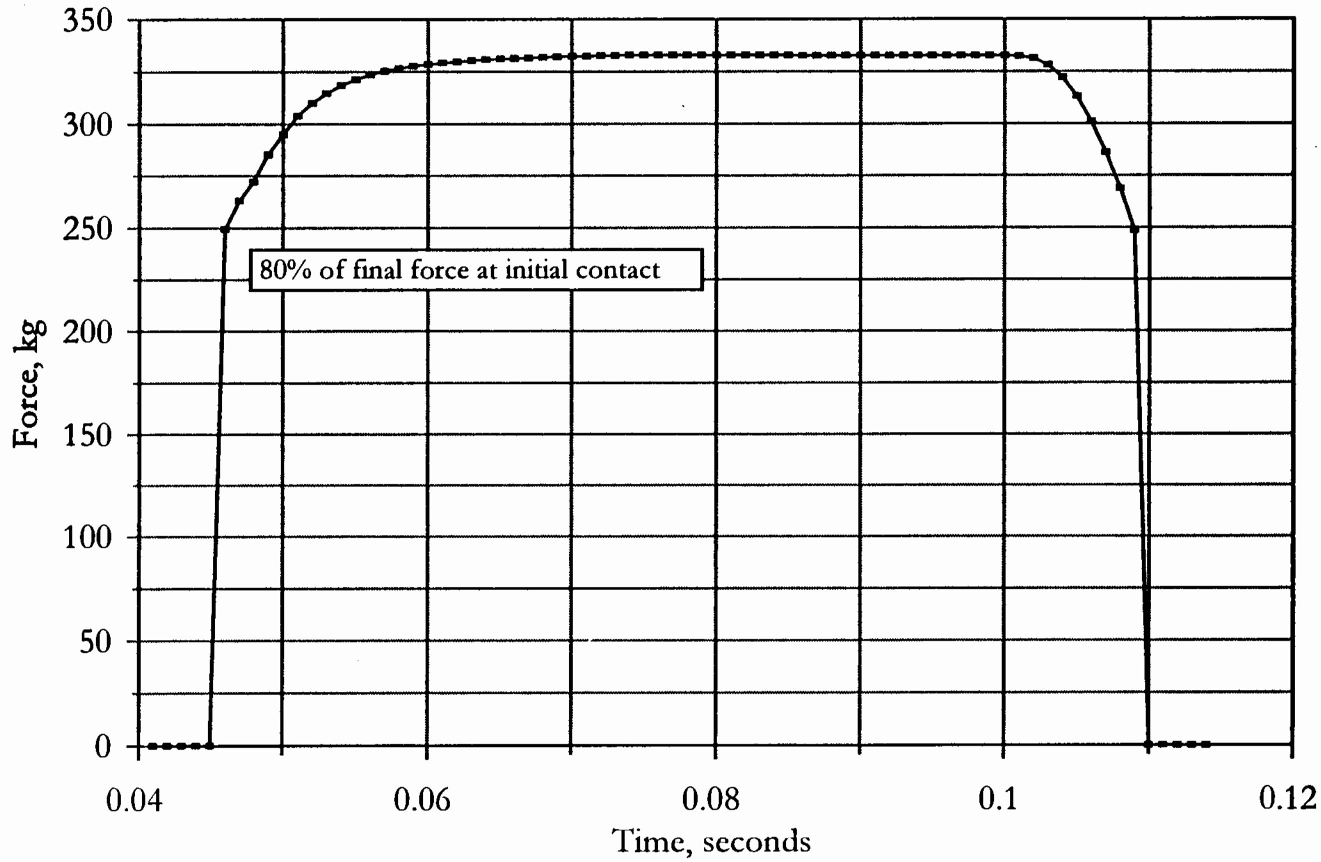


Figure 3-15: Vacuum Interrupter Contact Force Plot

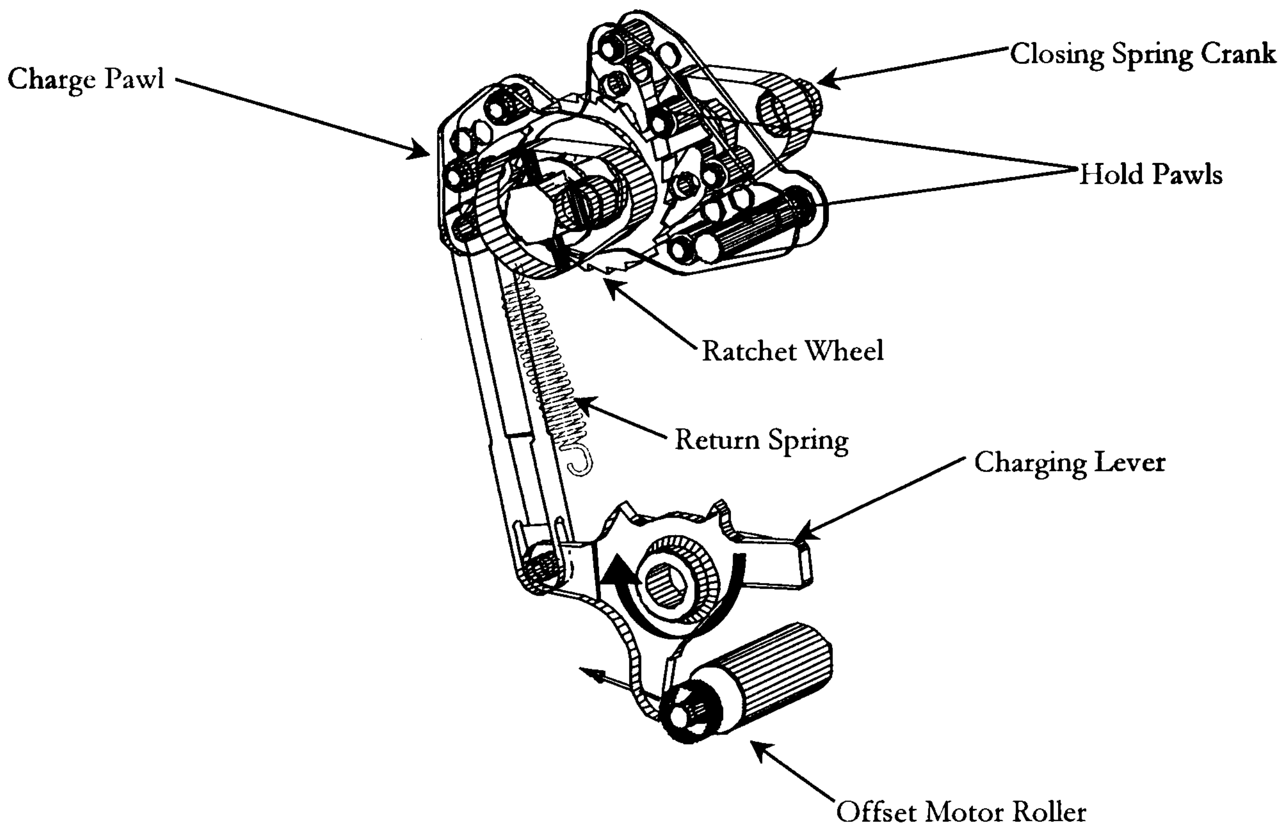


Figure 3-16: Charging System Analysis Model

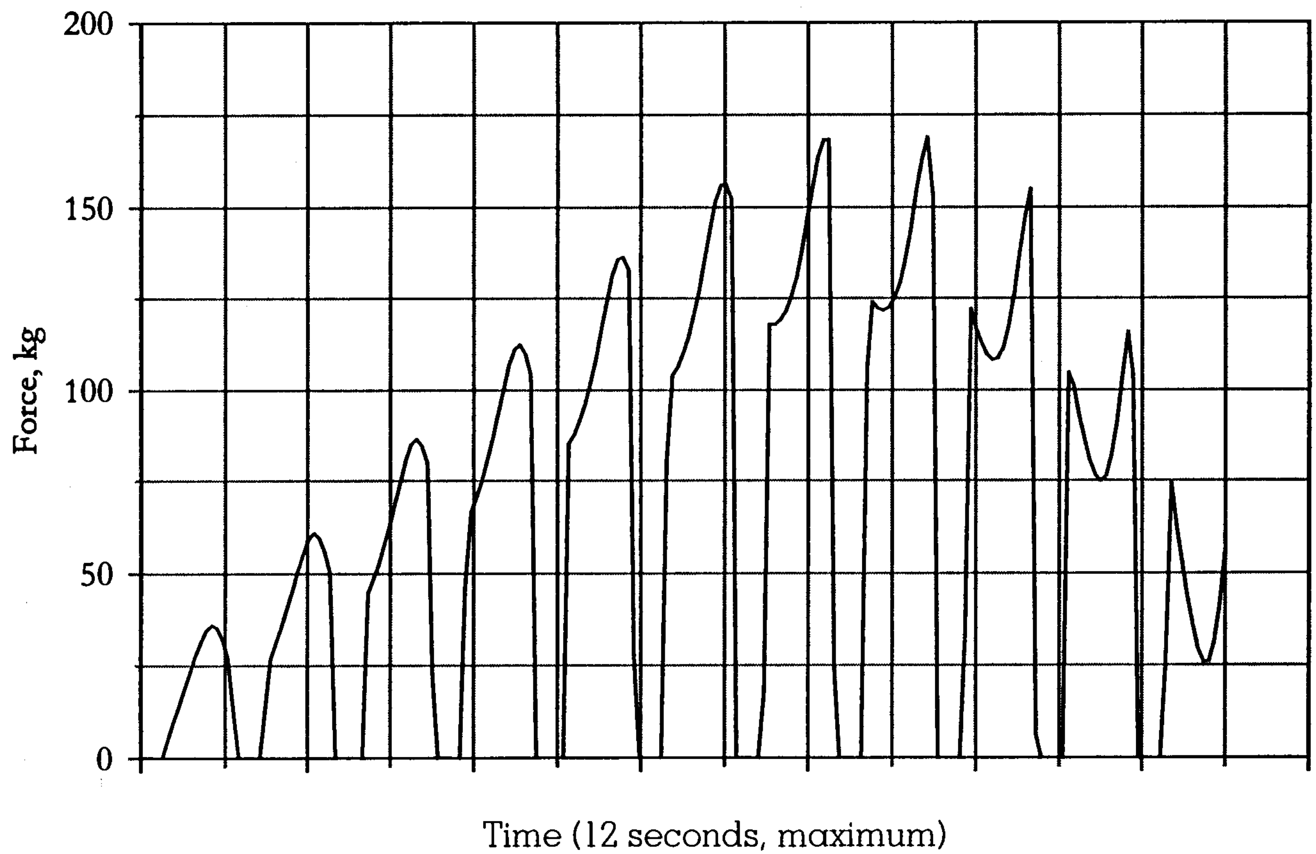


Figure 3-17: Charging Motor-Roller Force Plot

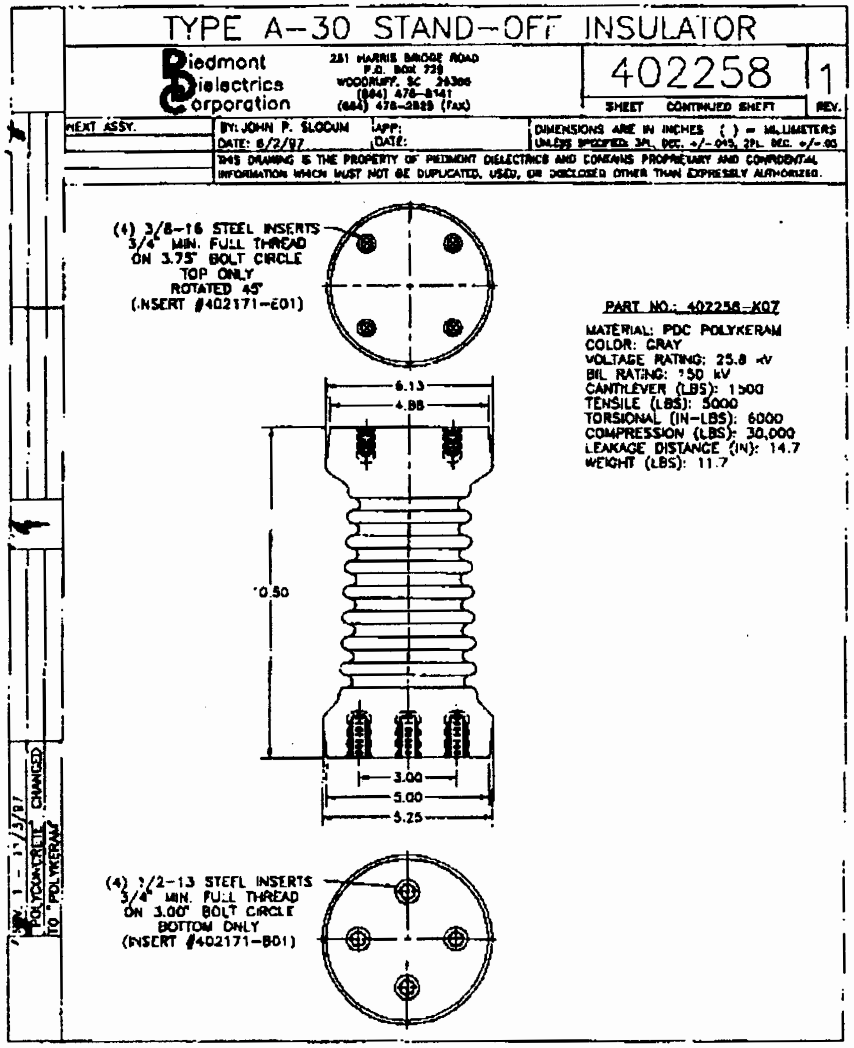


Figure 3-18: Insulator

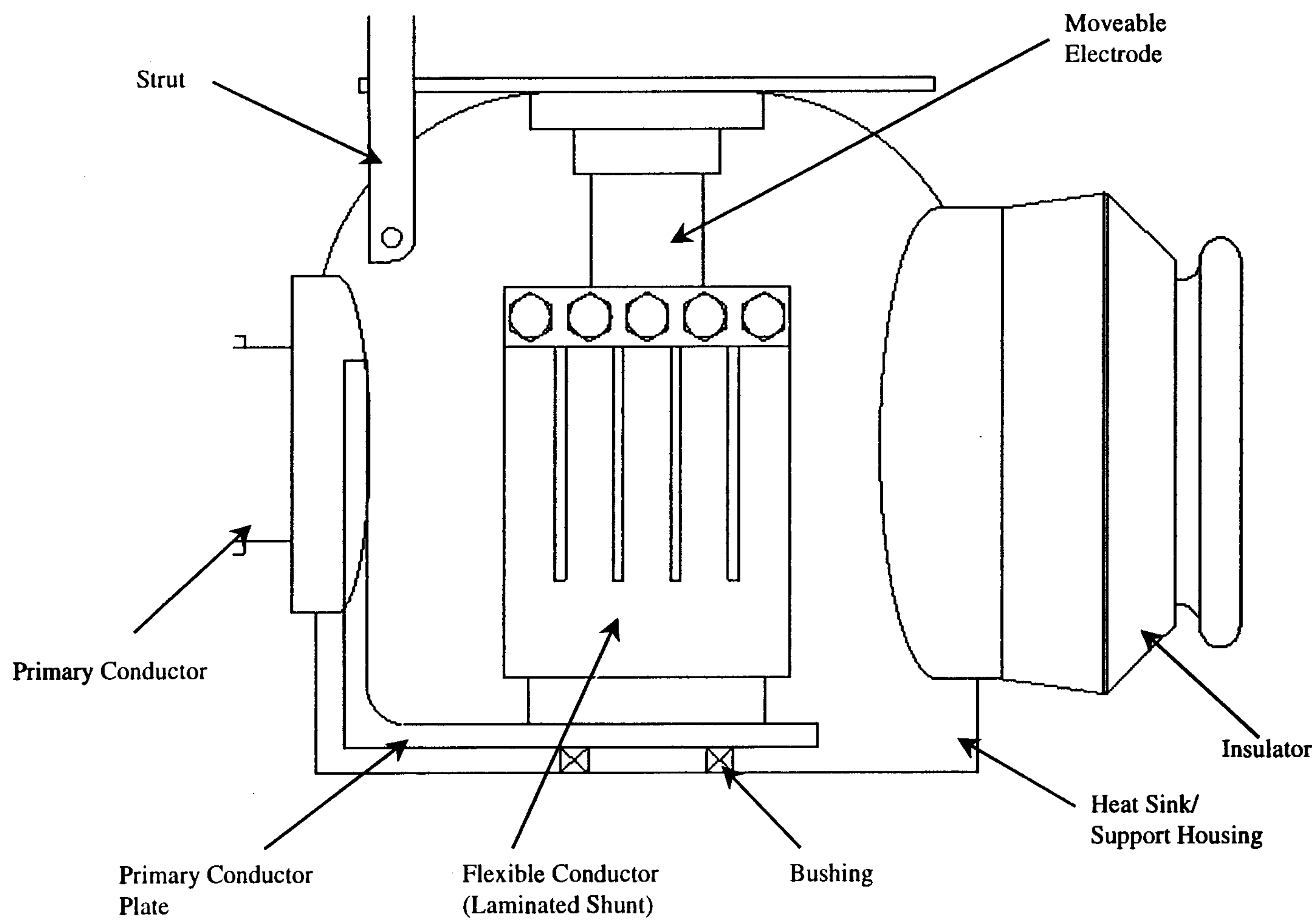


Figure 3-19: Heatsink/Support Housing: Option 1

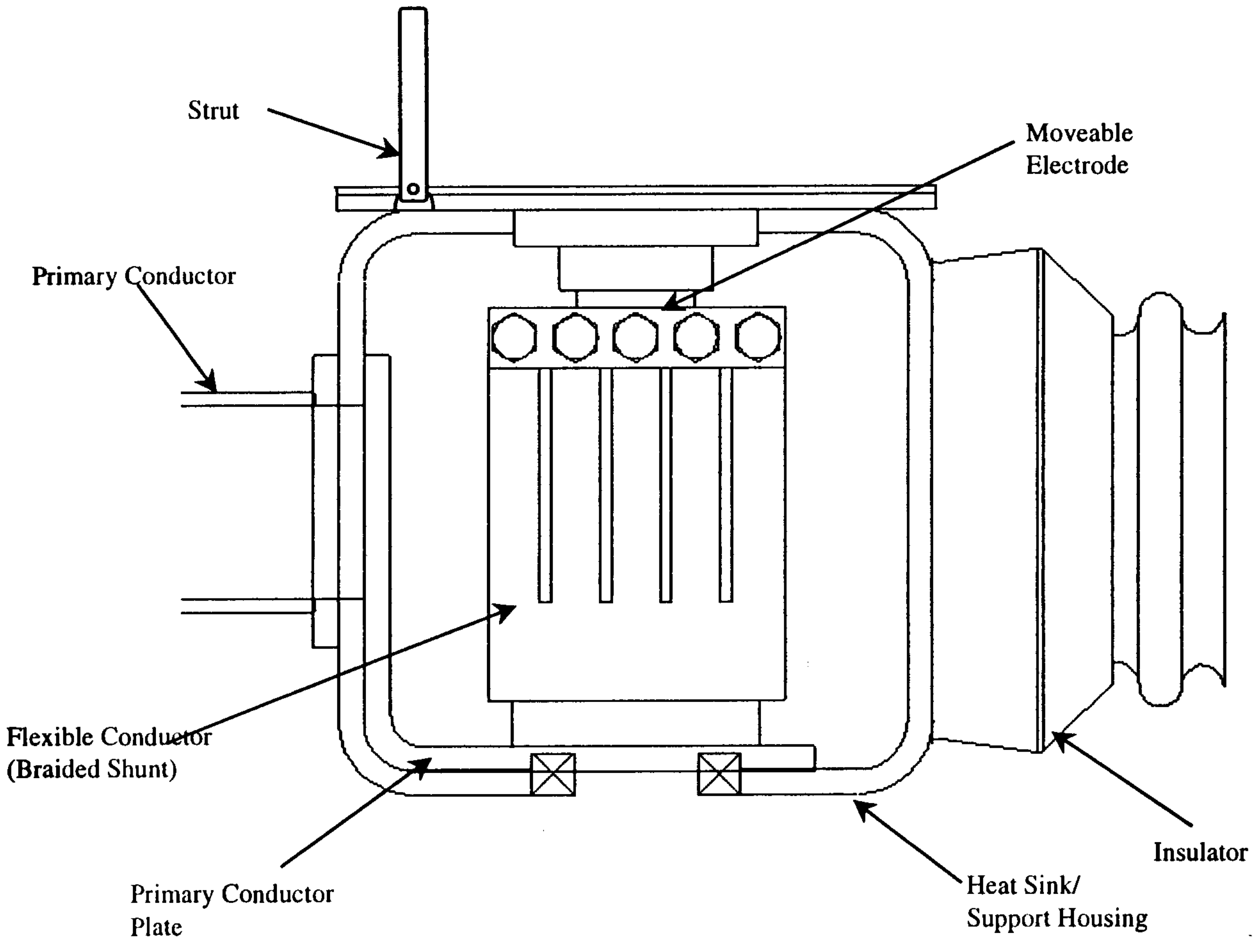


Figure 3-20: Heatsink/Support Housing: Option 2

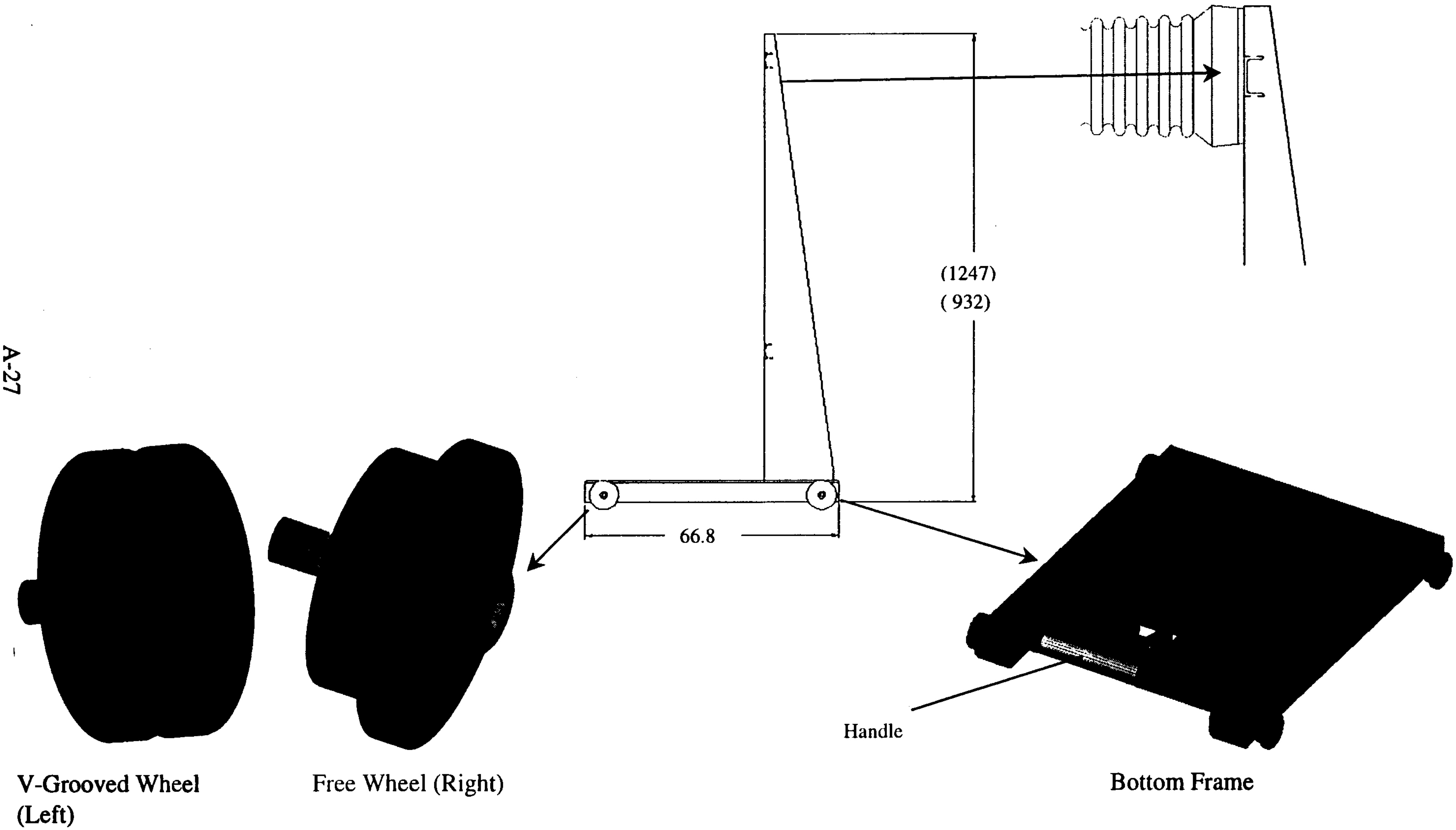


Figure 3-21: Circuit Breaker Truck Assemblies

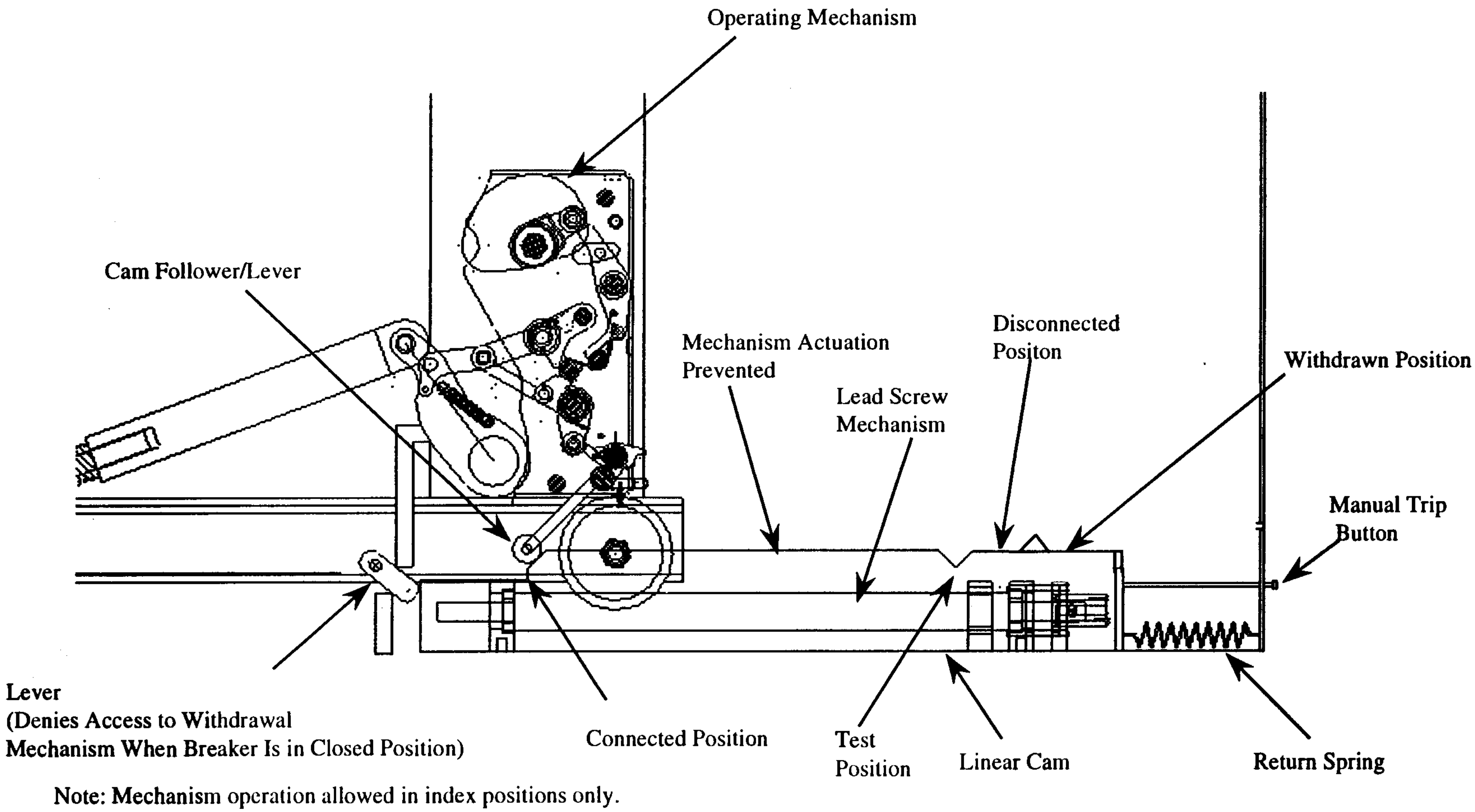


Figure 3-22: Circuit Breaker Interlock Mechanism Interfaces

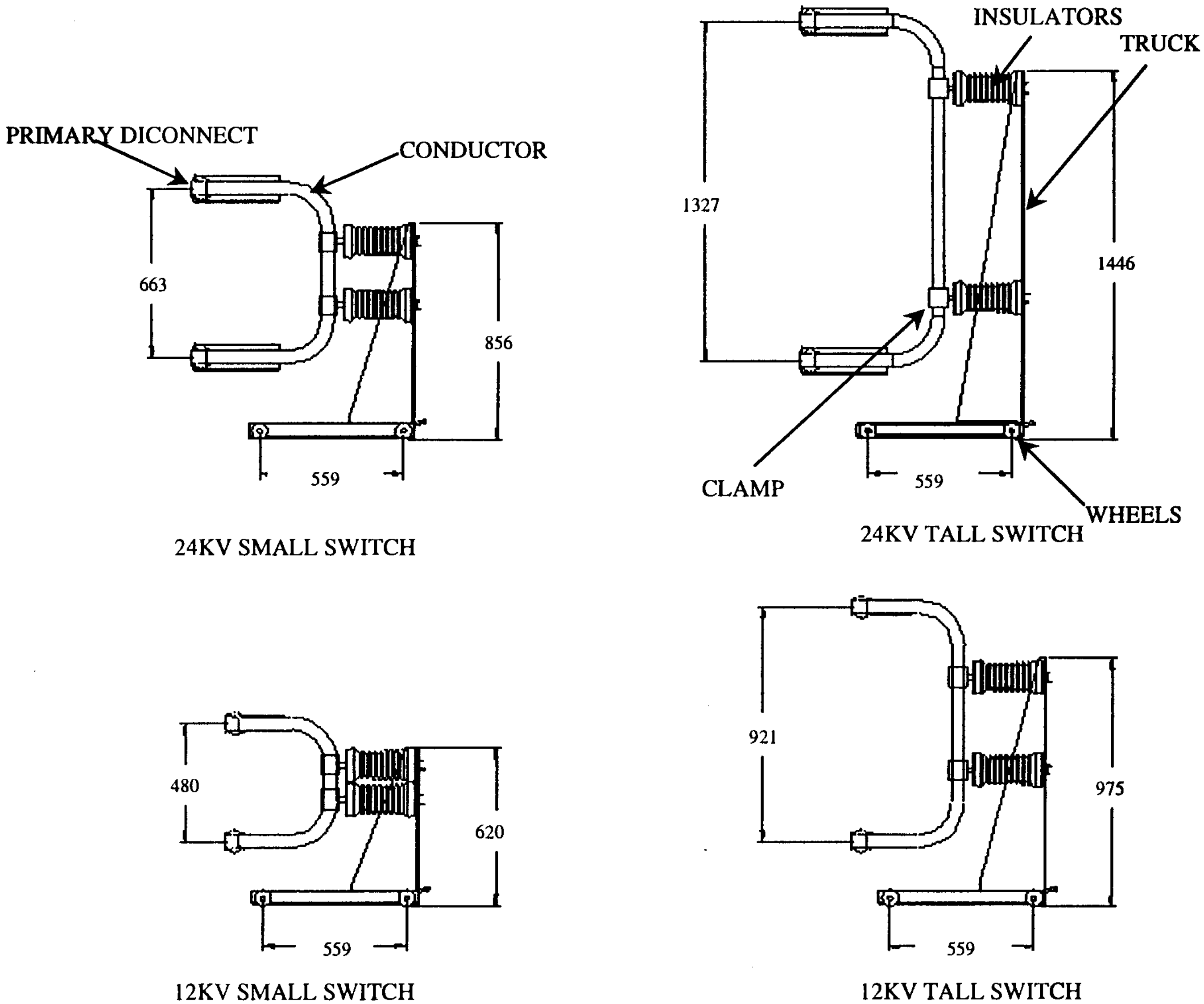
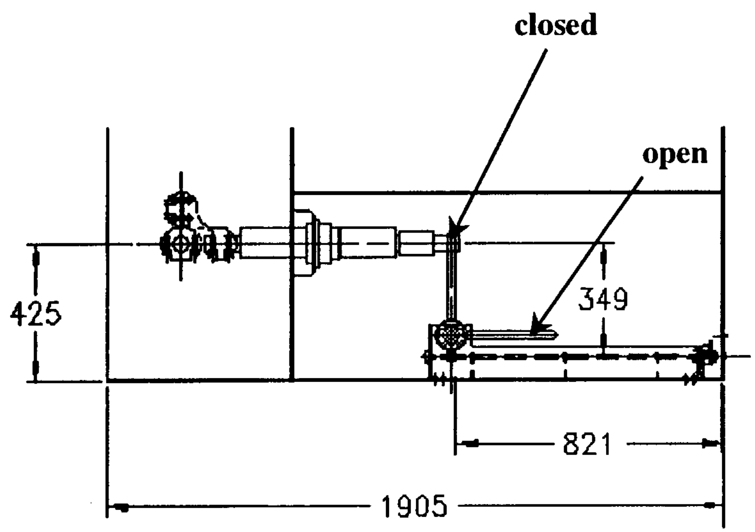
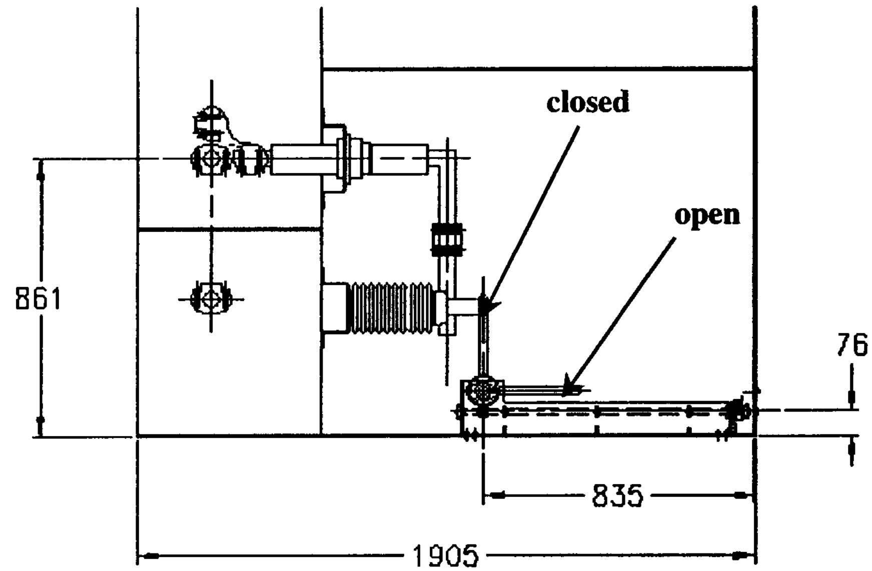


Figure 4-1: Test/Transfer and Incomer Disconnect Switch General Arrangements

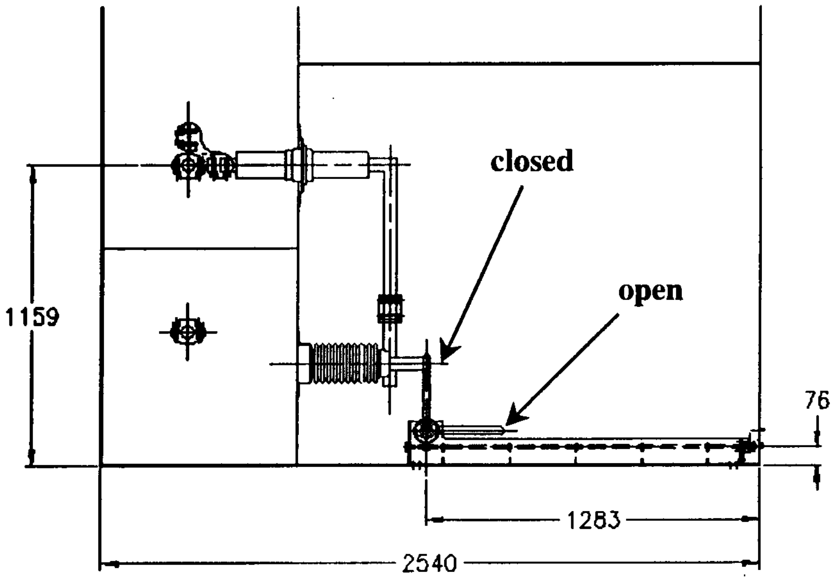


Main Bus Section Grounding Switch
(Bus Incomer Cubicle)

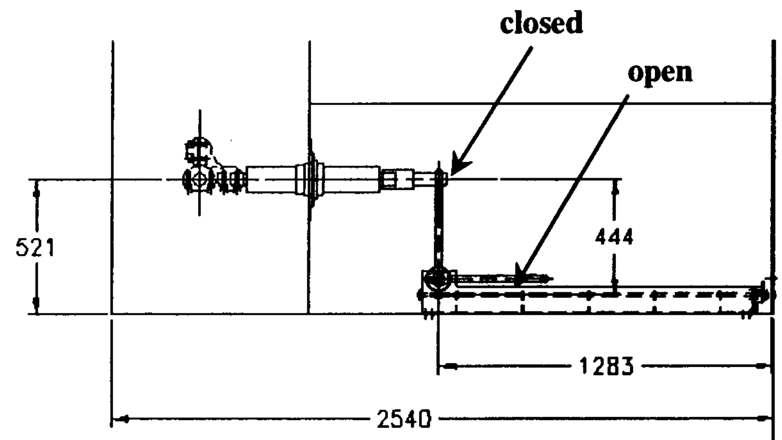


Trolley Circuit Grounding Switch
(Trolley Cubicle)

Figure 4-2: 12kV Ground Switch Arrangement



Feeder Circuit Grounding Switch
(Feeder Cubicle)



Main Bus Section Grounding Switch
(Bus Incomer Cubicle)

Figure 4-3: 24kV Ground Switch Arrangement

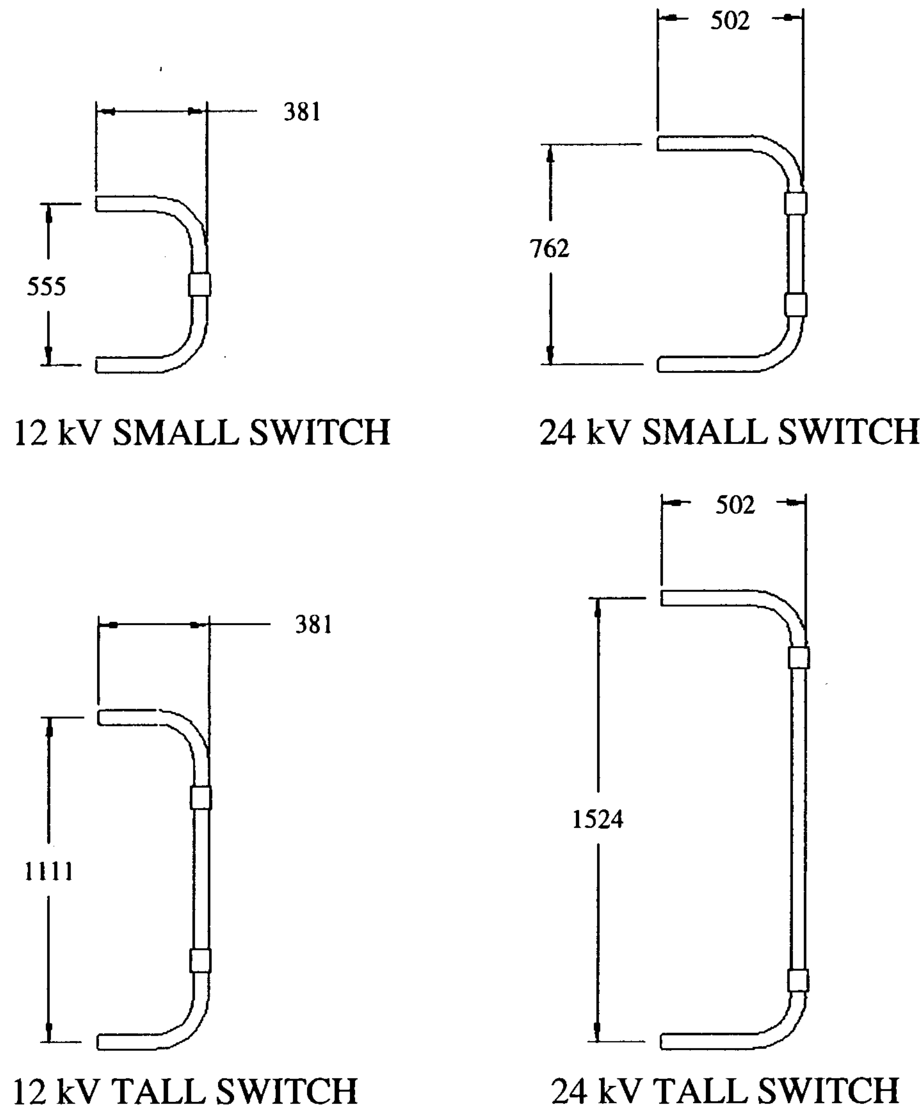


Figure 4-4: Test, Transfer, and Incomer Disconnect Switch Conductors

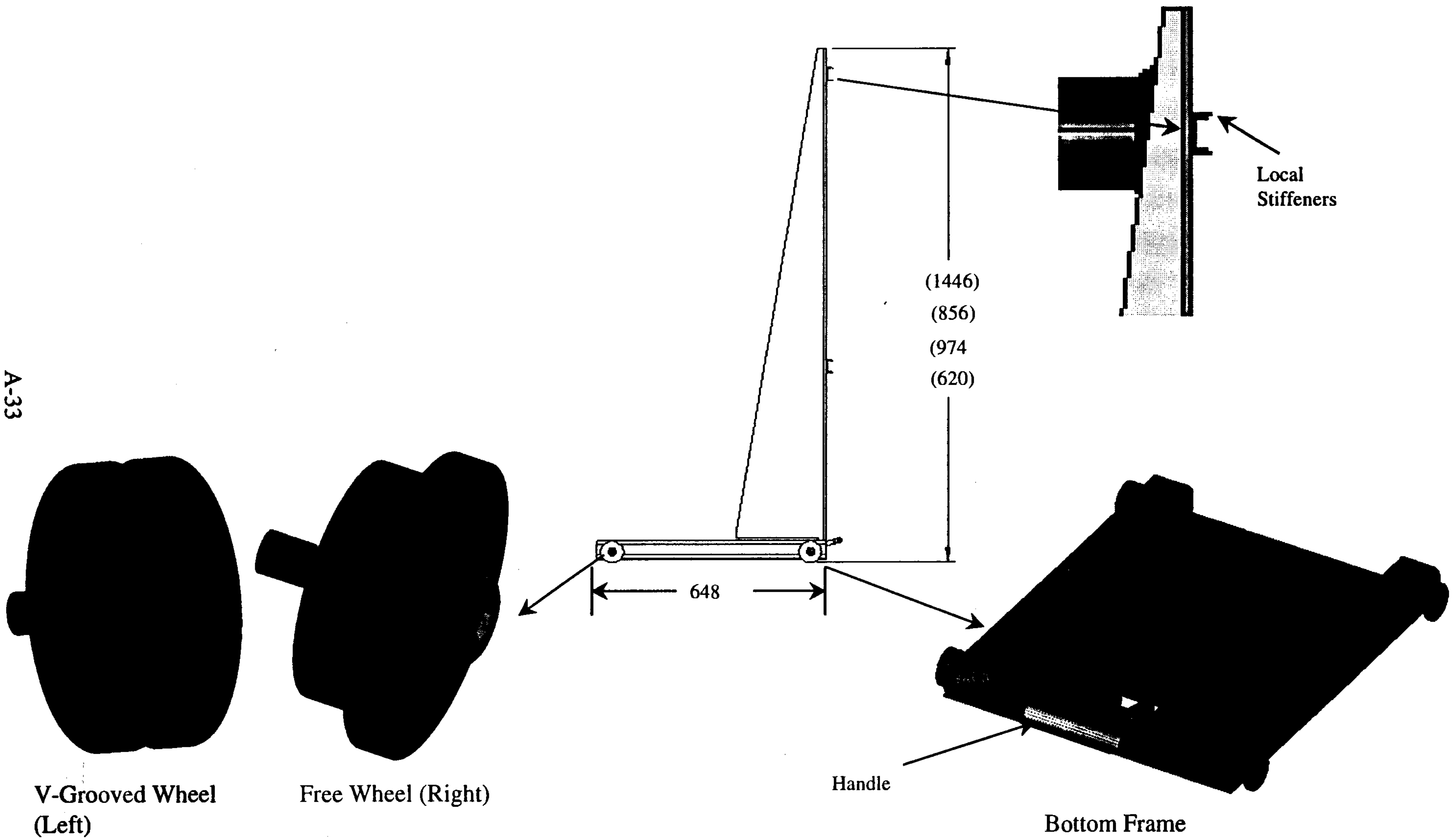
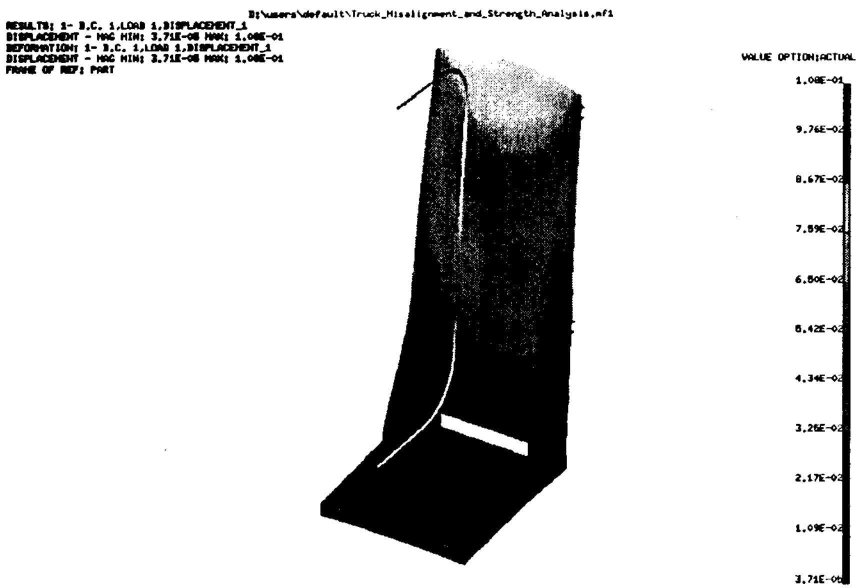
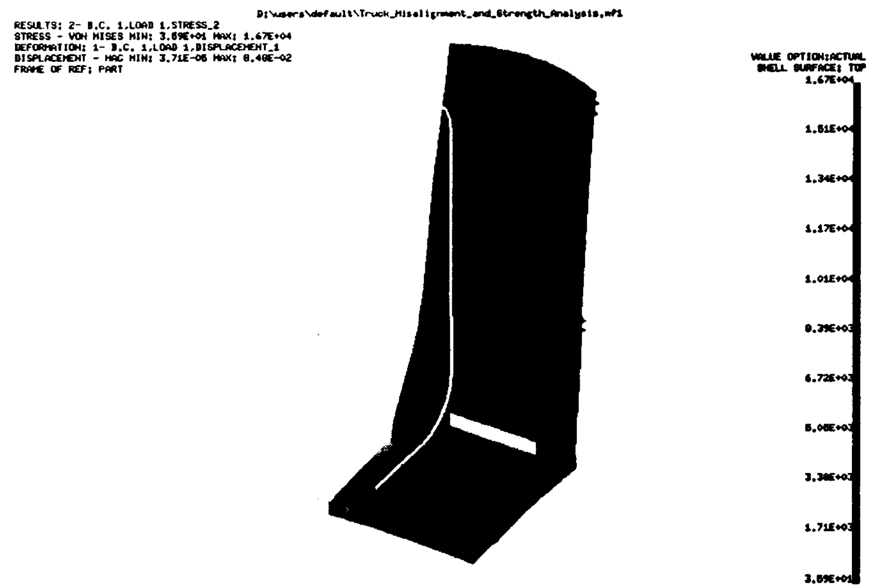


Figure 4-5: Test, Transfer and Incomer Disconnect Truck Assemblies

24 kV Tall Disconnect Switch



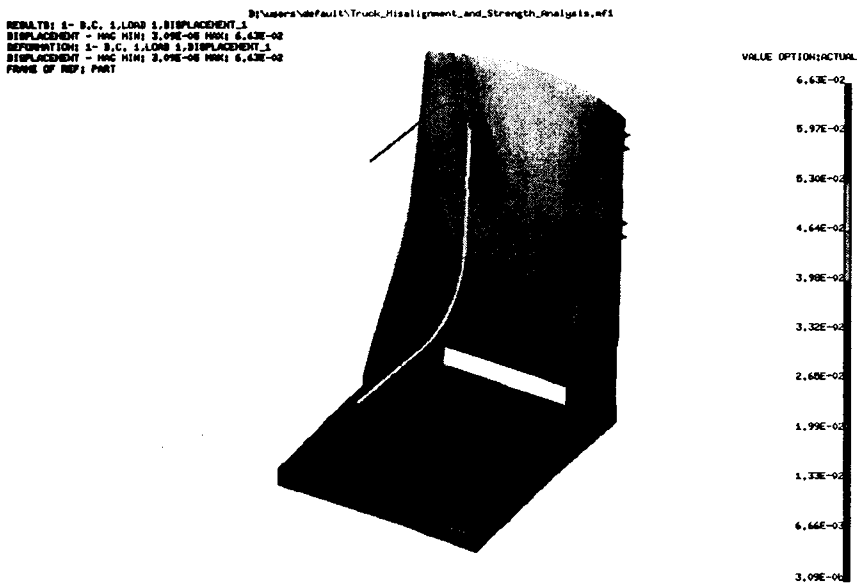
Deflection



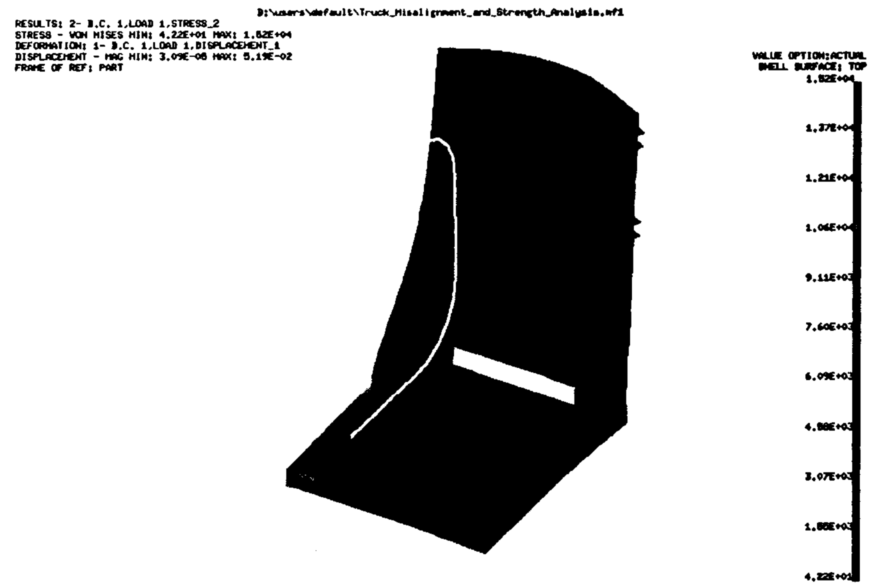
Stress

Figure 4-6A: Test, Transfer, and Incomer Disconnect Switch Truck Analysis Results

24 kV Small Disconnect Switch



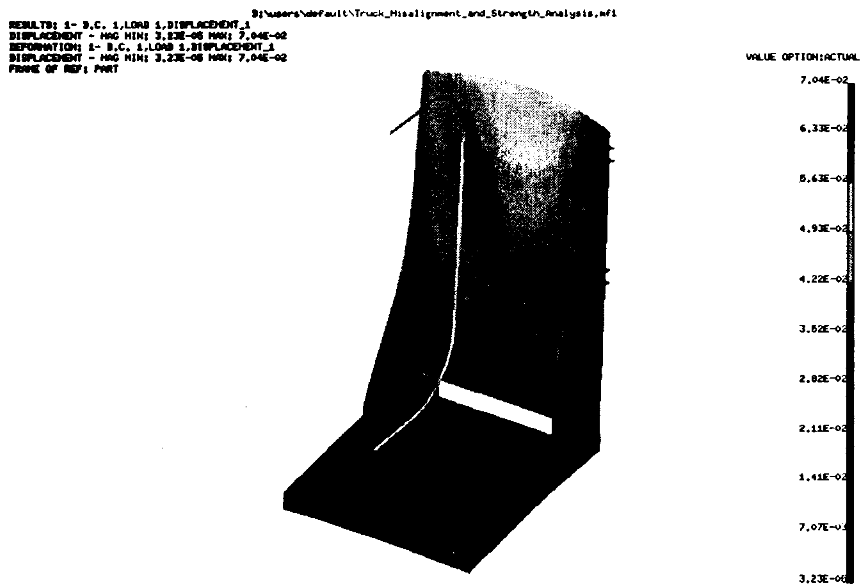
Deflection



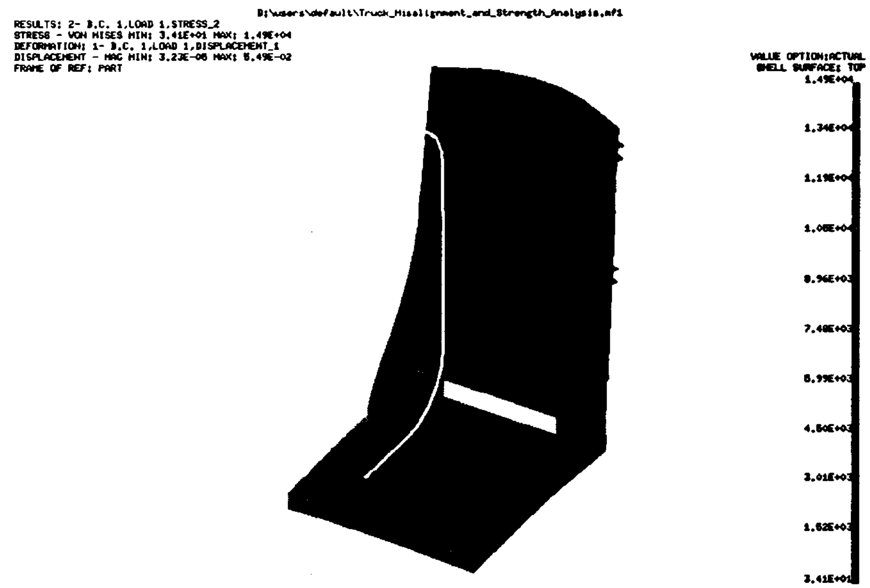
Stress

Figure 4-6B: Test, Transfer, and Incomer Disconnect Switch Truck Analysis Results

12 kV Tall Disconnect Switch



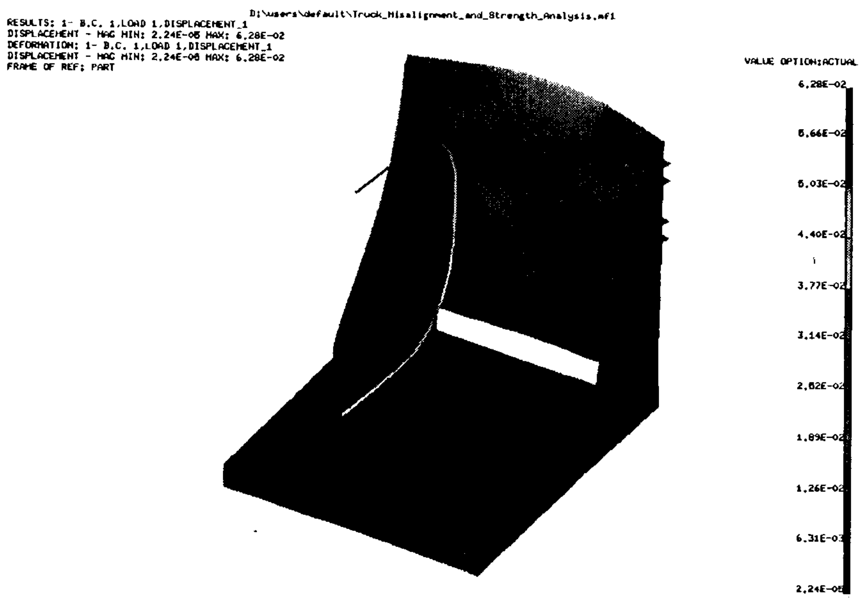
Deflection



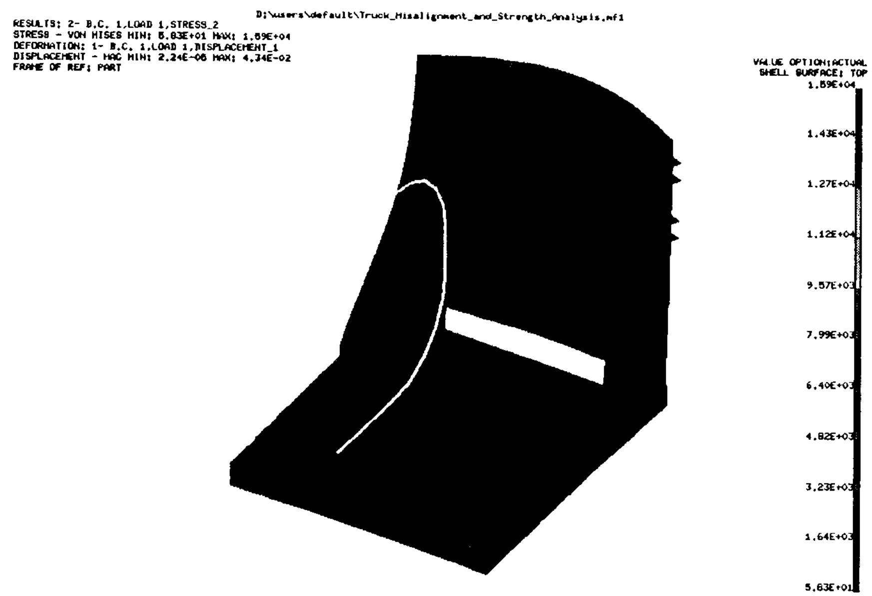
Stress

Figure 4-6C: Test, Transfer, and Incomer Disconnect Switch Truck Analysis Results

24 kV Small Disconnect Switch



Deflection



Stress

Figure 4-6D: Test, Transfer, and Incomer Disconnect Switch Truck Analysis Results

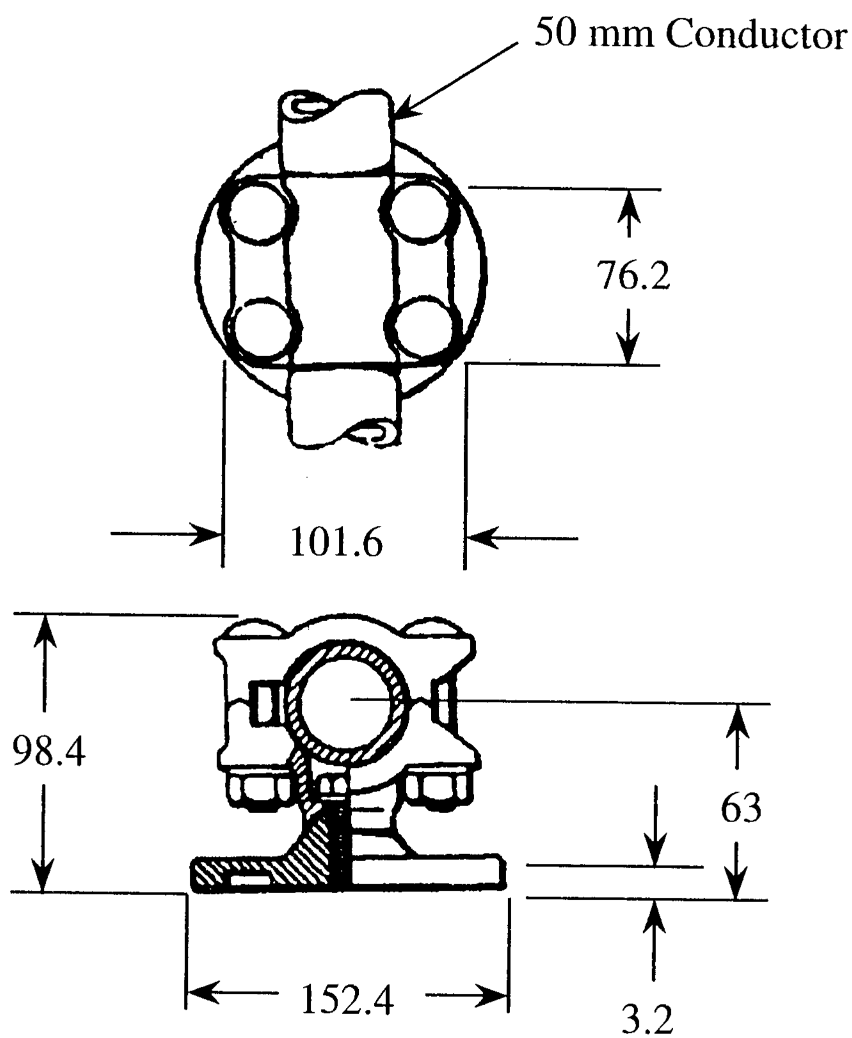


Figure 4-7: Conductor Support Clamp

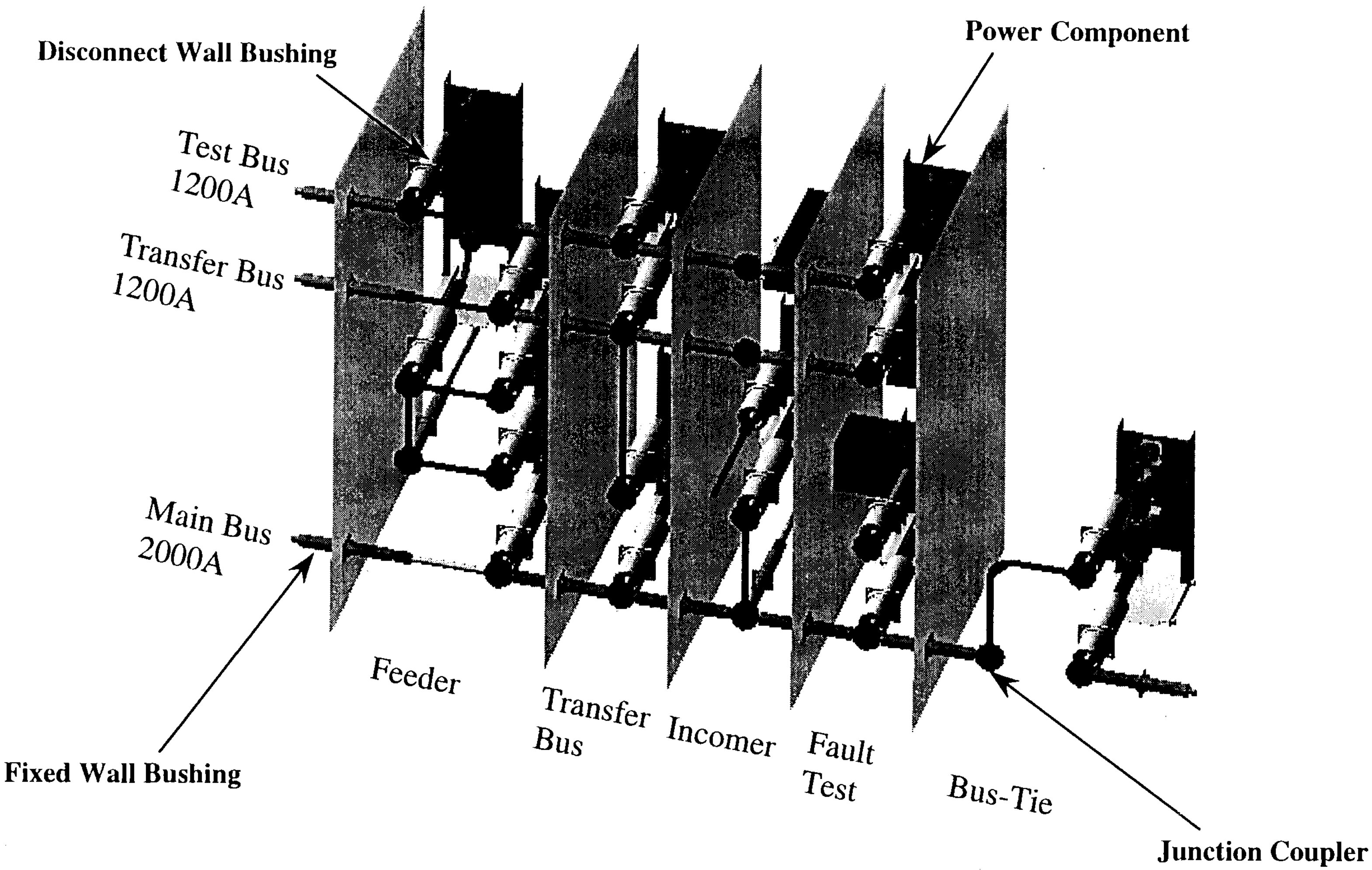


Figure 5-1: Representative Bus Structure

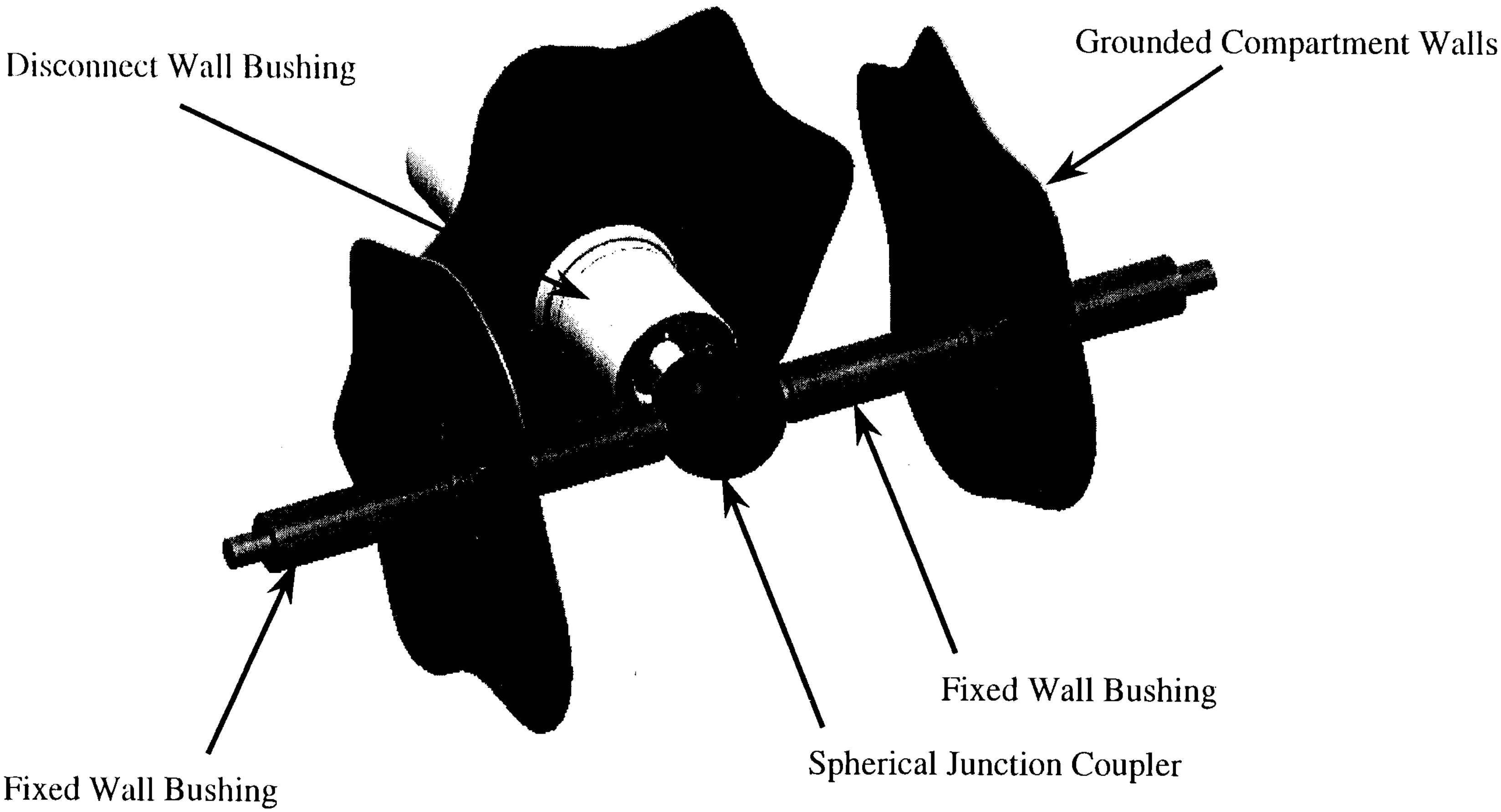


Figure 5-2: Typical Branch Circuit using Spherical Junction Coupler

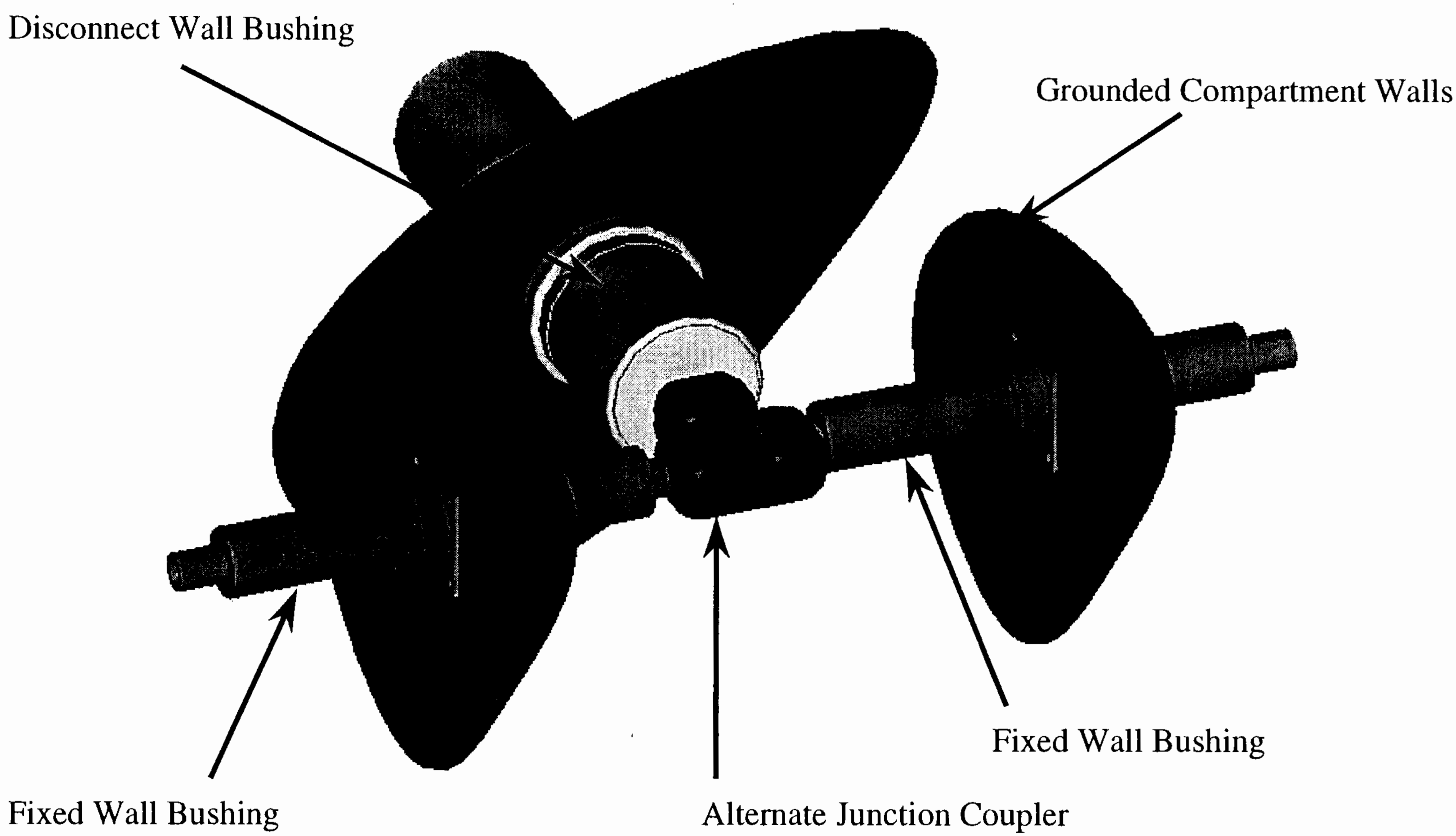


Figure 5-3: Typical Branch Circuit using Alternate Junction Coupler

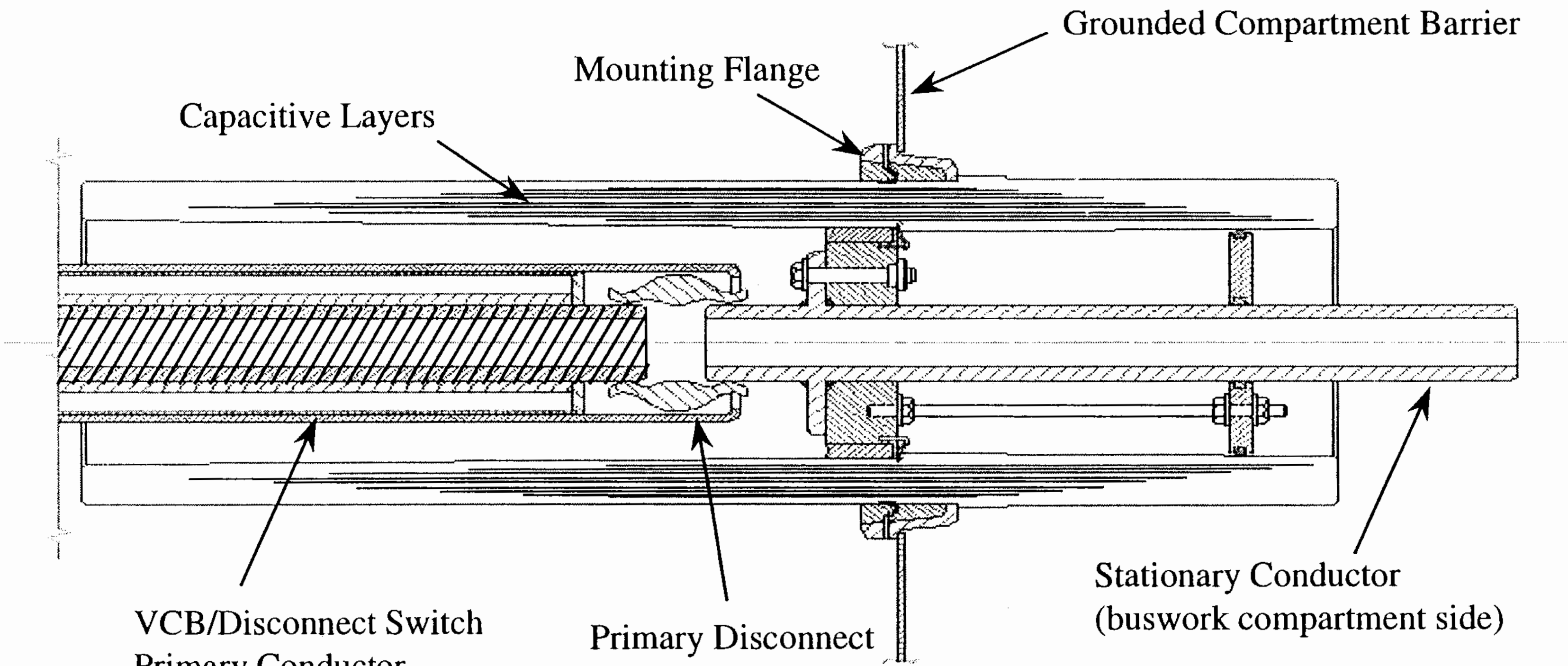


Figure 5-4: Primary Disconnect Bushing: Engaged

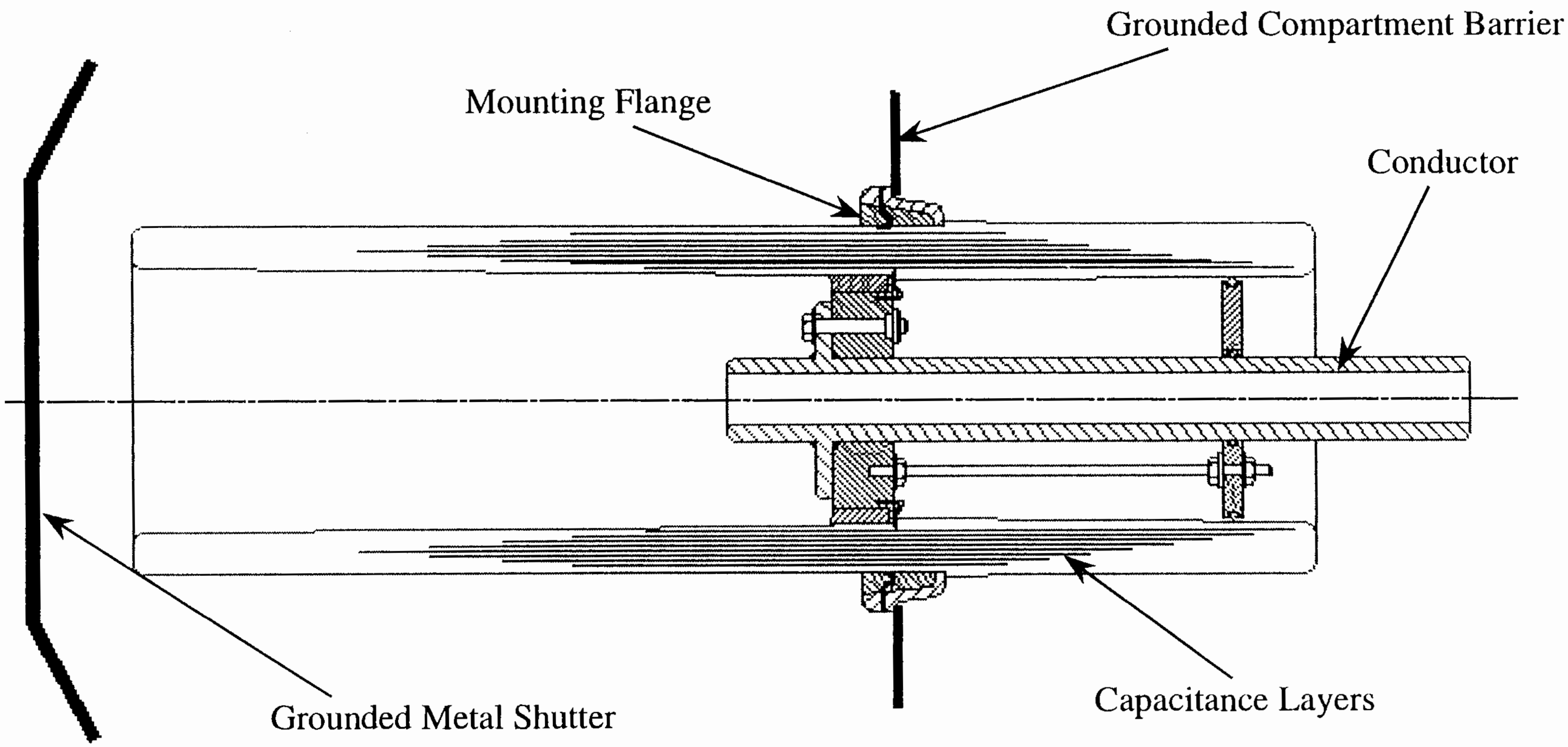


Figure 5-5: Primary Disconnect Bushing: Disengaged

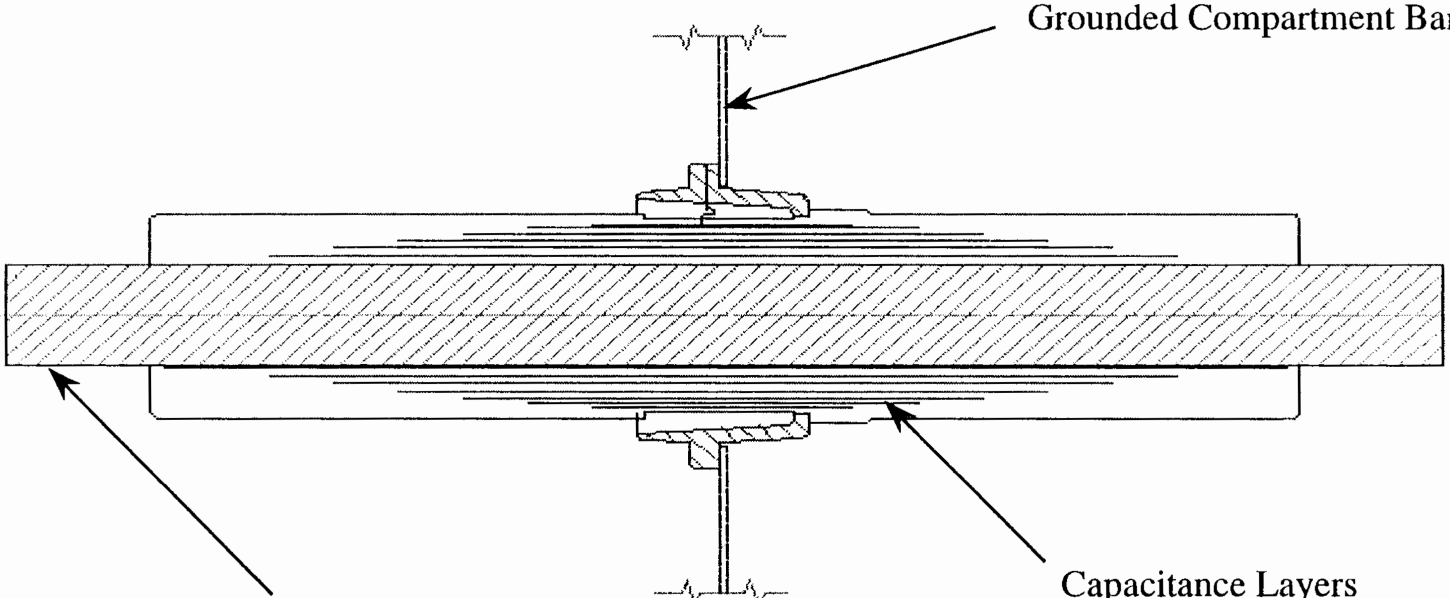


Figure 5-6: Fixed Wall Bushing

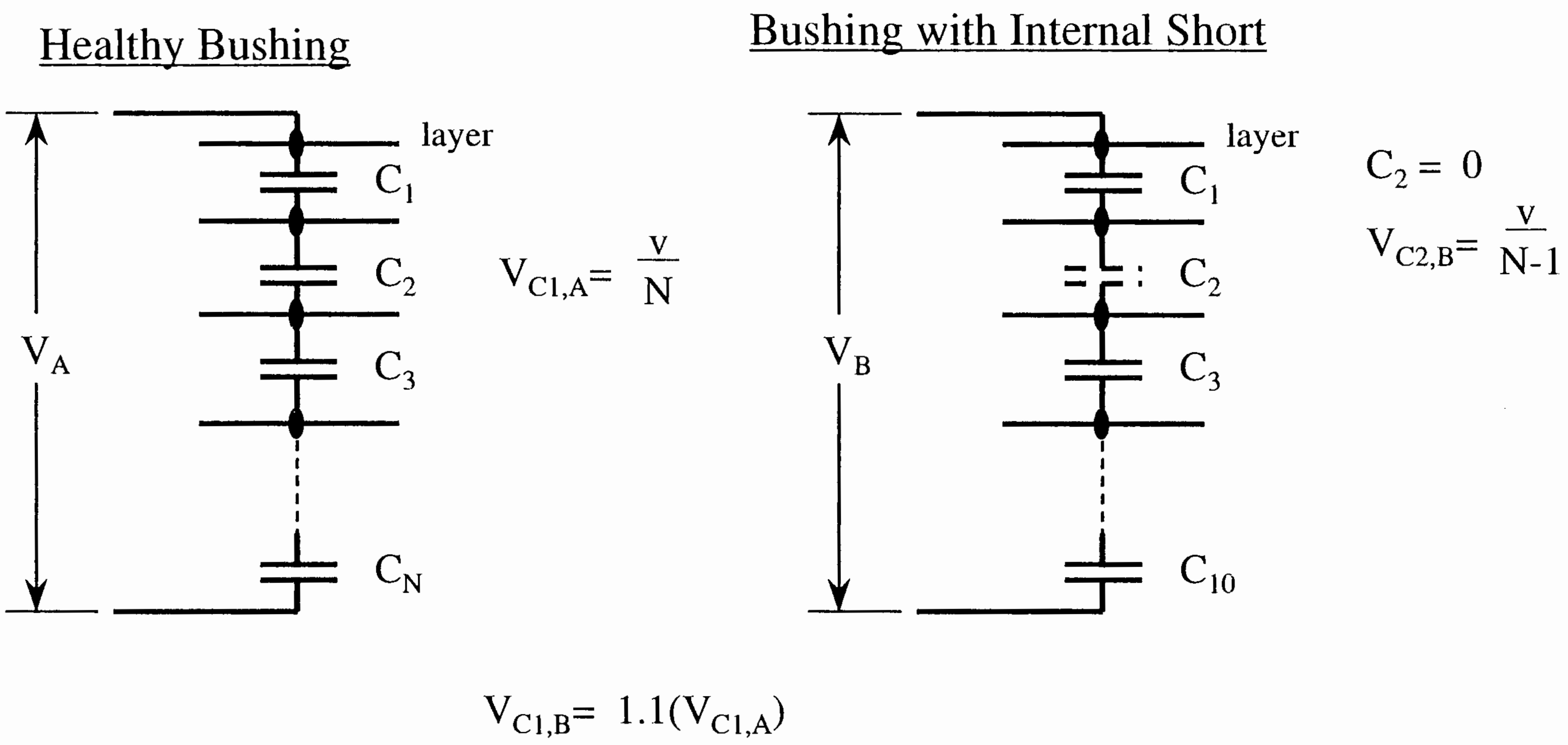


Figure 5-7: Capacitive Layer Failure Analysis Results

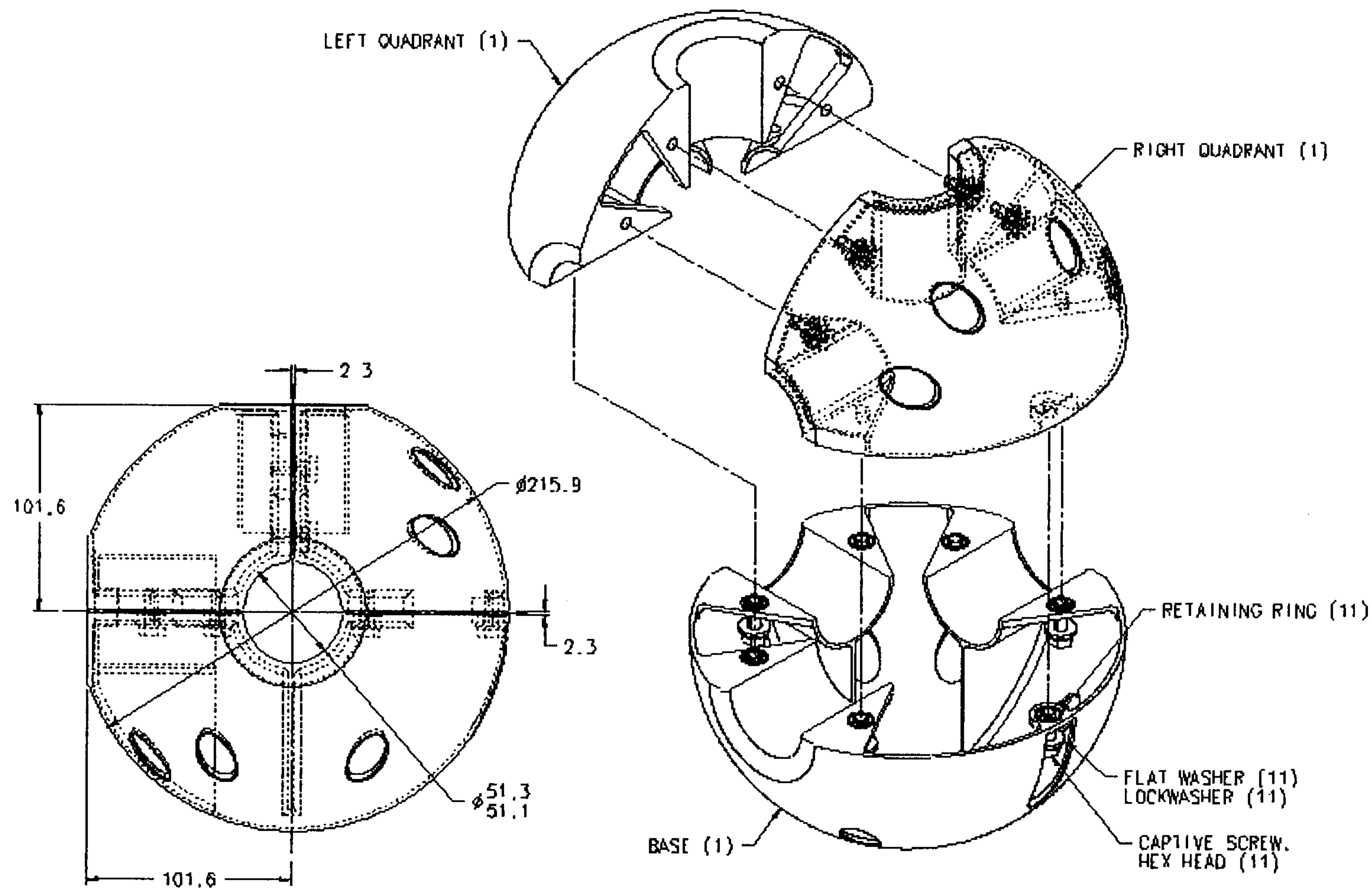


Figure 5-8: Spherical Junction Coupler

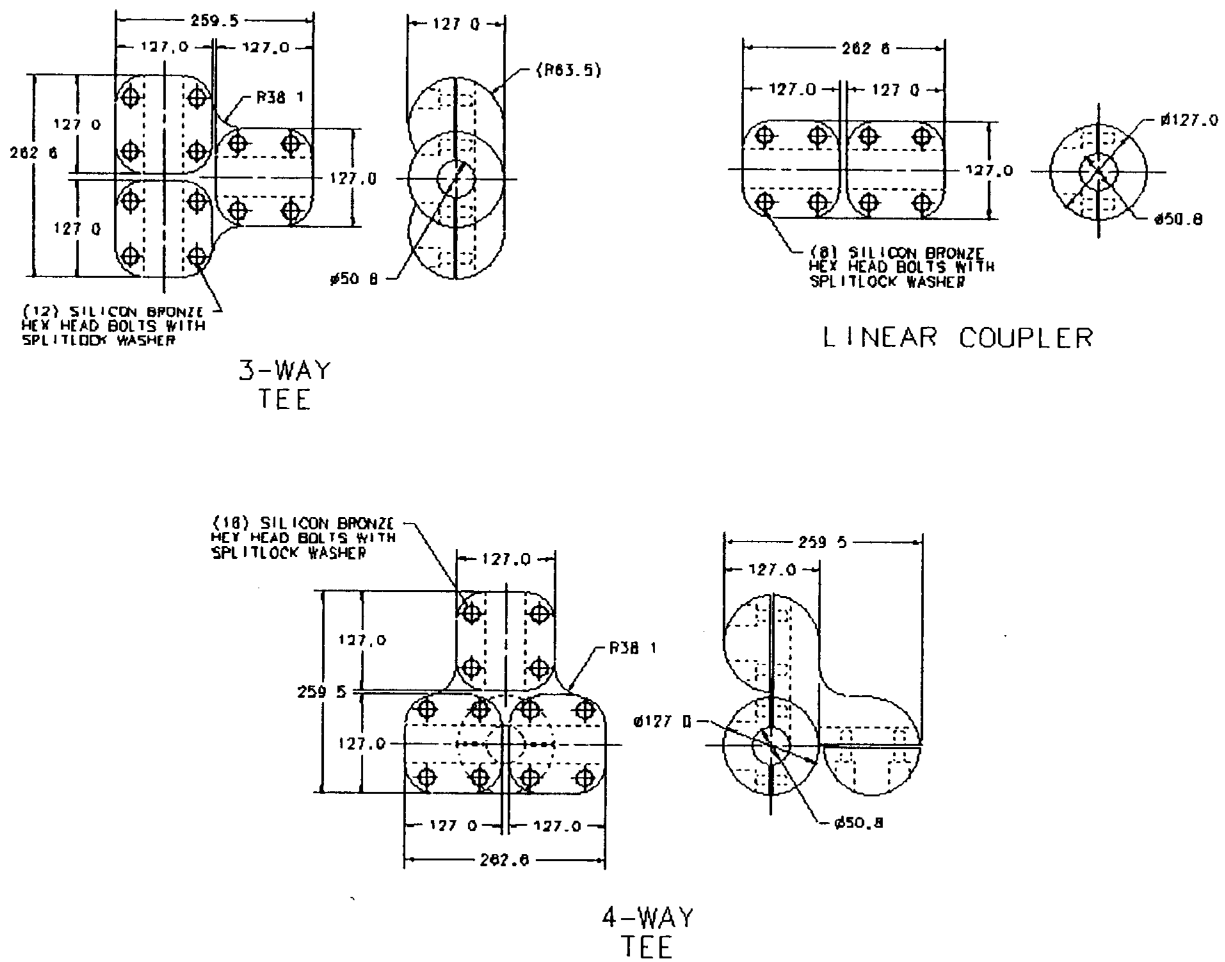


Figure 5-9A: Alternate Junction Coupler

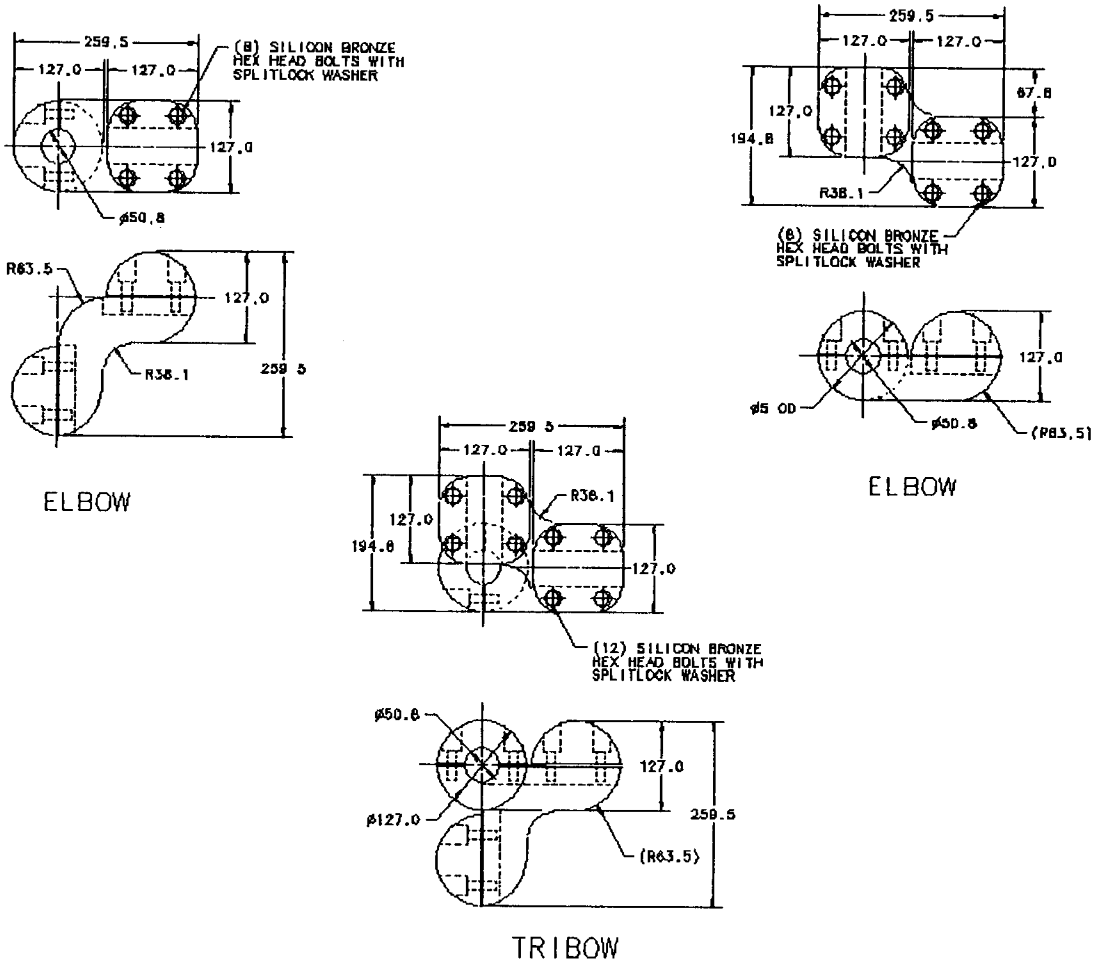


Figure 5-9B: Alternate Junction Coupler

Raysulate High-Voltage Material Properties

Material Properties		Test Method	Typical Data
Electrical	Volume resistivity	ASTM D-257, IEC 93	1.0×10^{13} ohm-cm
	Dielectric constant	ASTM D-150, IEC 250	5.0 max., 3.0 typical
	Dielectric strength	ASTM D-149, IEC 243	460 V/mil (180 kV/cm @ 2mm)
Electrical	Thermal endurance	IEEE 1-1969, IEC 216	105°C
	Accelerated aging	ISO 188	168 hr @ 120°C 300% elongation
Chemical	Flammability	ANSI C37.20-1987	Pass
	Water absorption	ISO/R 62, Procedure A	1% max. after 14 days @ 23°C
	Low-temperature flexibility	ASTM D-2671, Procedure C	No cracking after 4 hrs @ -40°C
	Corrosion	Copper Mirror, ASTM D-2671, Procedure B	Passed visual inspection after 168 hr @ 150°C
Physical	Tensile strength	ASTM D-638, ISO 37	1450 psi, 10 Mpa min.
	Ultimate elomgation	ASTM D-638, ISO 37	300 % min.
Product performance	Voltage withstand (Foil test)	ANSI C37.20-1987, section 5.2.1.3	36 kV on smooth bar

Figure 5-10: Conductor Insulation: Manufacturer's Specifications

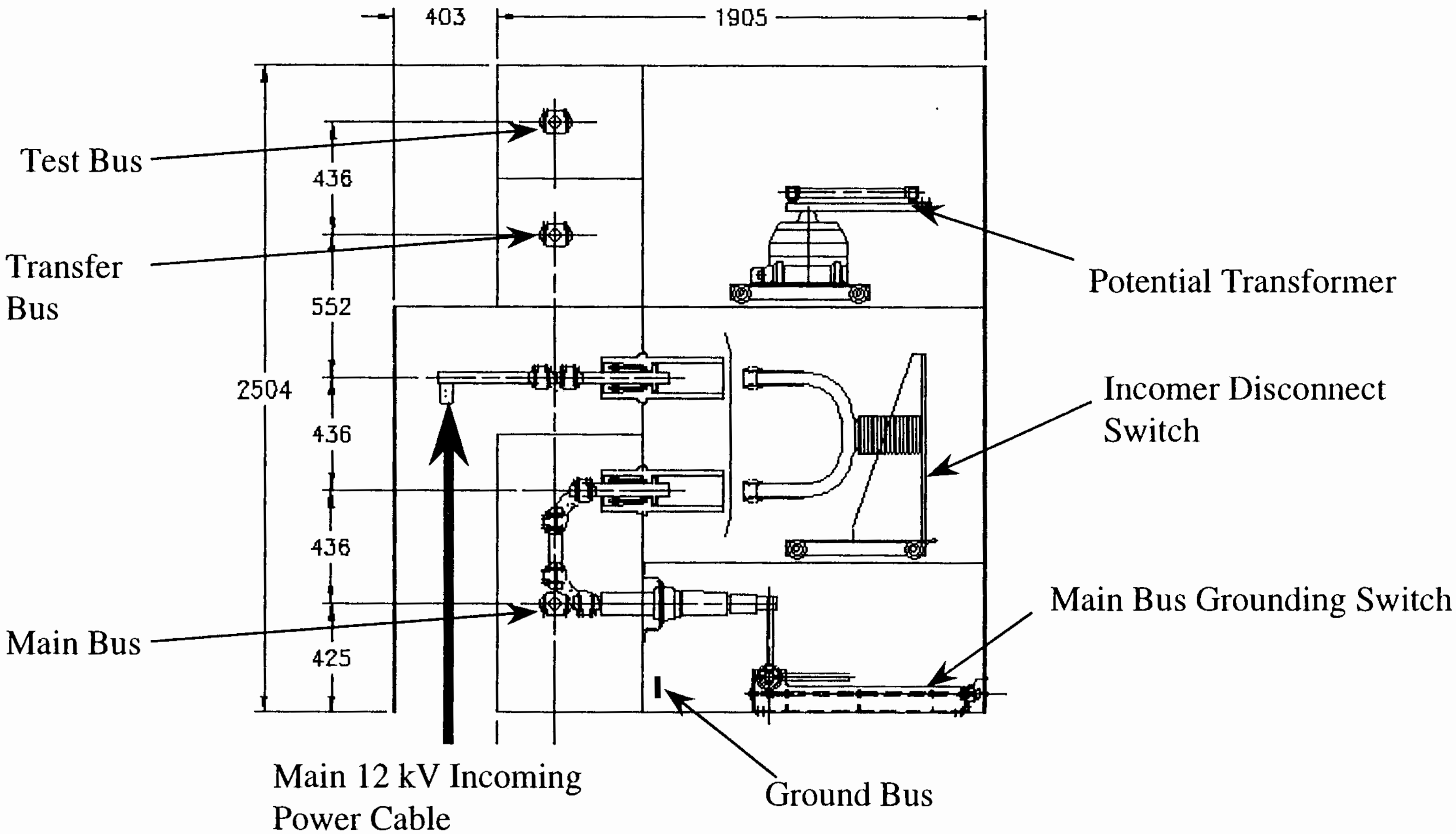


Figure 6-1: 12 kV Main Bus Incomer Cubicle Arrangement

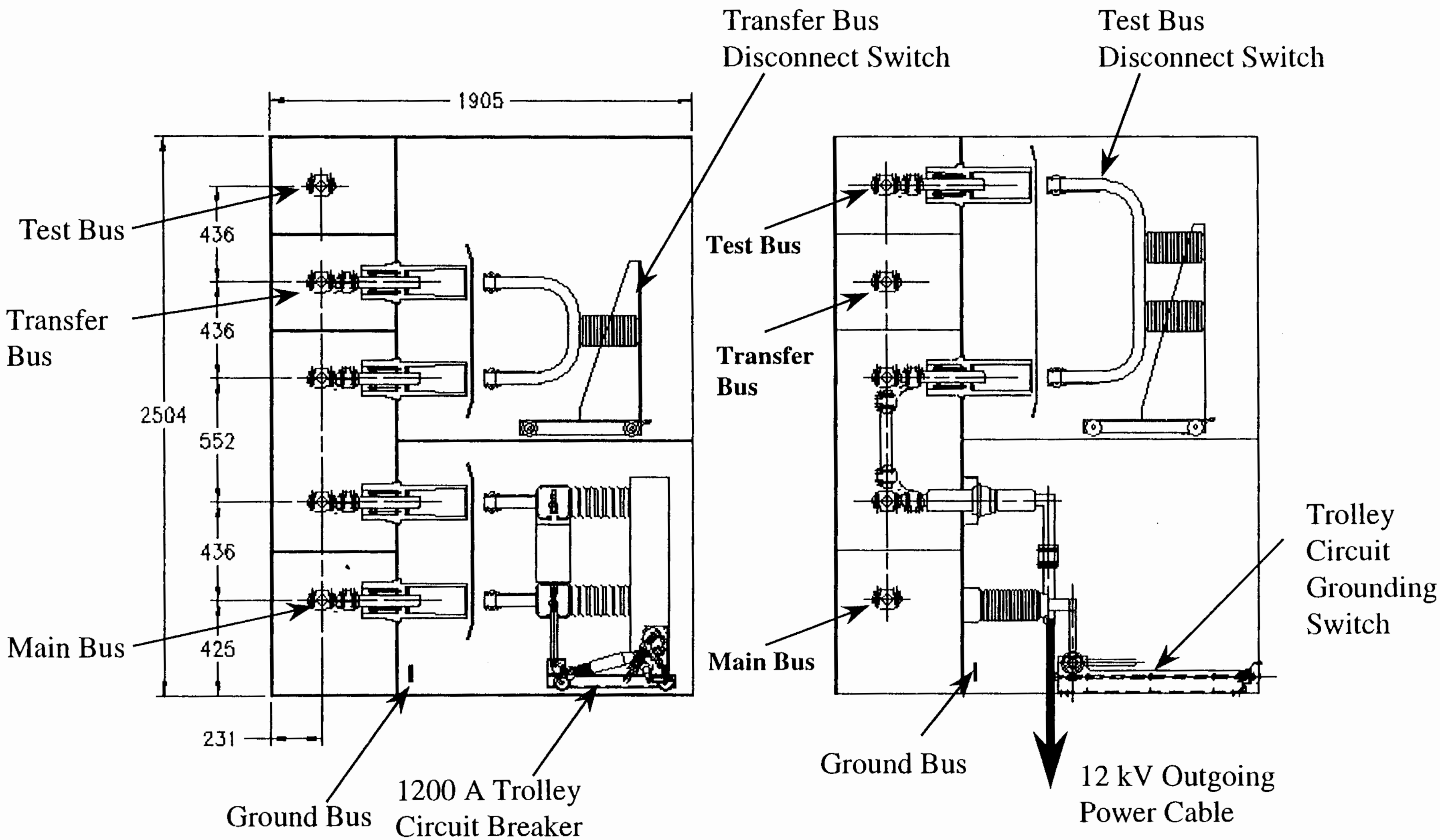


Figure 6-2: 12 kV Trolley Circuit Breaker Cubicle Arrangement

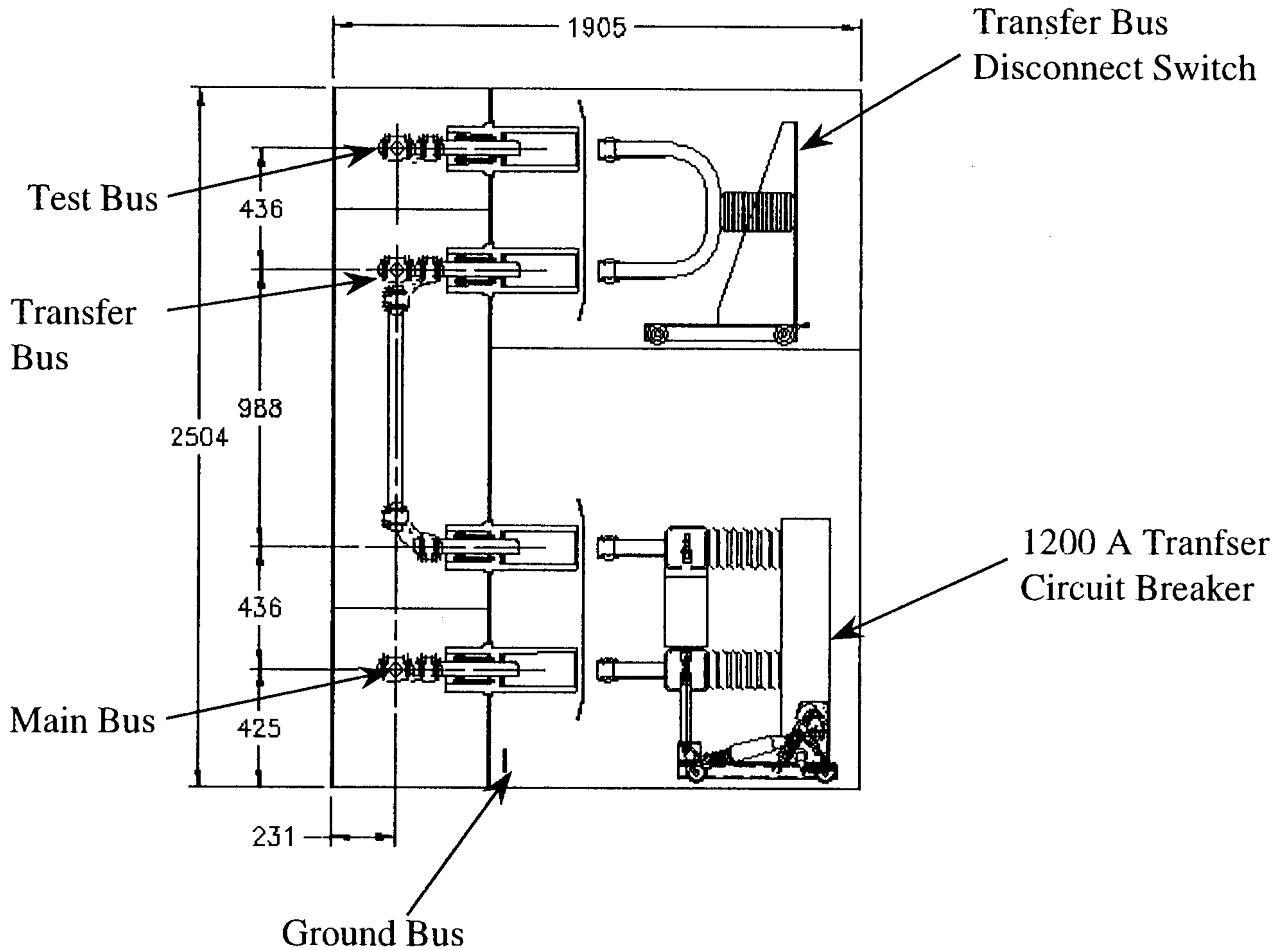


Figure 6-3: 12 kV Transfer Circuit Breaker Cubicle Arrangement

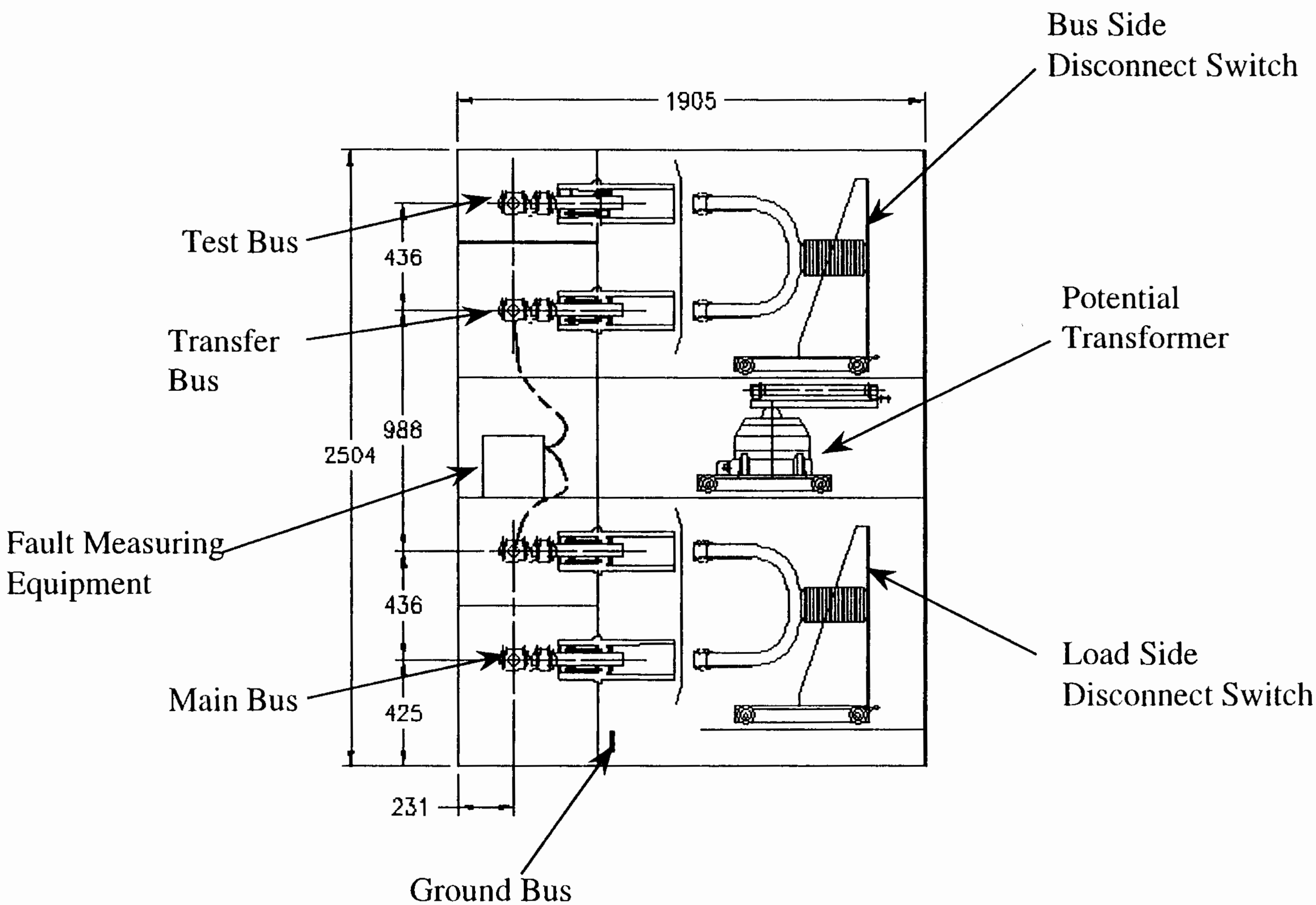


Figure 6-4: 12 kV Fault Test Cubicle Arrangement

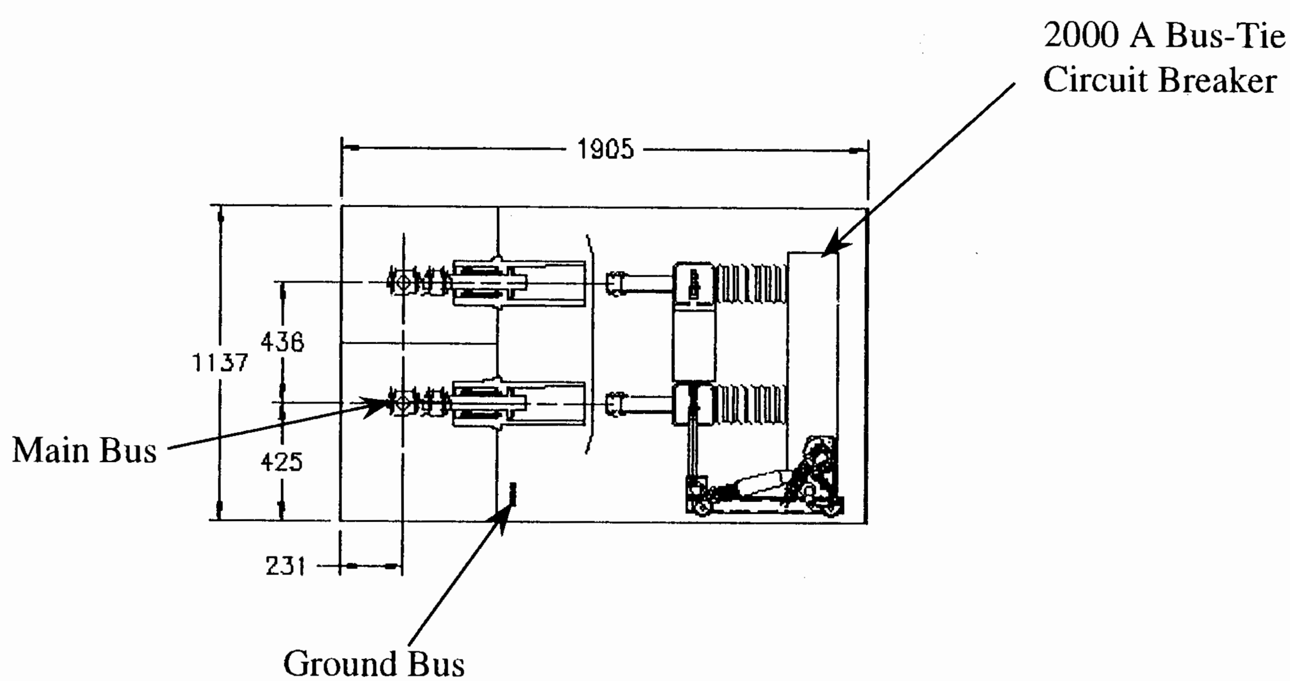


Figure 6-5: 12 kV Bus-Tie Circuit Breaker Cubicle Arrangement

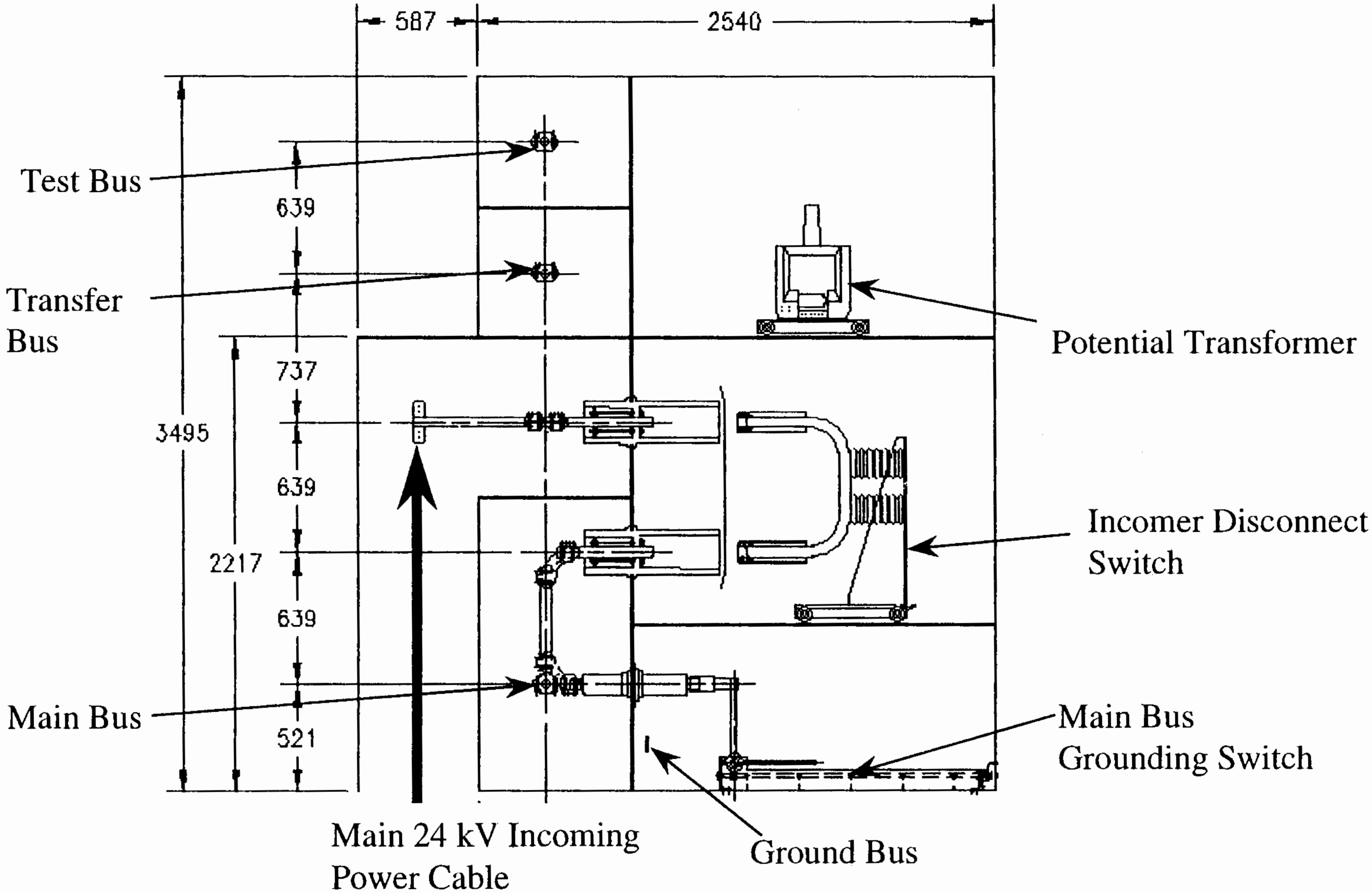


Figure 6-6: 24 kV Main Bus Incomer Cubicle Arrangement

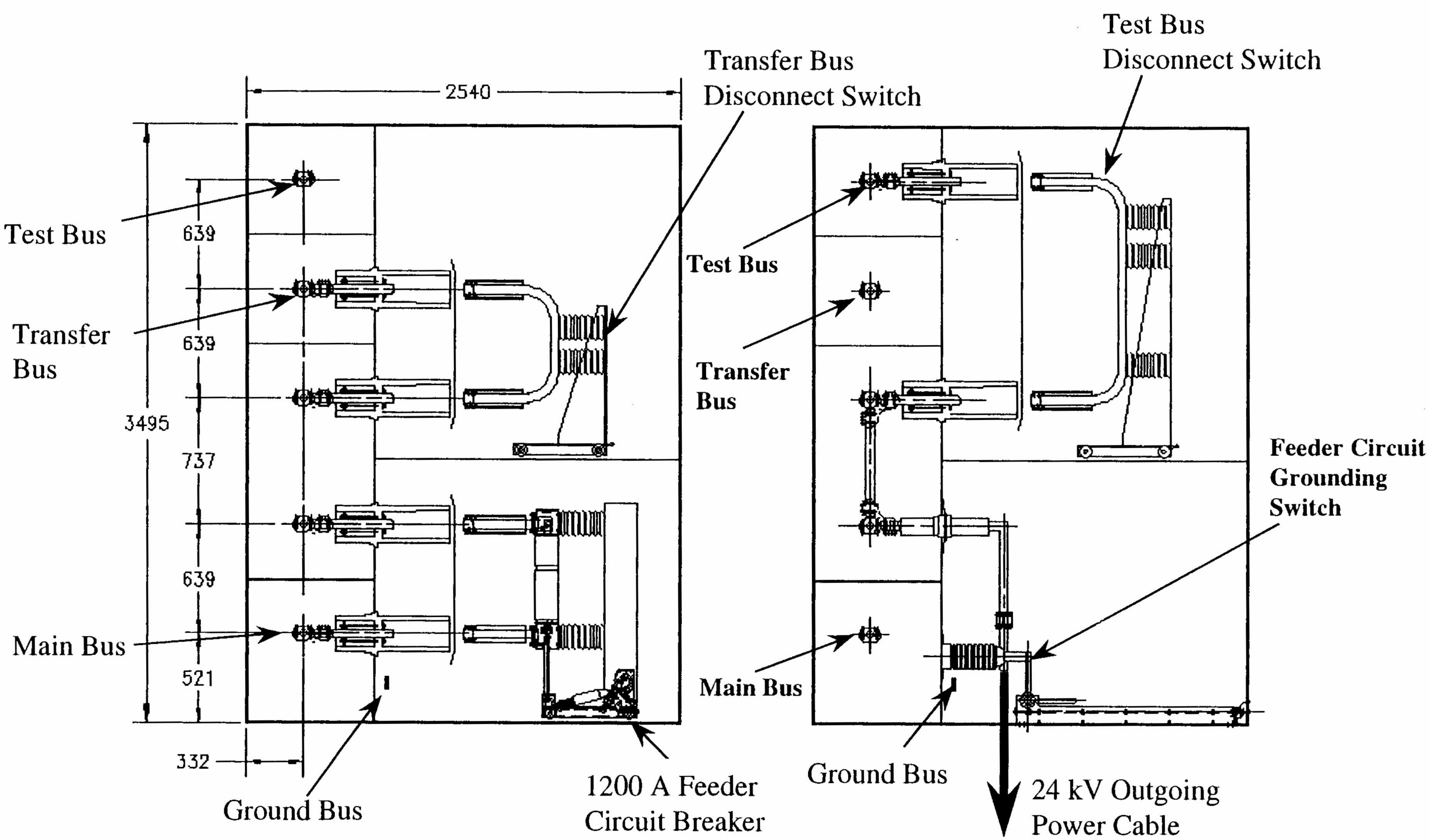


Figure 6-7: 24 kV Feeder Circuit Breaker Cubicle Arrangement

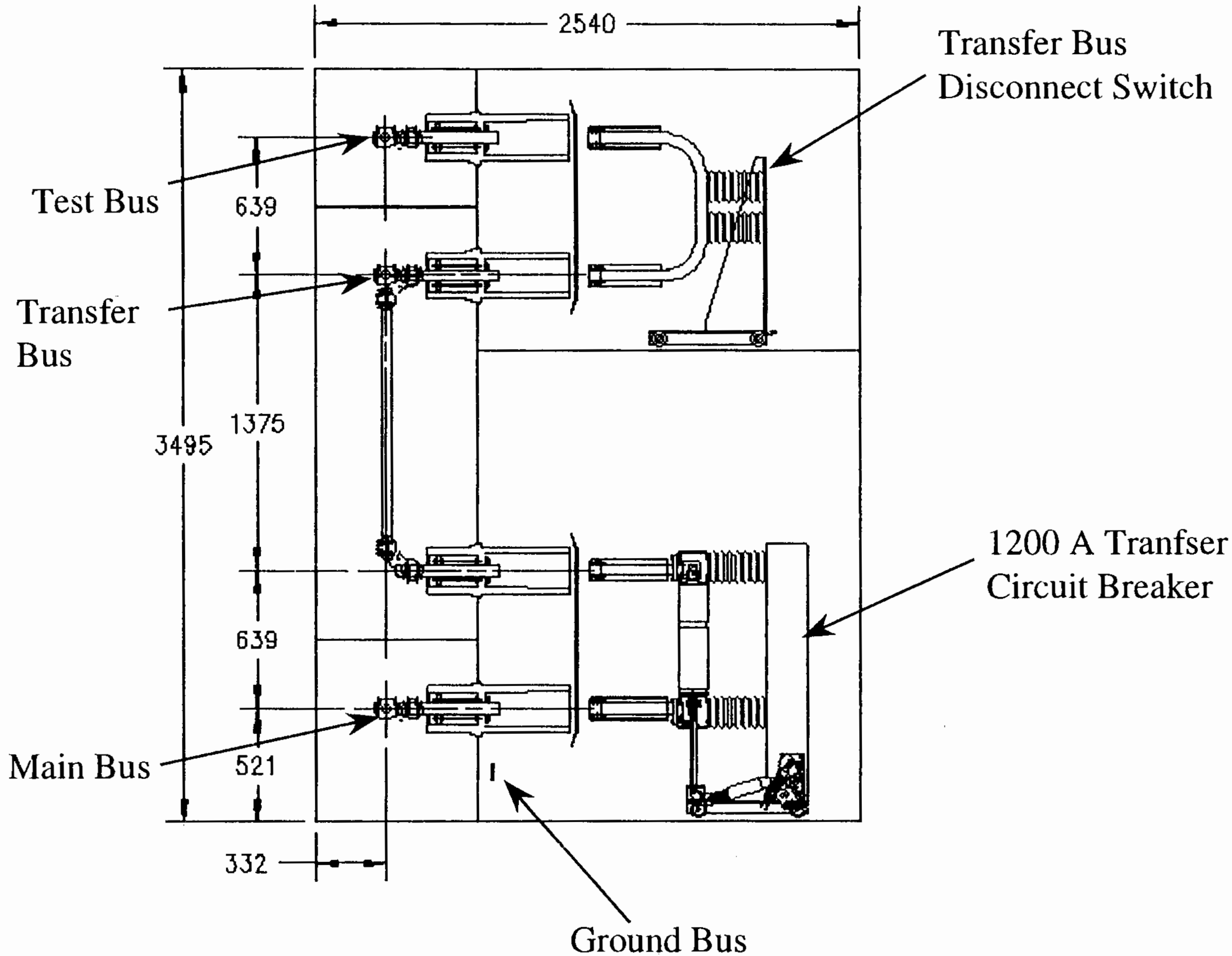


Figure 6-8: 24 kV Transfer Circuit Breaker Cubicle Arrangement

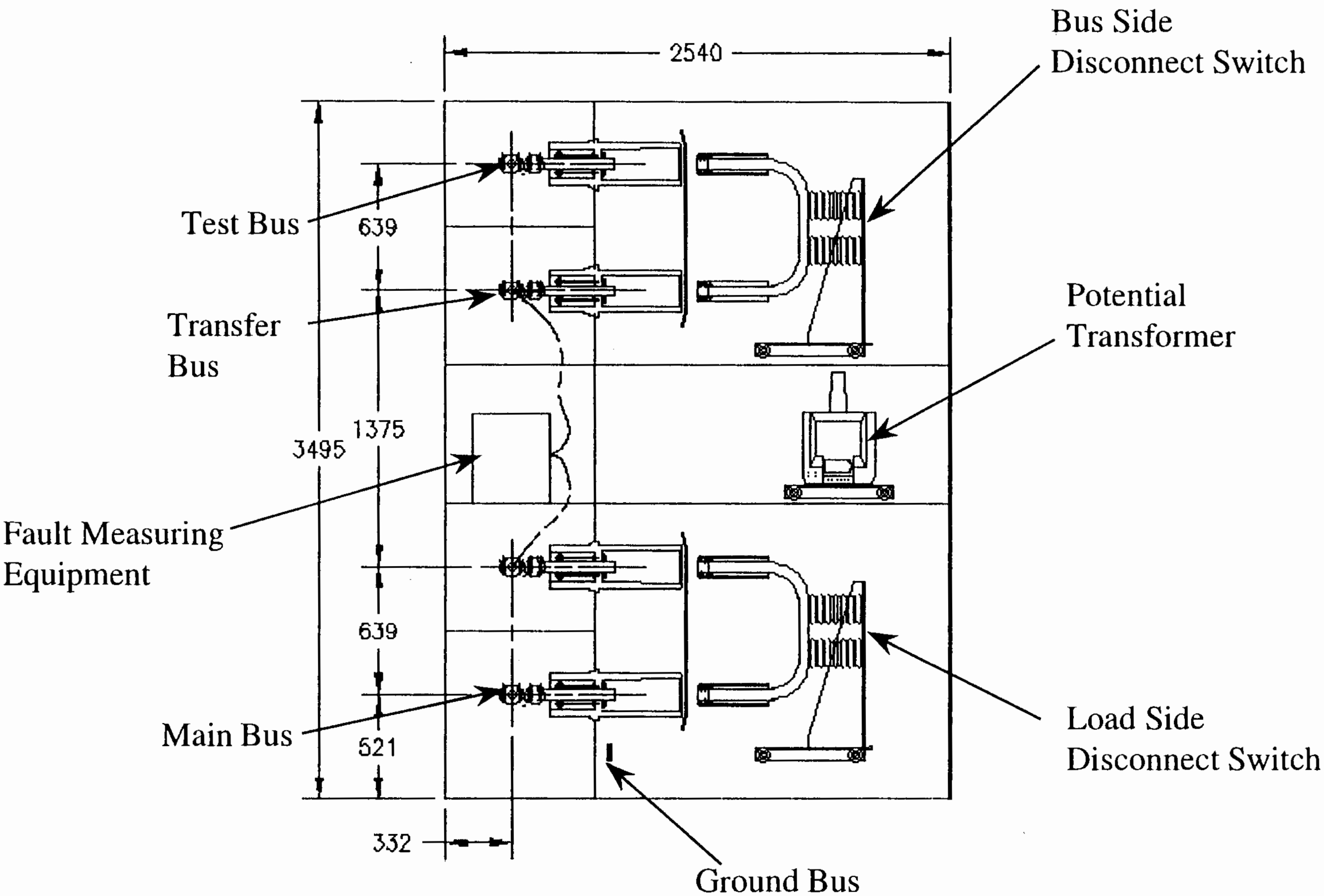


Figure 6-9: 24 kV Fault Test Cubicle Arrangement

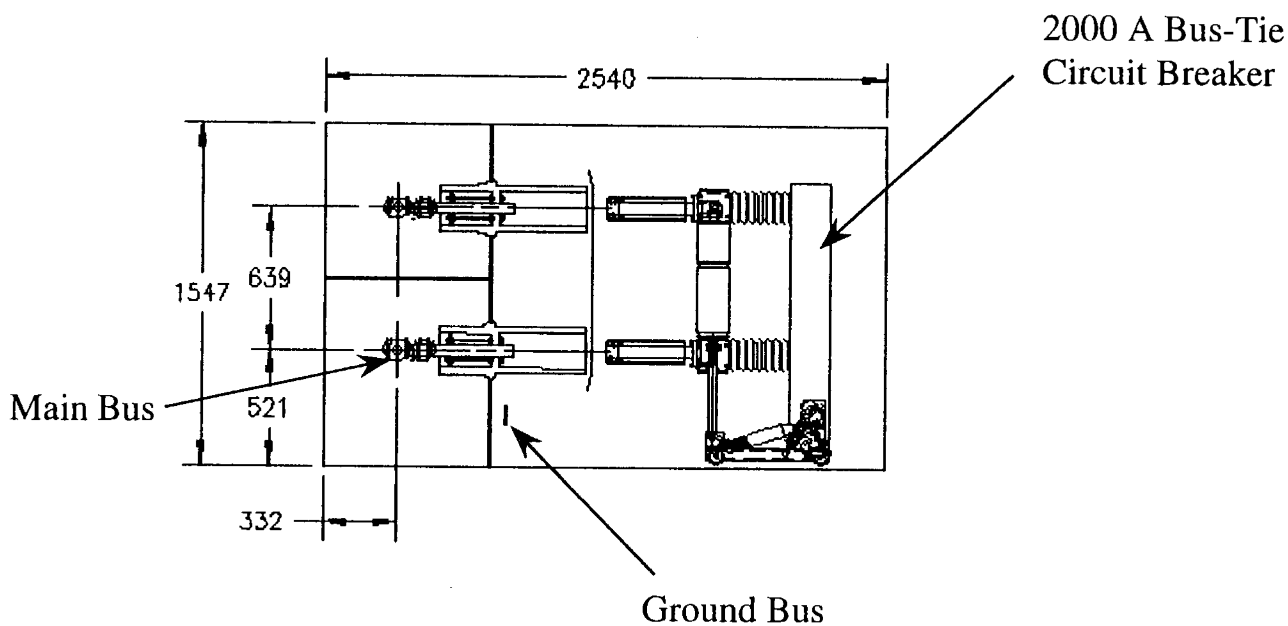


Figure 6-10: 24 kV Bus-Tie Circuit Breaker Cubicle Arrangement

- Footprint: 77 m^2
- Height: 2.5 m, Width: 40.5 m, Depth 1.9 m

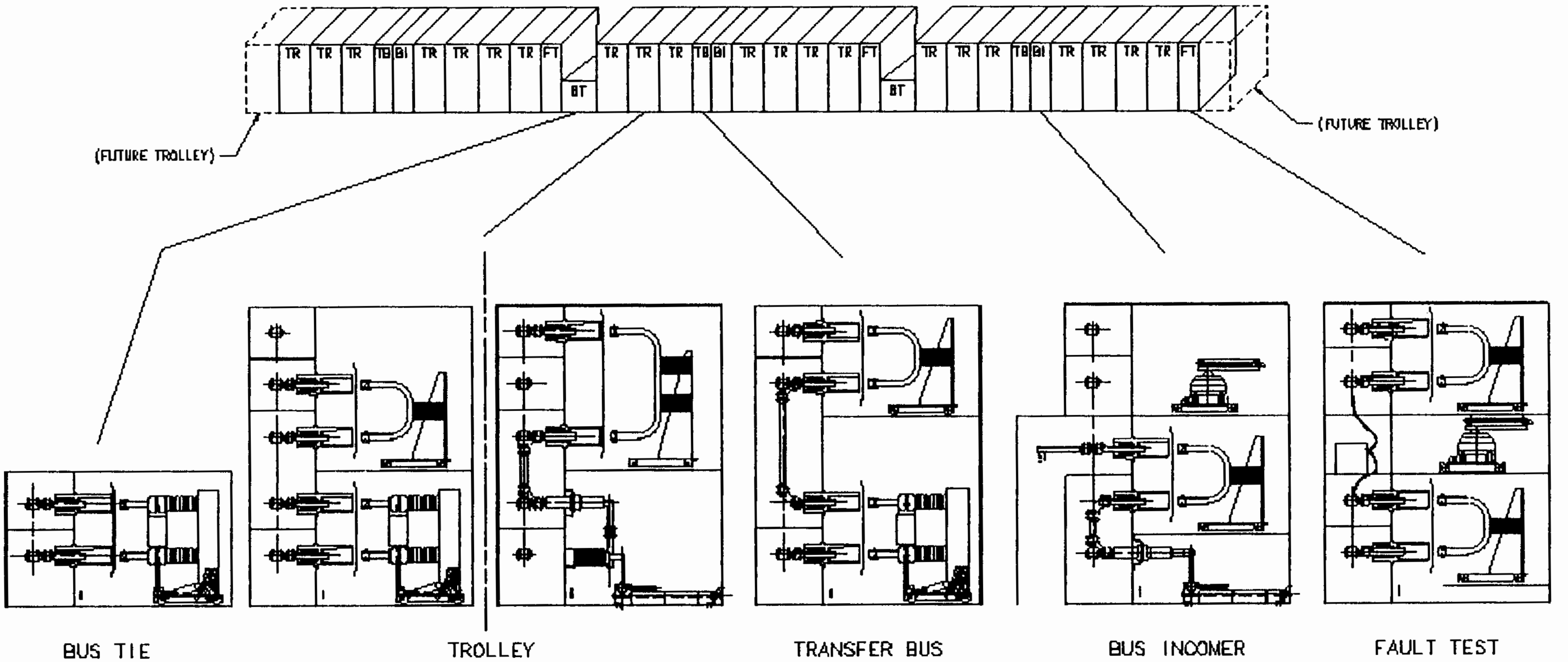


Figure 6-11: 12 kV Wayne Junction Switchgear Line-up Cross Sectional Views

- Footprint: 68.3 m^2
- Height: 3.5 m, Width: 27.3 m, Depth 2.5 m

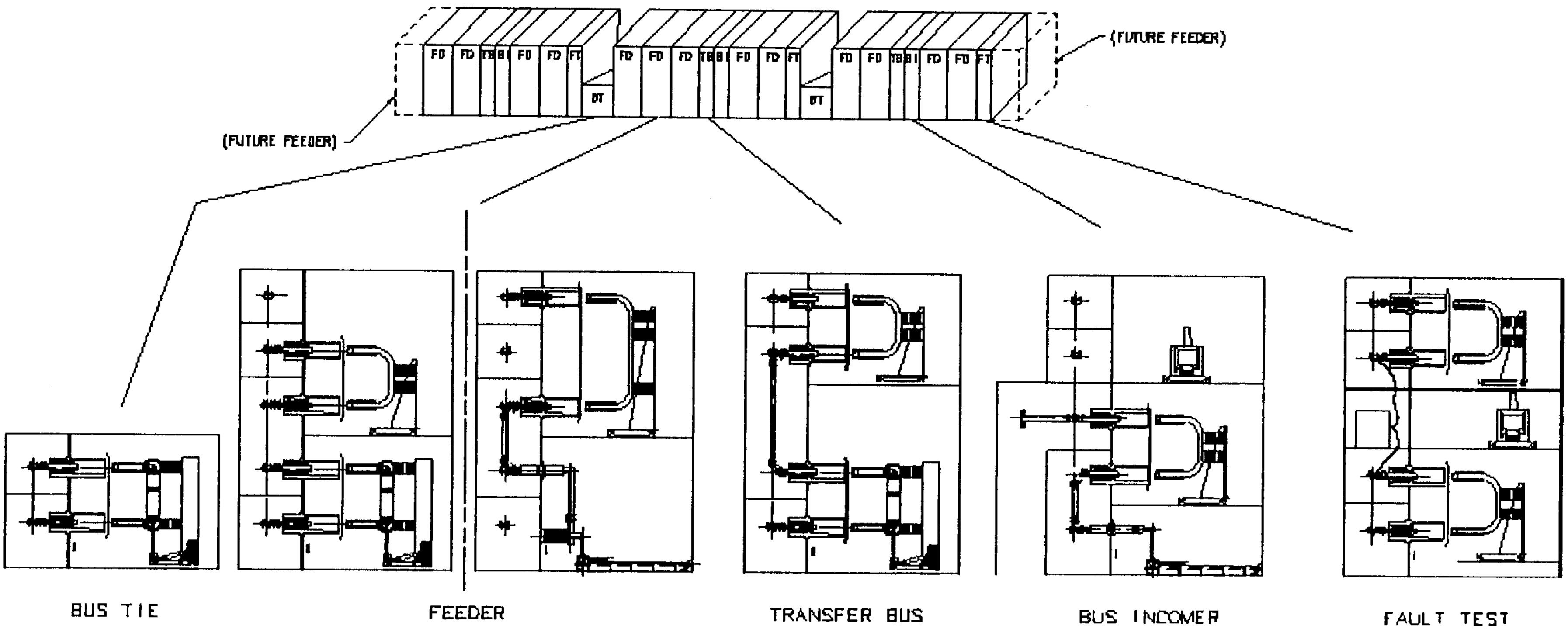


Figure 6-12: 24 kV Wayne Junction Switchgear Line-up Cross Sectional Views

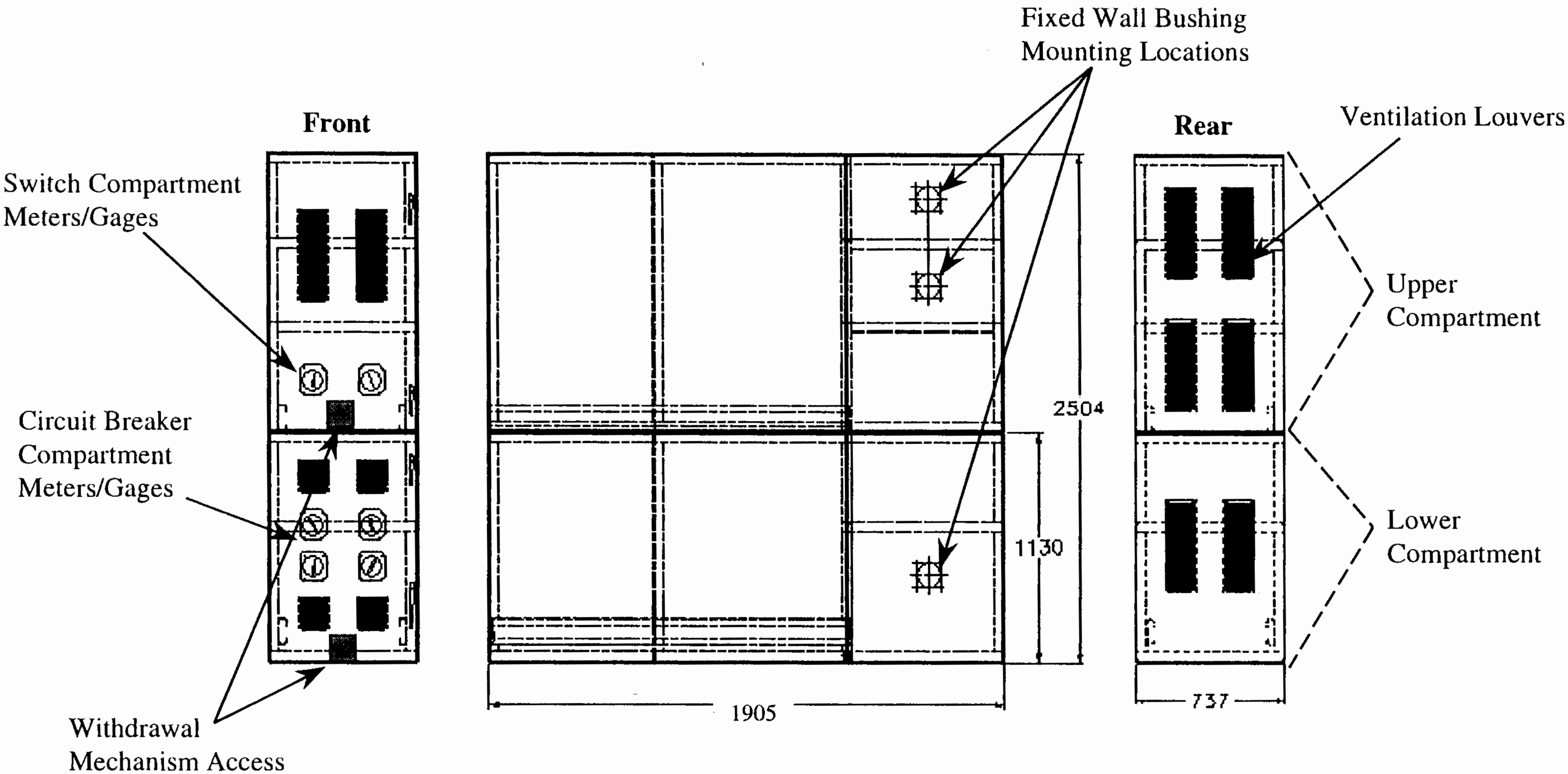


Figure 6-13: 12 kV Switchgear Enclosure Arrangement
(Trolley Cubicle-Circuit Breaker side shown)

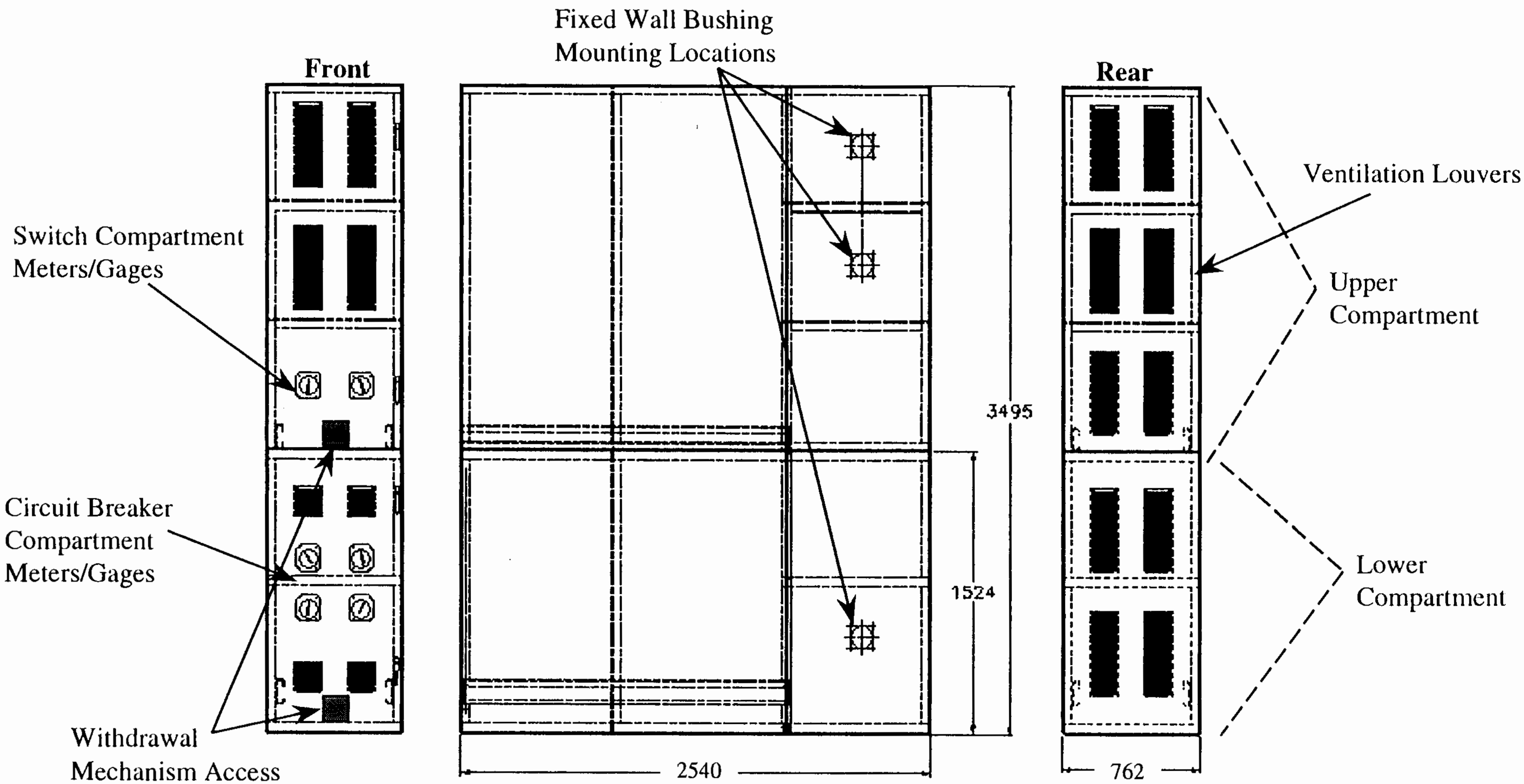
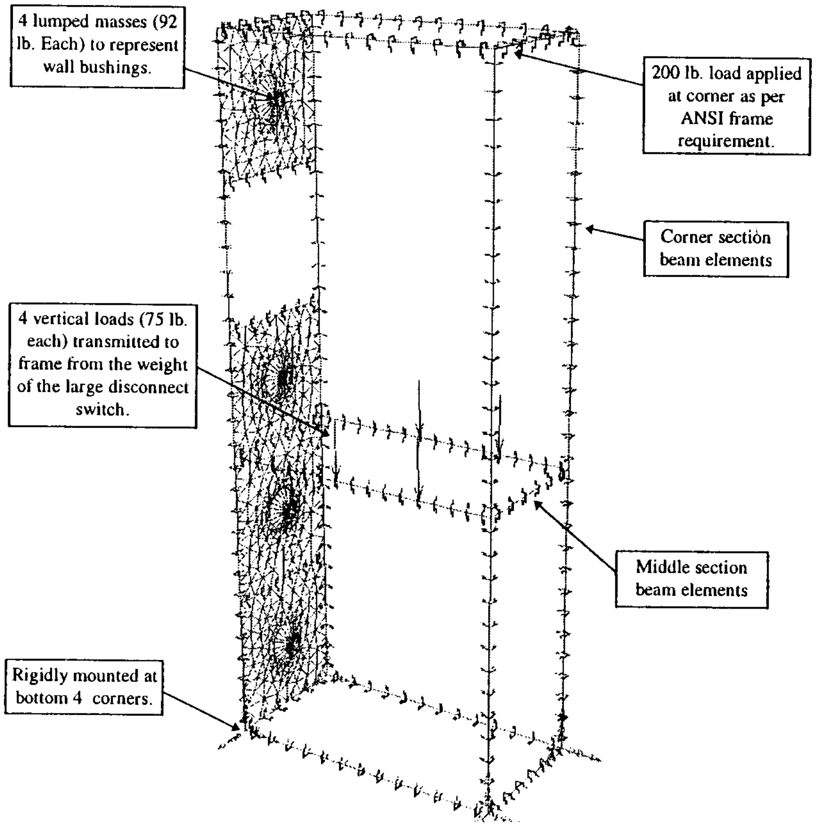
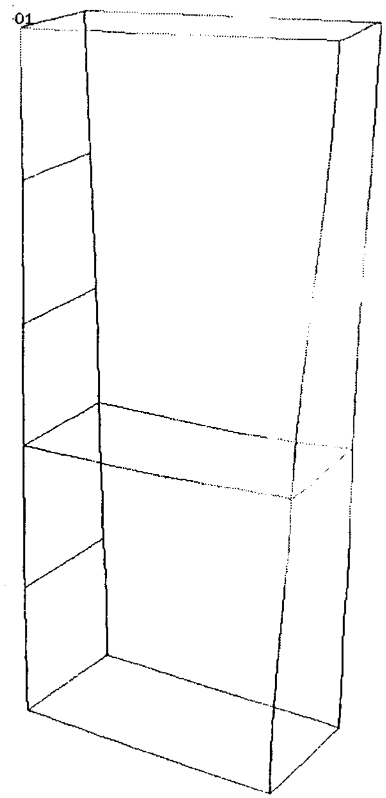


Figure 6-14: 24 kV Switchgear Enclosure Arrangement
(Feeder Cubicle-Circuit Breaker side shown)



Linear Statics
Study For Strength



Stiffness Study For
BIL Requirements

Figure 6-15: Sample Enclosure Analysis Results

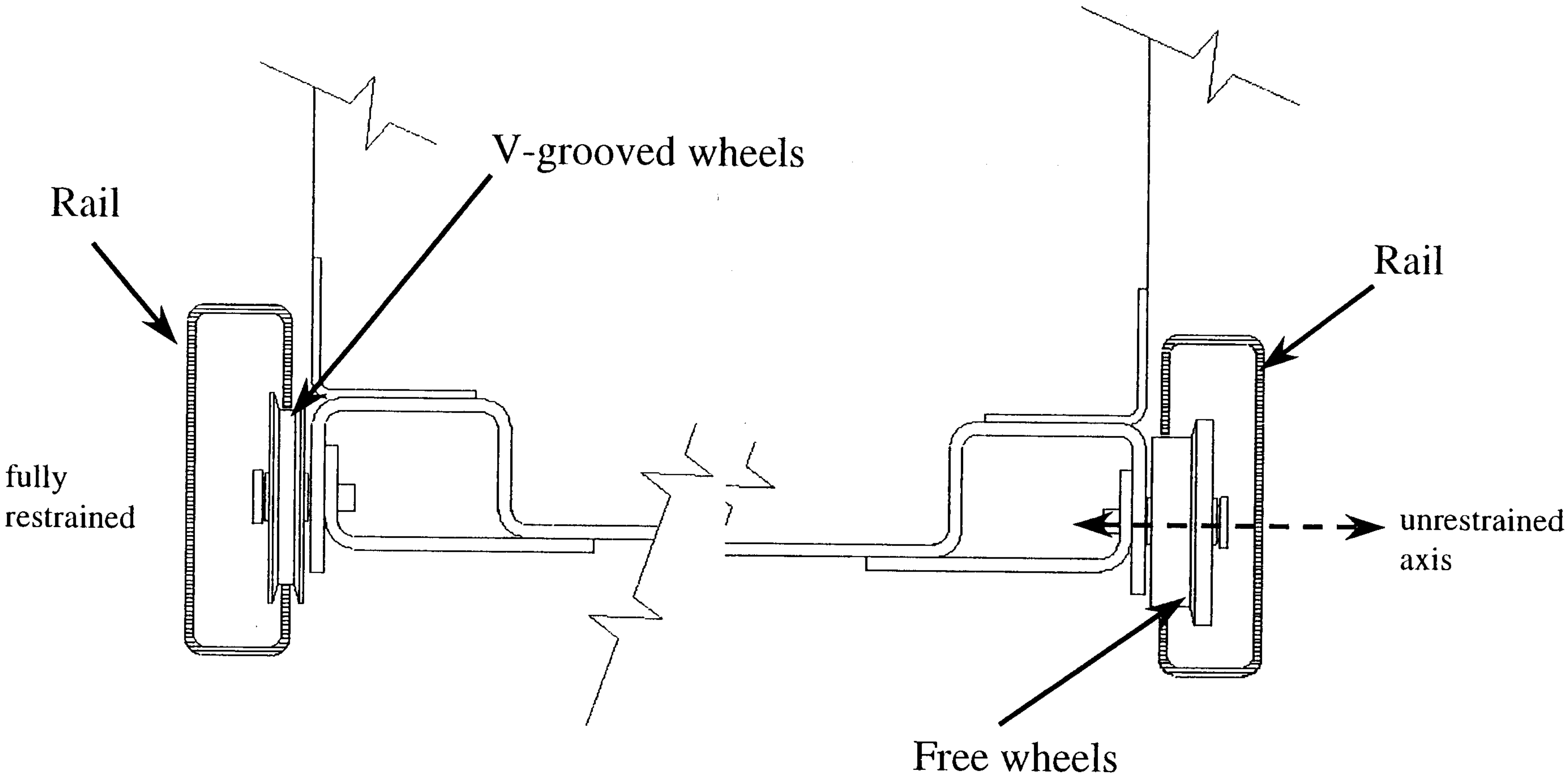


Figure 6-16: Power Component to Guide Rail Interface

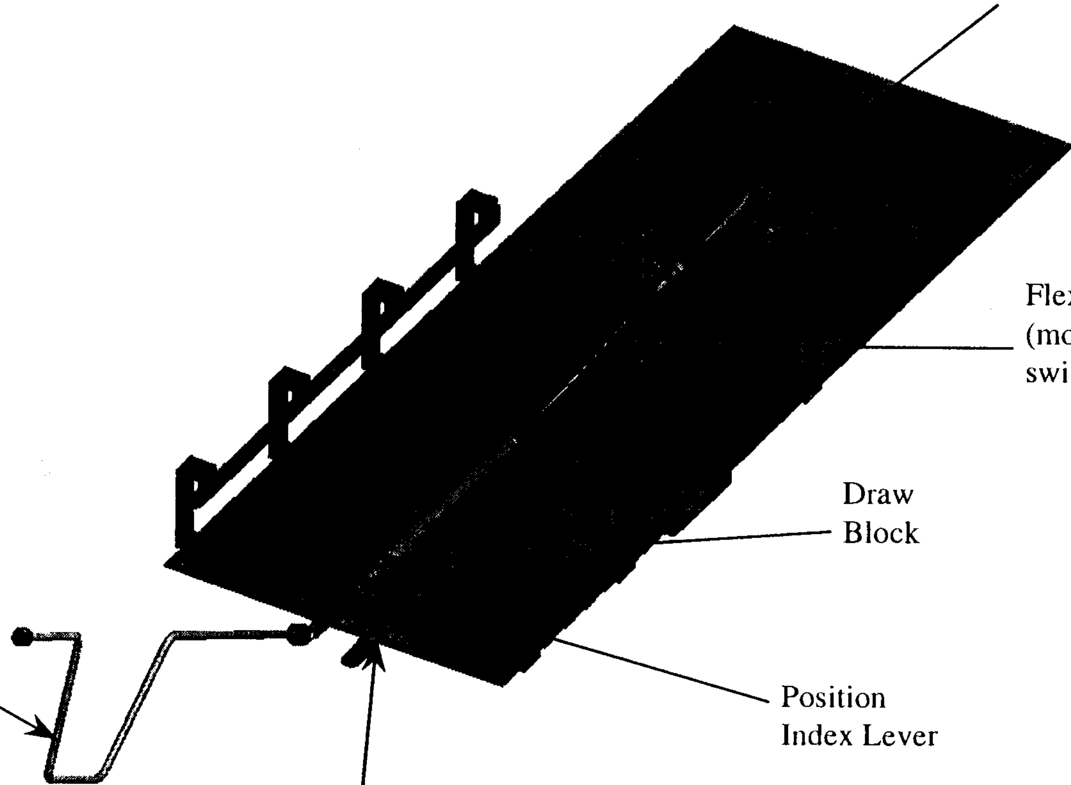


Figure 6-17: Power Component Withdrawal/Insertion Mechanism Arrangement

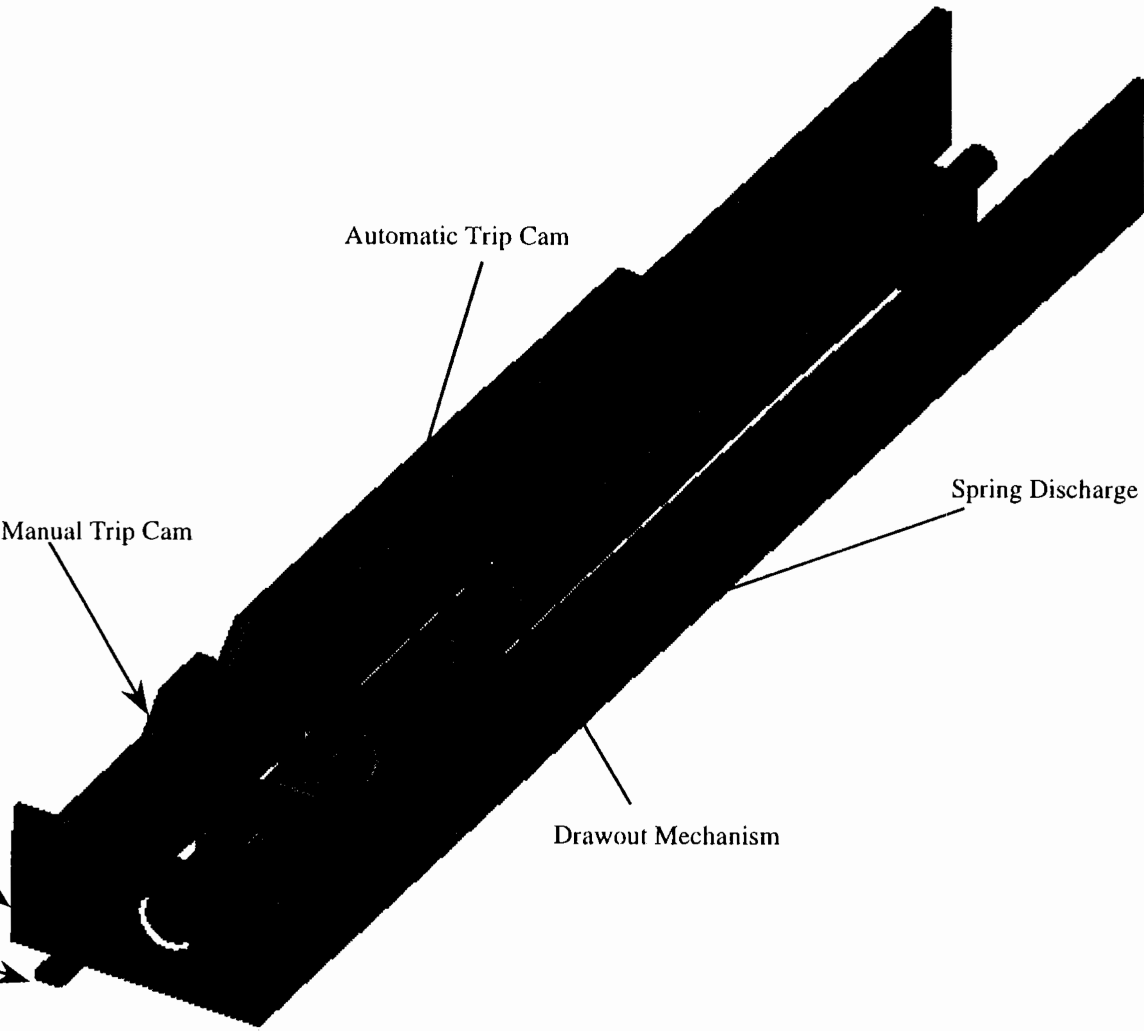


Figure 6-18: Circuit Breaker Interlock Mechanism Arrangement

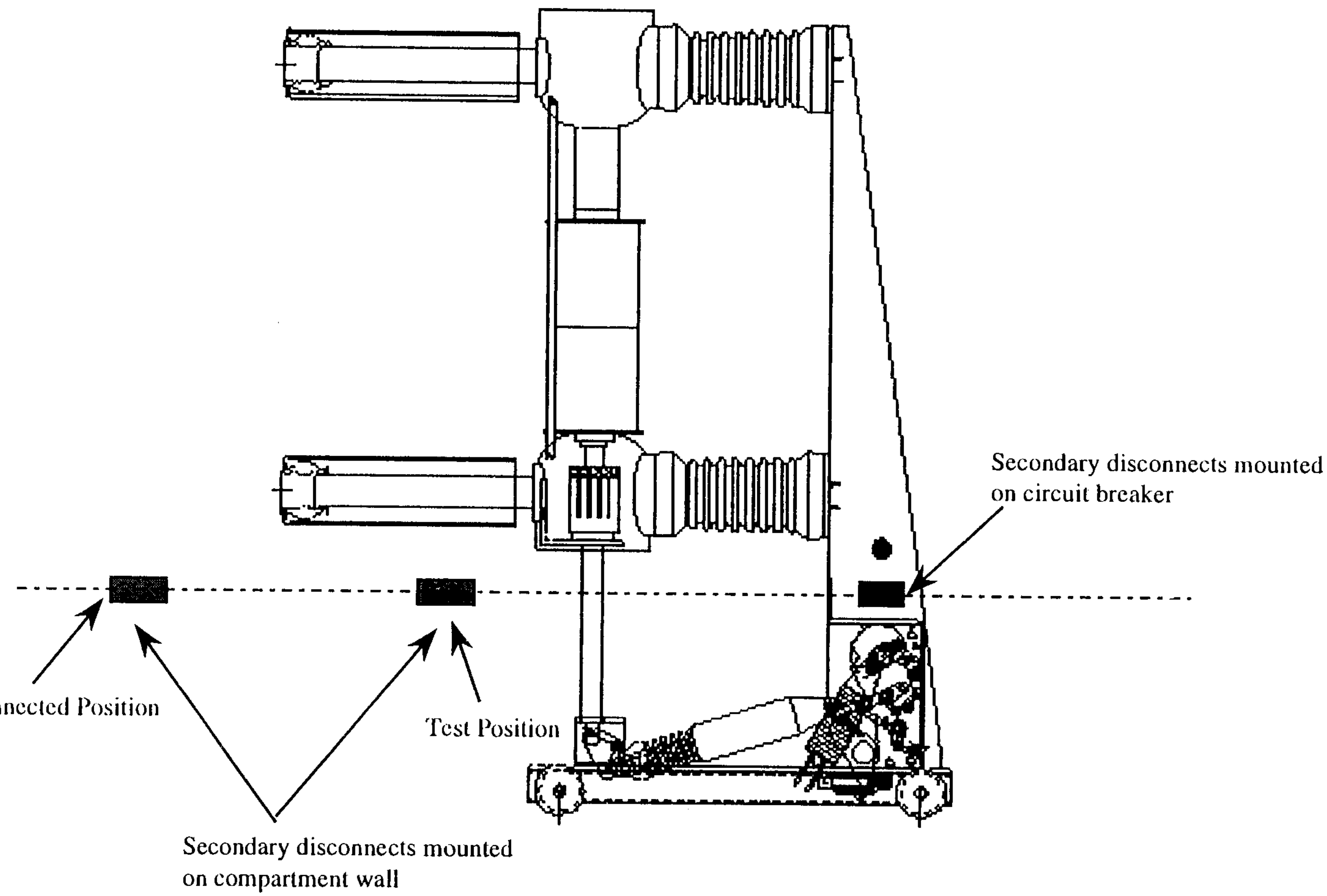
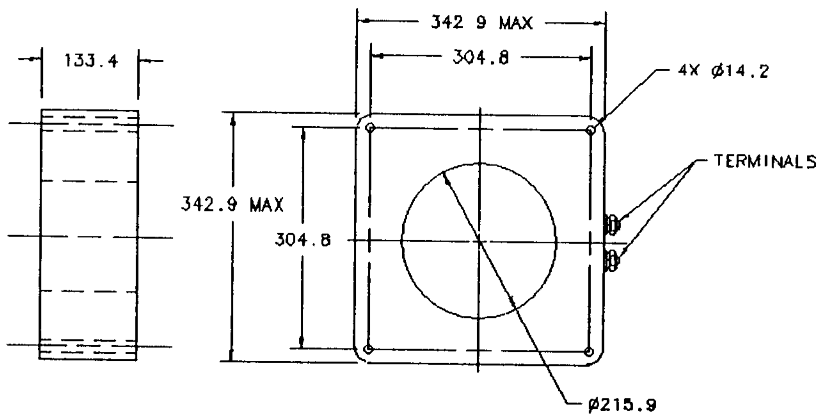
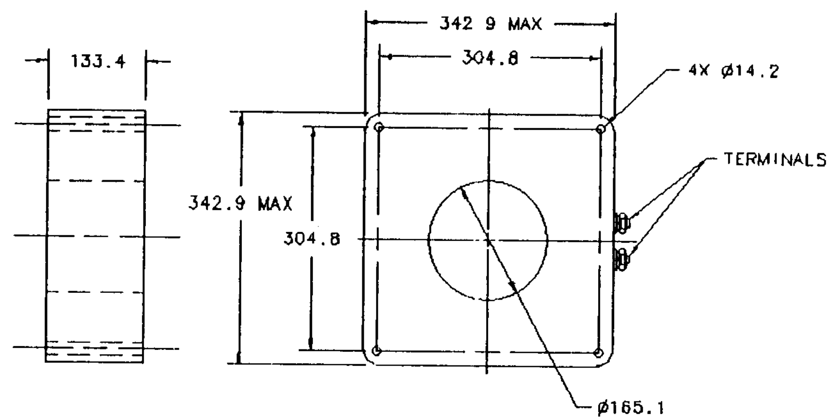


Figure 6-19: Placement of Circuit Breaker Secondary Disconnects

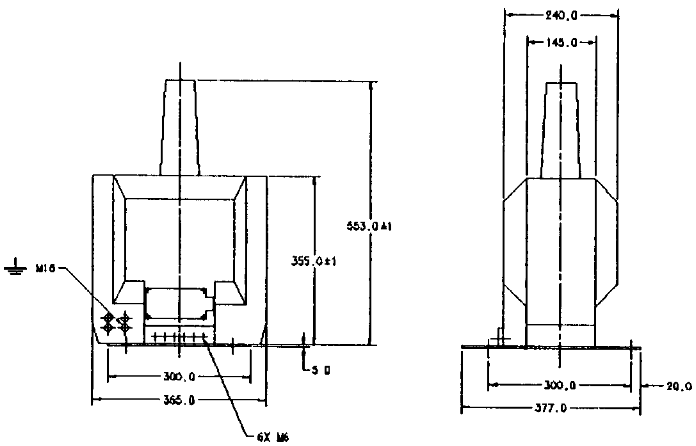


24 kV

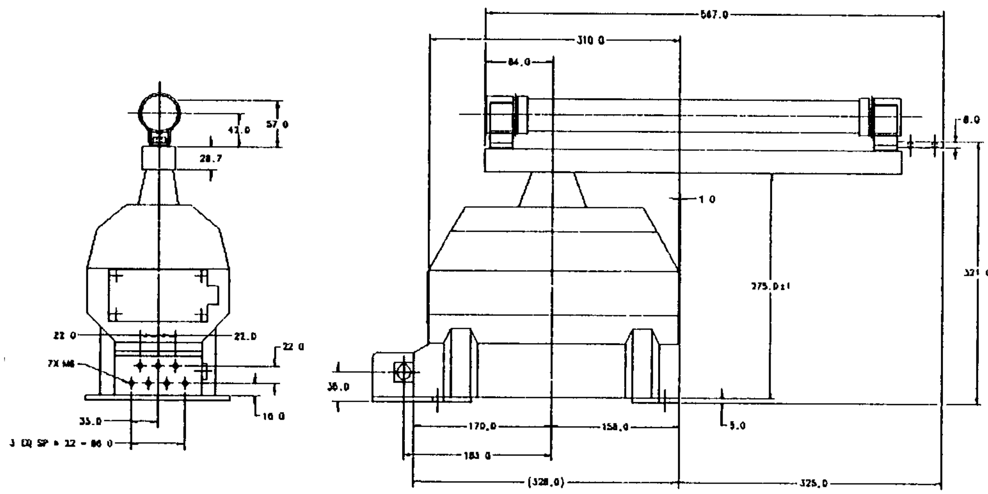


12 kV

Figure 6-20: Switchgear Current Transformers

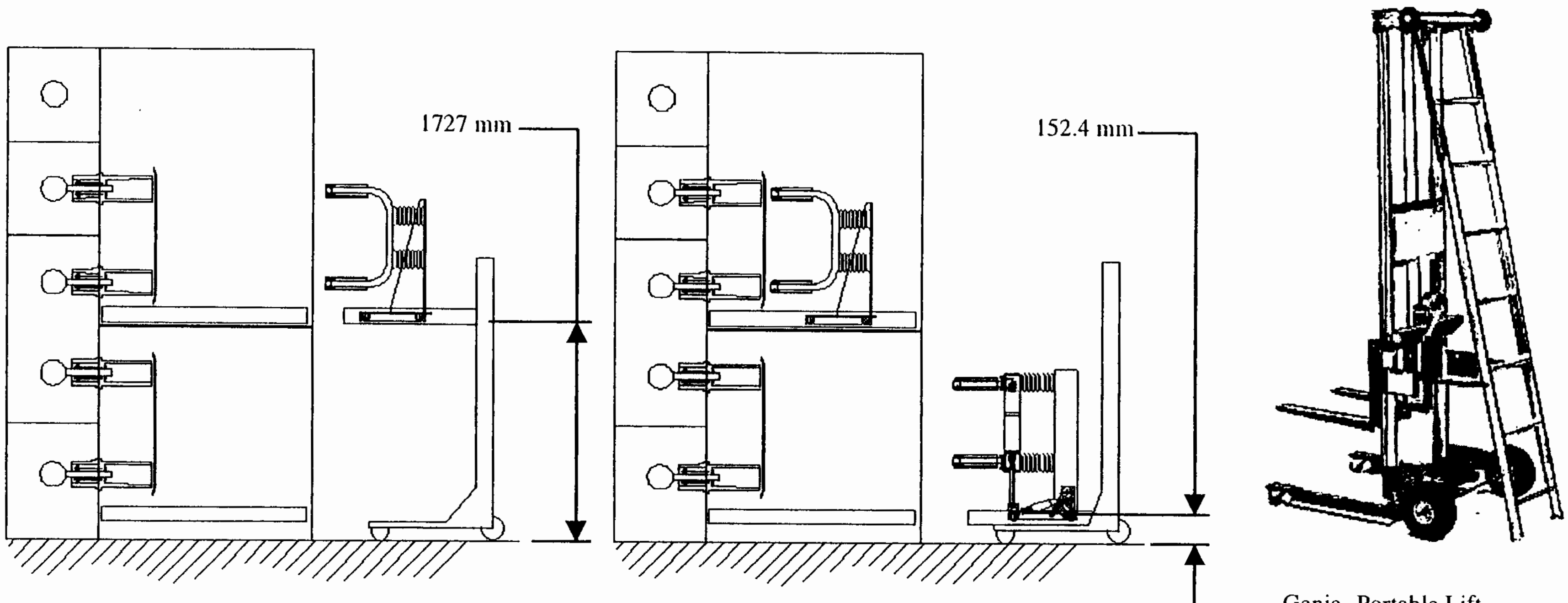


24 kV



12 kV

Figure 6-21: Switchgear Potential Transformers



Disconnect Switch Handling

Vacuum Circuit Breaker Handling

Genie® Portable Lift
Model GL-8
181 kg capacity
2500 mm maximum lift height
1700 mm height (stowed)
730 mm width
1092 mm depth

Figure 6-22: Power Component Handling Fixture

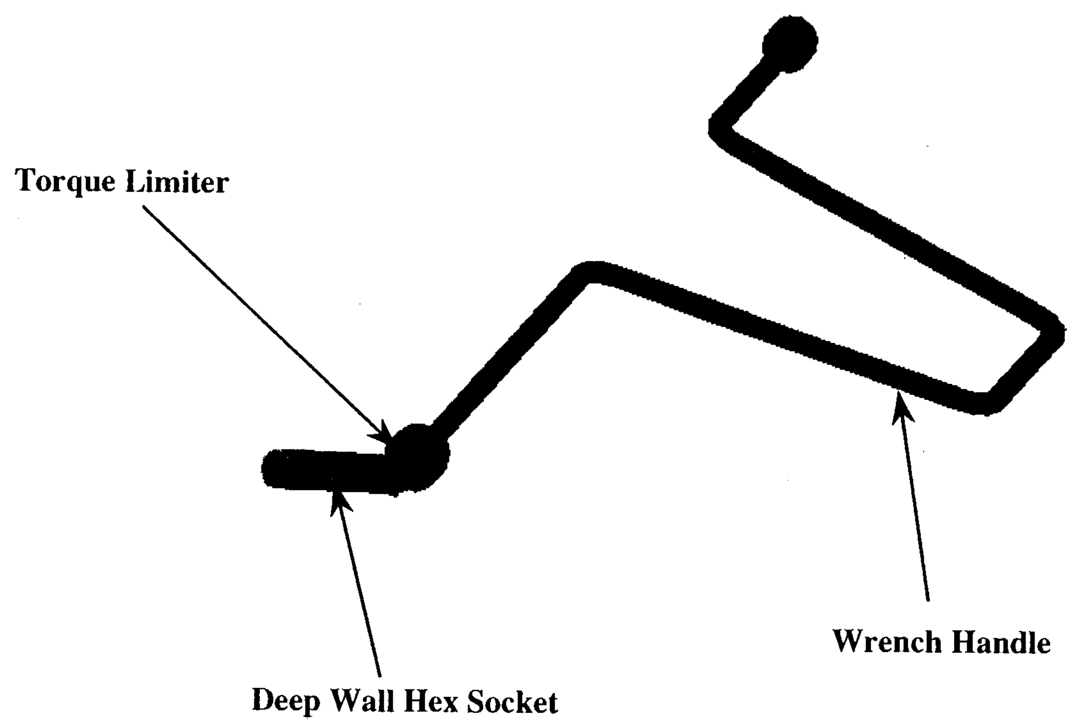


Figure 6-23: Manual Withdrawal Tool

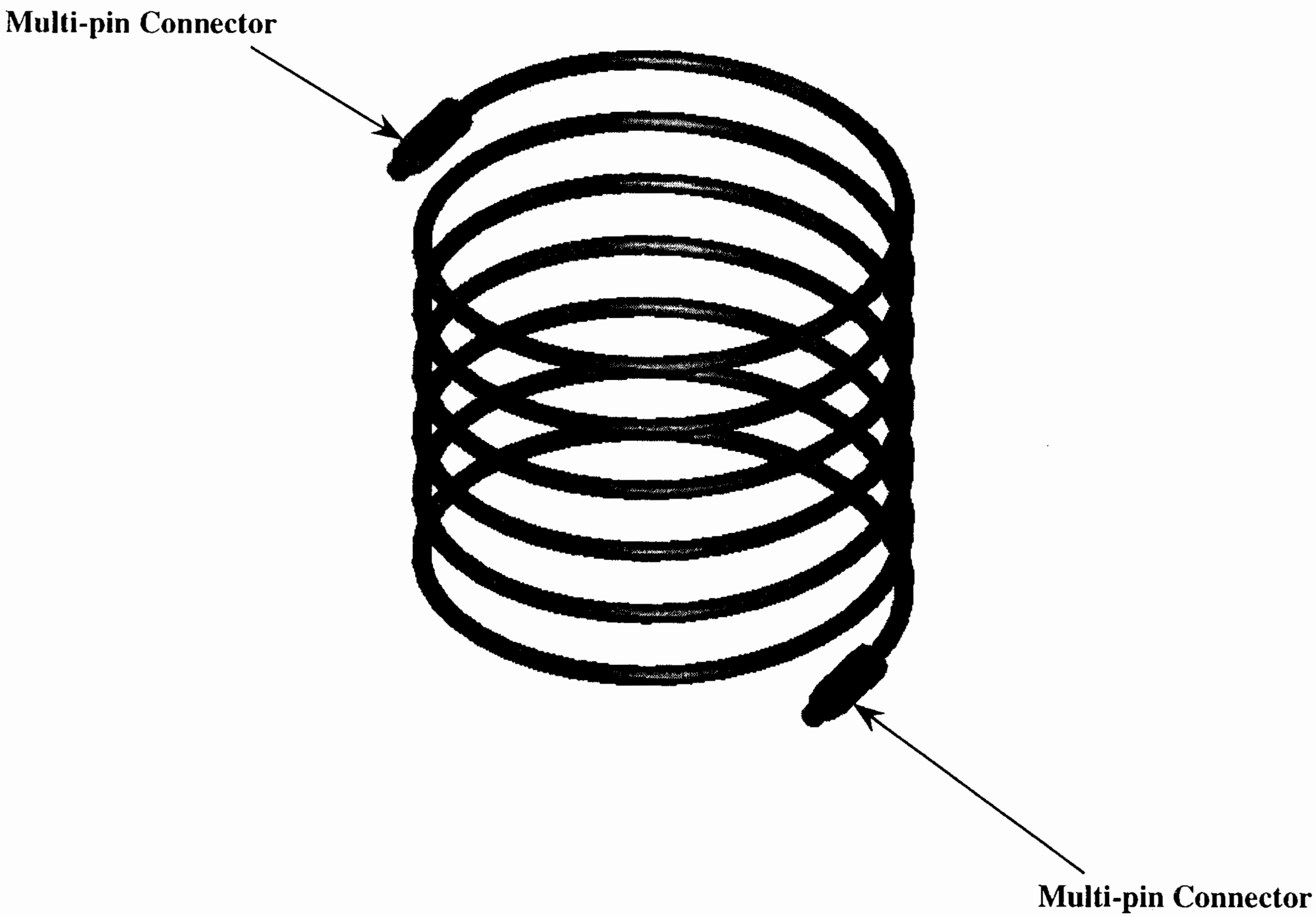


Figure 6-24: Circuit Breaker Secondary Test Cable

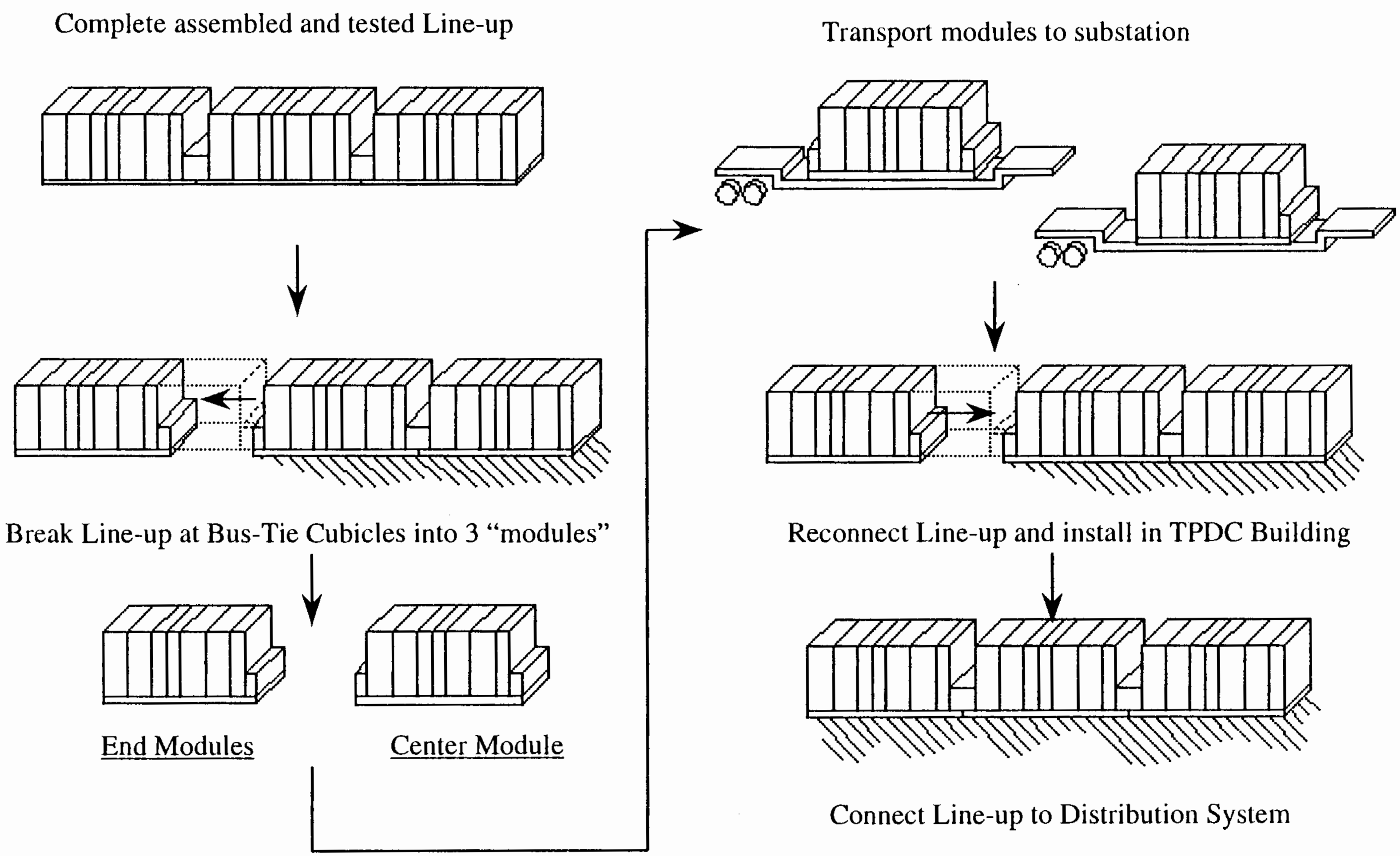
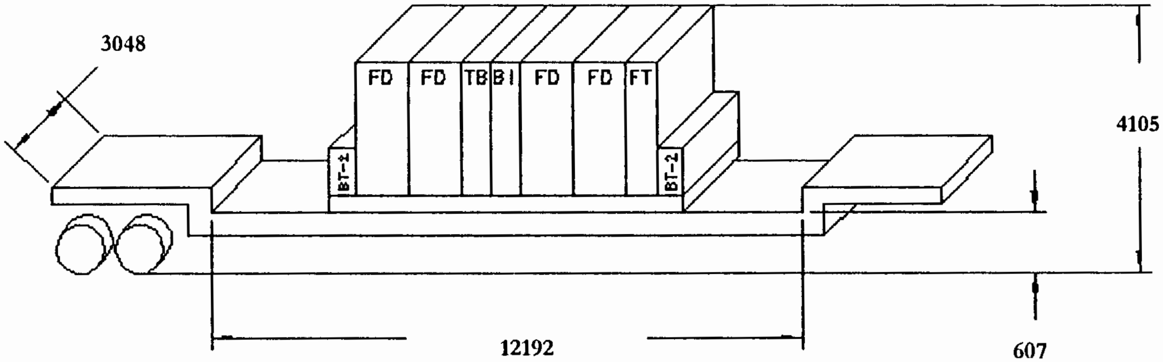
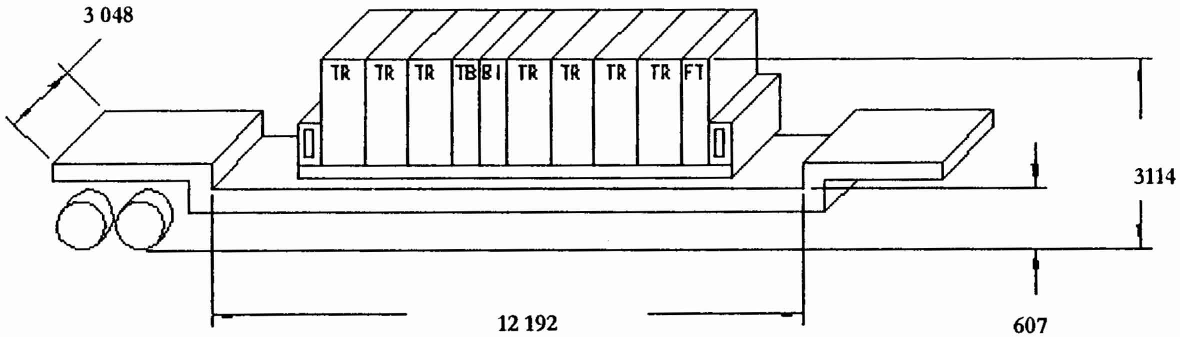


Figure 7-1: Switchgear Transportation/Shipping Flow Diagram

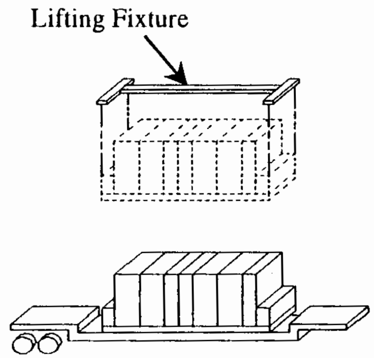


24 kV Switchgear

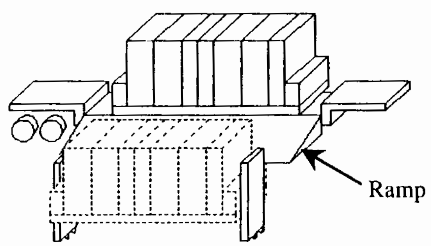


12 kV Switchgear

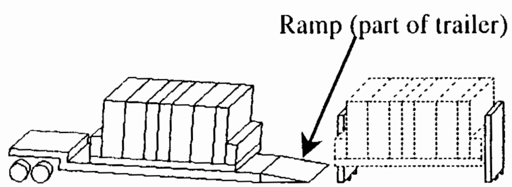
Figure 7-2: Worst Case Shipping Envelopes
(4115 mm is standard maximum height to allow for overpass clearance)



Option 1



Option 2



Option 3

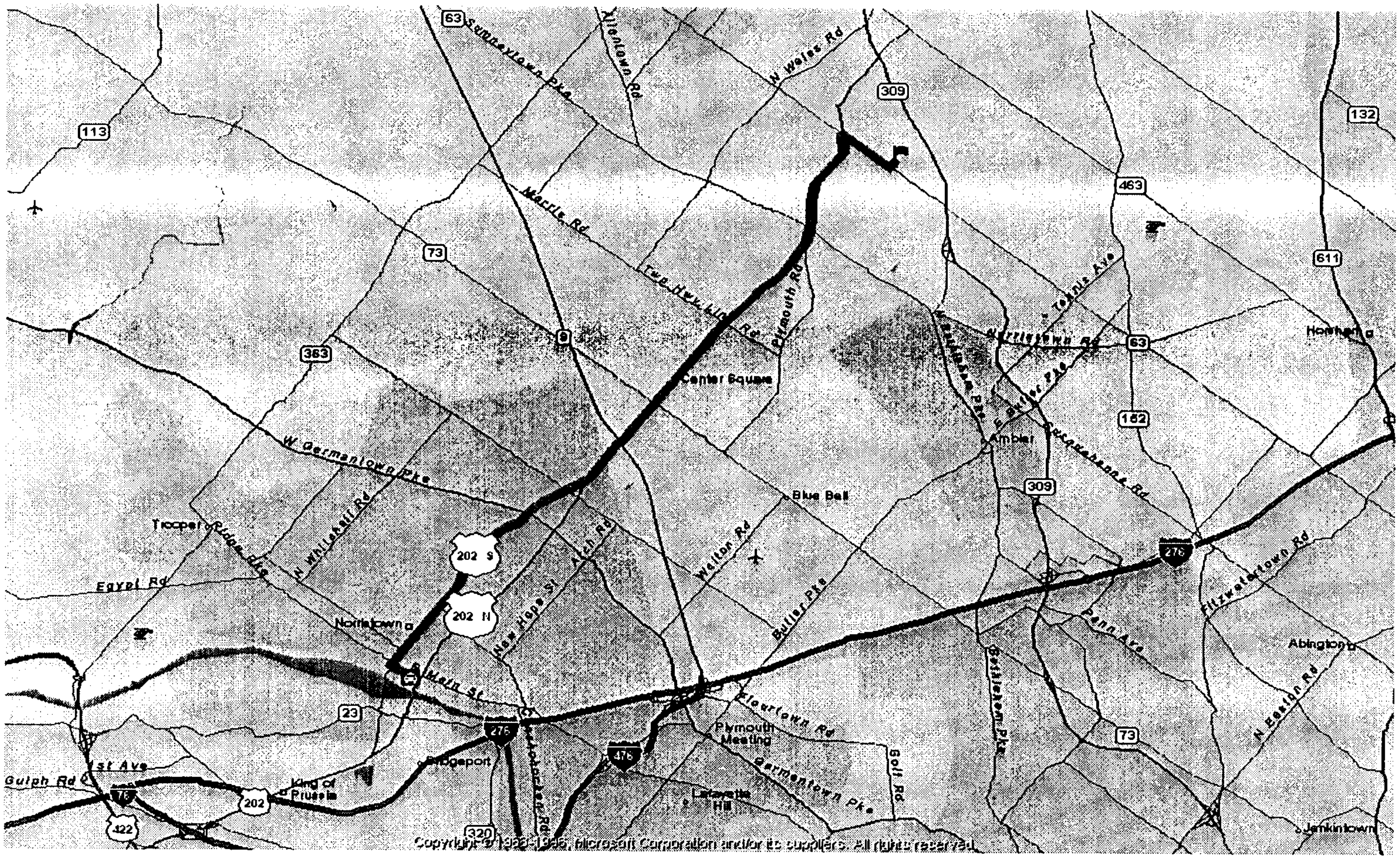
Category	Option 1	Option 2	Option 3
Safety risks	Least Favorable	Favorable	Most Favorable
Cost	Least Favorable	Favorable	Most Favorable
Logistics	Least Favorable	Favorable	Most Favorable
Auxiliary equipment requirements	Least Favorable	Favorable	Most Favorable
Adaptability to individual substation site requirements	Favorable	Most Favorable	Least Favorable
Time requirements	Least Favorable	Favorable	Most Favorable
Personnel requirements	Least Favorable	Favorable	Most Favorable

Most Favorable

Favorable

Least Favorable

Figure 7-3: Loading/Unloading Options Risk Assessment



Proposed route: Right turn from Keystone Dr. onto Welsh Rd. (PA 63), Left on Dekalb Pike (US 202), Left onto E. Lafayette St. into parking lot of Commonwealth Bank
17 km

Figure 7-4: Norristown Route Survey Results

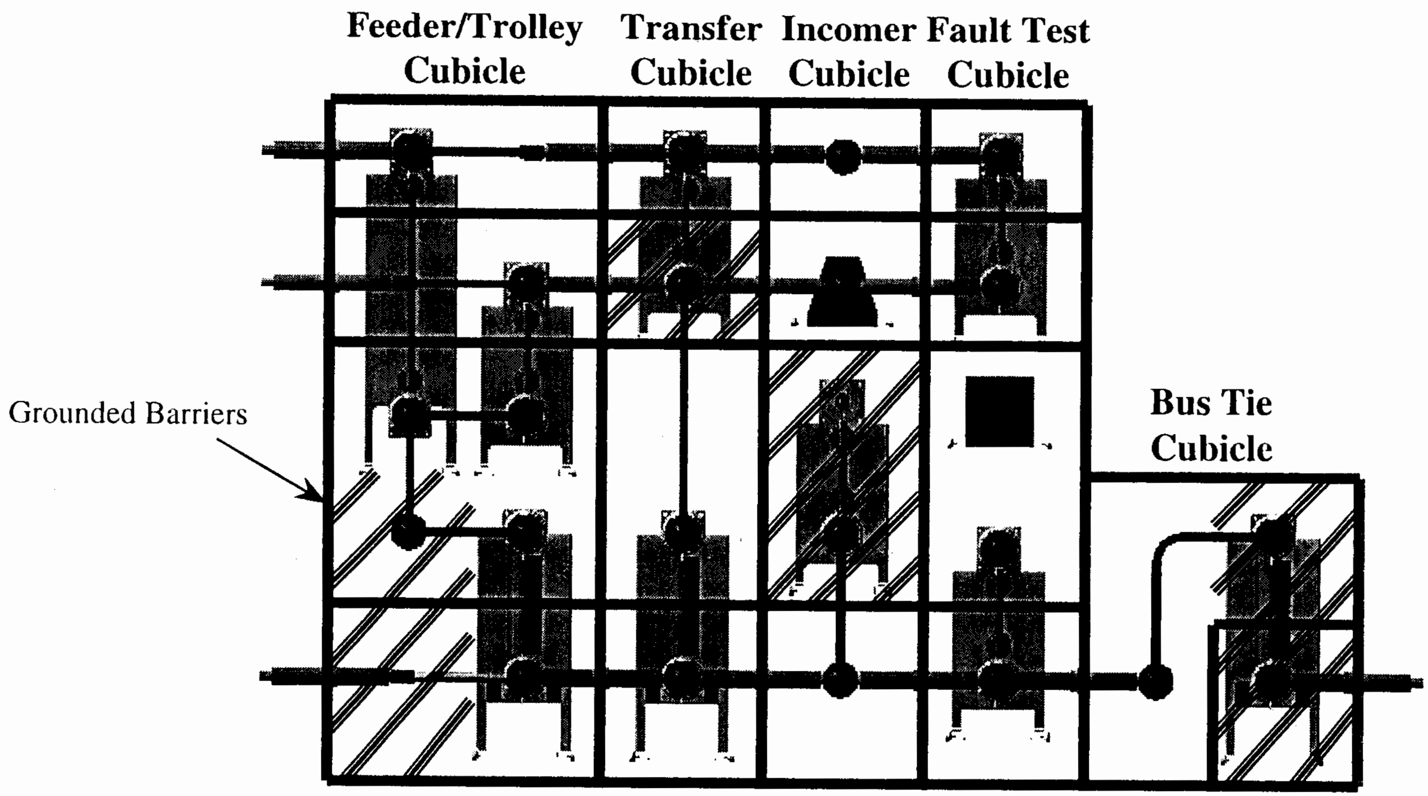


Figure 8-1: Critical Compartments for Analysis

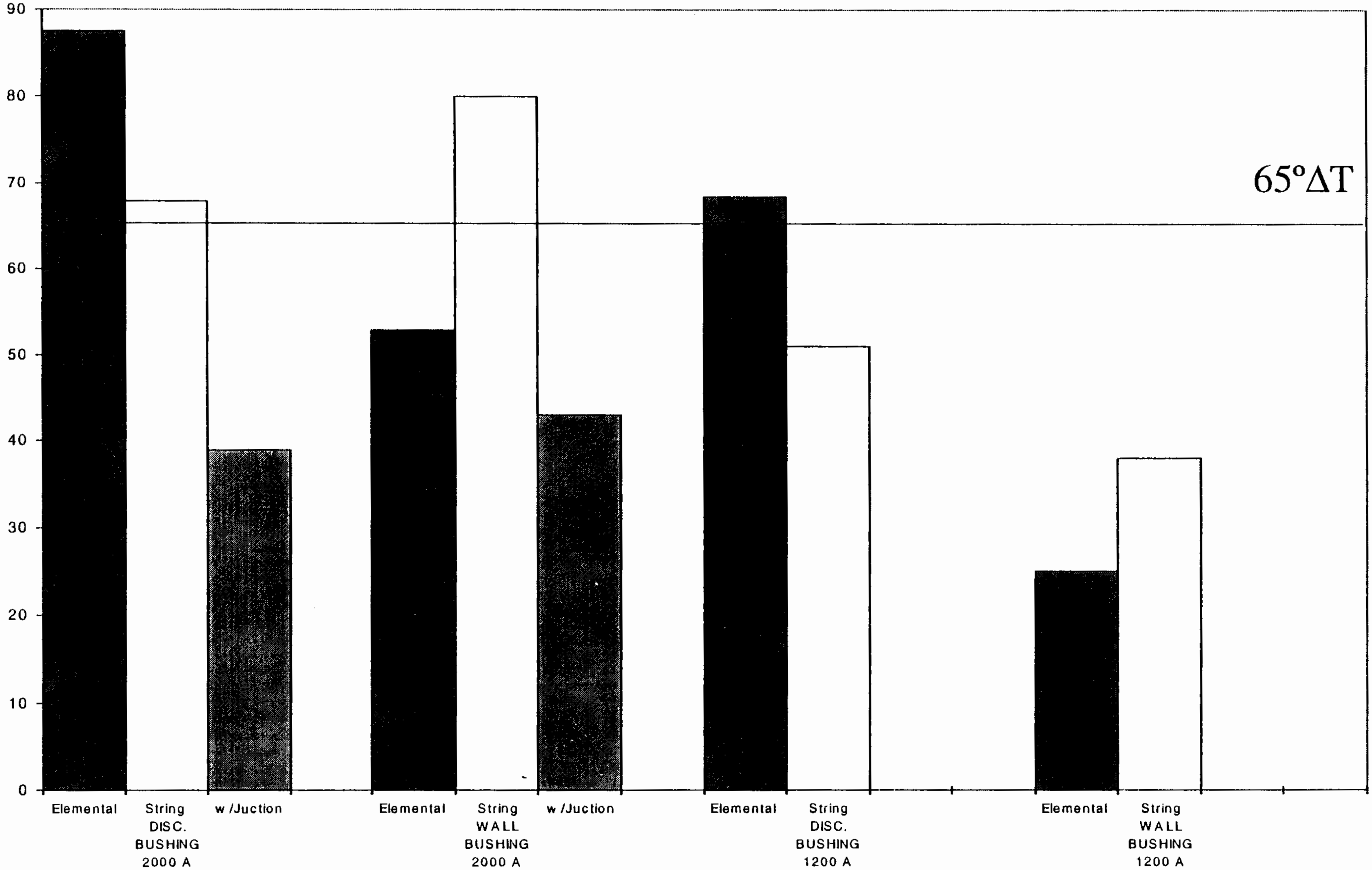


Figure 8-2: Temperature Rise Predictions, Bushing

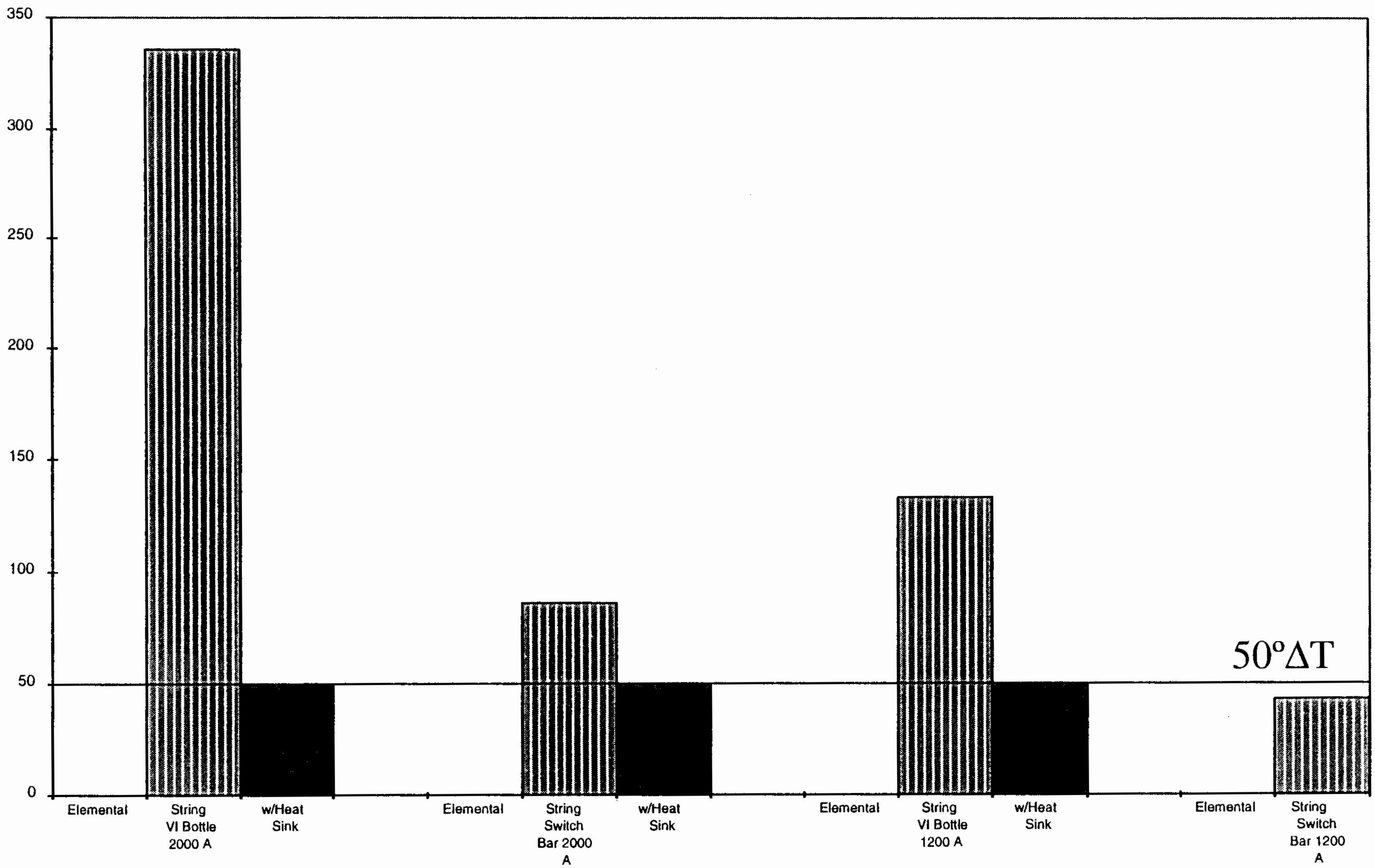


Figure 8-3: Temperature Rise Predictions, Conductor Insulation

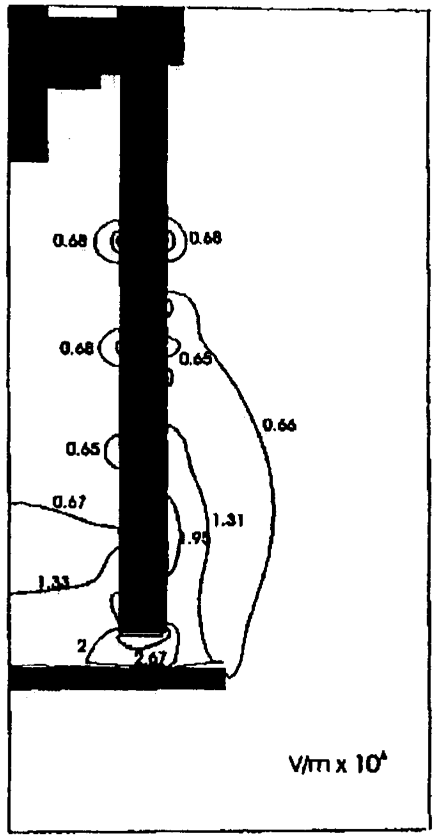


Figure 8-4: Electrostatic Field Plot of a Typical VCB or Disconnect Switch Compartment

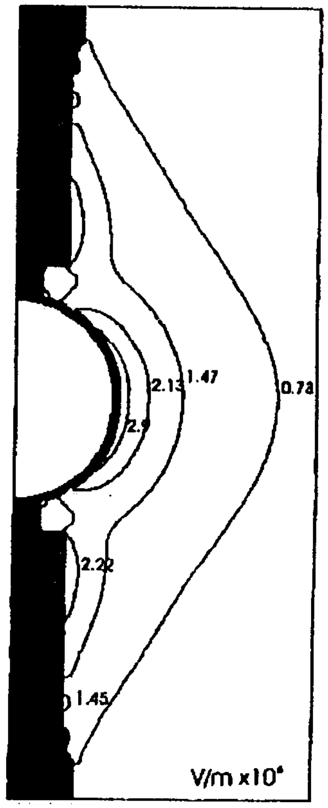


Figure 8-5: Electrostatic Field Plot of a Typical Bus Compartment

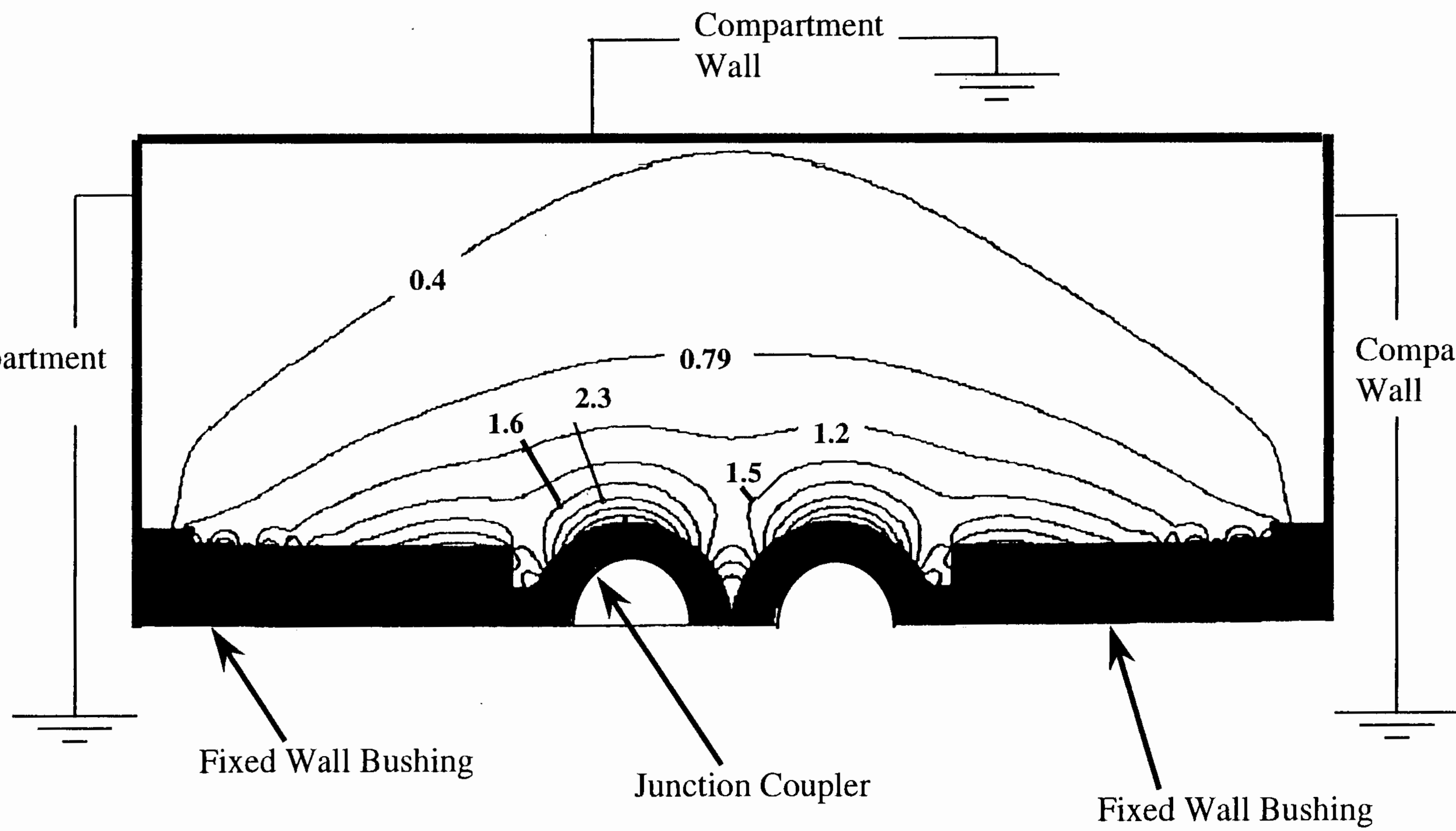


Figure 8-6: Junction Coupler Electrostatic Field Plot

Appendix B
Tables

Table 2-1: Key Technical Requirements

	"12kV Line-up"	"24kV Line-up"
Nominal Voltage	12kV	24kV
Type of System	1-PH	1-PH
Voltage Class— 3 Phase Equivalent	27kV	48.3kV
Operating Frequency	25Hz	25Hz
Basic Impulse Level	150kV	250kV
Nominal Frequency Withstand Voltage	60kV	105kV
Continuous Current	1200A/2000A	1200A/2000A
Interruption Ratings	25KA	12KA/8KA
Continuous Current Switching Total Mechanical Switching Switch Operations	10,000 opns 20,000 1500	10,000 opns 20,000 1500
Estimated Line-up Sizing: Height Depth Width	 122 in. (3.10m) 150 in. (3.81m) 1296 in. (32.92m)	 164 in. (4.17m) 148 in. (3.76) 1344 in. (34.14m)
Switchgear	Indoor, floor mounted, free standing, dead front, metal clad with drawout circuit breaker.	

Reference: Table 6-3 Minimum Switchgear Rating; Technical Specification for 12kV and 24kV Switchgear; Report 9 of 10, LTK Engineering Services.

Table 3-1: Circuit Breaker Requirements/Compliance Summary

Feature	Requirement	Source of requirement *	Compliance
1. Mechanical switching capability	20,000 operations	6.8	COMPLIES
2. Cont. switching capability	10,000 operations	6.8	COMPLIES
3. 12 kV short circuit switching capability	60 operations	6.8	COMPLIES: can close and latch on rated short circuit current (24 kA)
4. 24 kV short circuit switching capability	100 operations	6.8	COMPLIES: can close and latch on rated short circuit current (24 kA)
5. Continuous current	1200 A or 2000 A @25 Hz	6.8	Each mechanism will be consistent with operation at 1200 A or 2000 A
6. 12 kV vacuum bottle	Cutler-Hammer #WL-35632P	SPD	COMPLIES
7. 24 kV vacuum bottle	Cutler-Hammer #WL-35561	SPD	COMPLIES
8. (Service conditions)	-30 °C to +40 °C	5.1	COMPLIES
9. One size for both 12kV & 24kV		7.2.3	Not feasible due to different BIL requirements and different short circuit current levels. Commonality will be used wherever possible.
10. Spring charged, stored energy type		7.2.3	COMPLIES
11. Electrical spring charging motor	12 sec. max. charging time	7.2.3	COMPLIES
12. Close/open cycle on 1 motor charge		7.2.3	COMPLIES
13. Motor automatically charges all springs at end of one cycle		7.2.3	Used to charge closing springs only. Opening springs are charged automatically during the closing stroke. (industry standard)
14. Available charging motor voltage	130 VDC nominal 100 VDC min., 136 VDC max.	SEPTA 5/2/97	COMPLIES
15. Manual spring charging		7.2.3	COMPLIES, except when cubicle door is closed
16. Manual charging handle	to be provided	7.2.3	COMPLIES
17. Closing solenoid		7.2.3	COMPLIES
18. Tripping device		7.2.3	COMPLIES
19. Springs used to provide necessary contact pressure		7.2.3	COMPLIES
20. Opening springs		7.2.3	COMPLIES: Opening springs are charged automatically during the closing stroke. (industry standard)
21. Mechanically trip free		7.2.3	COMPLIES
22. Electrically trip free		7.2.3	COMPLIES
23. Electrical and manual operation		7.2.3	COMPLIES
24. Fast interruption	The goal is arc interruption at the first current zero of the major loop	7.2.8	COMPLIES with vacuum interrupter bottle manufacturer's specified operating speed limits
25. Quiet operation		7.2.8	COMPLIES

* Source of requirement is "SEPTA Technical Spec. for 12 kV and 24 kV Switchgear" unless otherwise noted

Table 3-1: Circuit Breaker Requirements/Compliance Summary

Feature	Requirement	Source of requirement *	Compliance
26. Long service life	Contact erosion shall limit life	7.2.8	COMPLIES
27. Buffer	Decelerate opening speed to limit over-travel	SPD	COMPLIES
28. Operations counter	Signal to be provided	7.16.1	COMPLIES: Electrical signal available thru aux. switch
29. Manual charged/discharged indicator	To be provided	7.14.2	COMPLIES
30. VI contact erosion indicator	To be provided	7.14.2	COMPLIES
31. Open and close indicating lights	Signal to be provided	7.14.2	COMPLIES: Electrical signal available thru aux. switch
32. Under-voltage tripping	None required		COMPLIES
33. Aux. switches	(Quantity and ratings TBD)	7.16.3	COMPLIES
34. BIL clearance distance	150 kV BIL: 165mm clearance from any insulated conductor to ground. 250 kV BIL: 267mm clearance from any insulated conductor to ground	SPD	COMPLIES
35. Anti-pump		SPD/ANSI	COMPLIES
36. Fault measuring provisions prior to closing of the circuit breaker		7.4.1	COMPLIES: Will be accomplished thru control system inputs. (Not part of operating mechanism)
37. Discharge springs and trip on rack-out or rack-in		7.8.2.1	COMPLIES
38. Automatic trip when jacking handle inserted		SPD (industry standard practice)	COMPLIES Note: Access to leadscrew denied when in connected position, unless breaker is tripped (prevents accidental tripping of live breaker)
39. Automatically trip from test to connected, or connected to test		7.8.2.1	COMPLIES
40. Withdrawal mechanism padlock provisions		SPD (industry standard practice)	COMPLIES
41. No close between connected and test positions	No closing until indexed into test position	7.8.2.1.2	COMPLIES
42. No close between test and connected interlock	No closing until indexed into connected position	7.8.2.1.2	COMPLIES
43. Electrical interlock: In connected pos. CB shall be permitted to close only when system wide conditions are met		7.8.2.2 7.8.2.3 7.8.2.4	COMPLIES : Note: Will NOT be provided as part of operating mechanism. Will be accomplished electrically as part of control system

* Source of requirement is "SEPTA Technical Spec. for 12 kV and 24 kV Switchgear" unless otherwise noted

Table 3-1: Circuit Breaker Requirements/Compliance Summary

Feature	Requirement	Source of requirement *	Compliance
44. Electrical operation only in connected and test positions		7.8.2.1	COMPLIES
45. Manual operation possible only in indexed connected, test positions (or in withdrawn position)		7.8.2.1	COMPLIES
46. Manual trip or close possible with door open or closed		SPD (industry standard)	COMPLIES
47. Interrupter: contacts sealed inside arc chamber, vacuum of 10-7 torr for 20 yr. min, metal bellows guaranteed for 30,000 operations		7.2.1	COMPLIES
48. Interrupter support	Flame retardant, track resistant, high mechanical strength	7.2.2	COMPLIES
49. Truck	Welded steel	7.2.4	COMPLIES
50. Truck	Guide rails and wheels	7.2.4	COMPLIES
51. Truck	Connected to ground bus through ground contact shoe	7.2.4	COMPLIES
52. Primary contacts	Automatic, self aligning, self coupling, silver plated, spring biased hard copper fingers on drawout element. Stationary cell studs on stationary structure recessed within insulated supports. Sufficient cross section of Cu to permit removal of heat from fingers and studs, to avoid localized high loads, to maintain high conductivity	7.2.5	COMPLIES

* Source of requirement is "SEPTA Technical Spec. for 12 kV and 24 kV Switchgear" unless otherwise noted

Table 3-1: Circuit Breaker Requirements/Compliance Summary

Feature	Requirement	Source of requirement *	Compliance
53. Secondary contacts	Control, auxiliary and interlocking circuits between circuit breaker & stationary structure made by automatic, self aligning and self coupling devices. Multi-contact receptacles and plugs with sufficient numbers of contacts to for all secondary circuits & spares, with out the use of auxiliary relays	7.2.5	COMPLIES
54. Circuit breaker positions	Connected: both primary and secondary contacts connected	7.2.6	COMPLIES
55. Circuit breaker positions	Test: Primaries disconnected, secondaries connected	7.2.6	COMPLIES
56. Circuit breaker positions	Disconnected: Primaries and secondaries disconnected. Closing & opening springs discharged	7.2.6 (and input from SEPTA)	COMPLIES
57. Circuit breaker positions	Withdrawn: Primaries and secondaries disconnected. Closing & opening springs discharged	SPD (industry standard practice)	COMPLIES
58. Circuit breaker positions	Shall have indicator on cubicle door	7.2.6	COMPLIES
59. Drawout mechanism	Manual, horizontal. Shall move from connected to test to disconnect positions and back w/ cubicle door open or closed. Crank inserted thru hole in door or front panel	7.2.7	COMPLIES
60. Drawout mechanism	May be fully racked in or out in one minute by one man. In fully racked out position the circuit breaker can be withdrawn from cubicle	7.2.7	COMPLIES
61. Drawout mechanism	At end of travel drawout mech. shall automatically disengage. Over-travel prevented by positive stops	7.2.7	COMPLIES

* Source of requirement is "SEPTA Technical Spec. for 12 kV and 24 kV Switchgear" unless otherwise noted

Table 3-2: Circuit Breaker Endurance Specifications

	WE/CH	GE	Toshiba	Meiden.	Siemens	MG	SPD	ANSI C37.06-1987
Electrical life:								
Continuous current			10,000	10,000		10,000		100
Breaking/ switching				20				
Inrush								100
Mechanical life:								
Total		10,000	10,000	10,000	60,000			2,500 (for 250 vA BIL) 1,500 (for 150 vA BIL)
Between servicing		2,000						500

Mechanical Endurance Specifications for Circuit Breaker Withdrawal Mechanism

	SPD	ANSI C37.06-1987
Min. # of cycles	1500	100 (between connected and test positions)

Mechanical Endurance Specifications for Drawout Switches

	SPD	ANSI C37.34-1984	ANSI C37.20.3-1987
Min. # of cycles	1500	1000	50 (between connected and test positions)

Table 3-3: Conceptual Spring Charging Motor Specifications

Parameter	Specification (Conceptual Data Only)
SPD Part Number	758002-A01
Maximum Voltage	136 VDC
Output Speed (at 136 VDC)	121 RPM
Nominal Voltage	130 VDC
Output Speed (at 130 VDC)	106 RPM
Minimum Voltage	100 VDC
Output Speed (at 100 VDC)	81 RPM
Output Torque	13.56 N-m
Mounting Bolt Pattern	Face-mounted, bolt pattern TBD
Shaft Diameter	7.92 mm
Nominal Frequency Withstand Voltage	60 Hz
Dielectric Withstand Voltage (1 minute)	1260 VAC
Gear Ratio	25.2 to 1
Insulation	Class F

Table 3-4: Circuit Breaker Position/Interlock vs. Operation Matrix

Position	Electrical Operation	Manual Operation
Connected	1, 2, 3 } Possible	1 Possible, with door open * 2 Possible 3 Possible
Test	1, 2, 3 } Possible	1 Possible, with door open * 2 Possible 3 Possible
Disconnected	1 No electricity available 2 Prevented 3 Prevented	1 Possible, with door open * 2 Prevented 3 Prevented
Withdrawn	1, 2, 3 } No electricity available. Operation possible via umbilical cord.	1, 2, 3 } Possible

* Charging Lever must be inserted directly into operating mechanism

NOTE: Confirmed at SEPTA Wayne Junction 5/9/97; additions underlined

Legend:

1 = Charging (Spring) Operation
2 = Close Operation
3 = Trip Operation

Table 4-1: Disconnect Switch Requirements/Compliance Summary

Feature	Requirement	Source of requirement *	Compliance
1. Mechanical switching capability	No load switching	7.3.11	COMPLIES
2. Mechanical operations	1,500 operations (no load)	ANSI C37.20.3-1987, SPD	COMPLIES
3. Continuous current	1200 A or 2000 A @25 Hz	6.8	COMPLIES
4. (Service conditions)	-30 °C to +40 °C	5.1	COMPLIES
5. BIL clearance distance	150 kV BIL: 165mm clearance from any insulated conductor to ground. 250 kV BIL: 267mm clearance from any insulated conductor to ground	SPD	COMPLIES
6. Standoff support	Flame retardant, track resistant, high mechanical strength	7.2.2	COMPLIES
7. Truck	Welded steel	7.2.4	COMPLIES
8. Truck	Guide rails and wheels	7.2.4	COMPLIES
9. Truck	Connected to ground bus through ground contact shoe	7.2.4	COMPLIES
10. Primary contacts	Automatic, self aligning, self coupling, silver plated, spring biased hard copper fingers on drawout element. Stationary cell studs on stationary structure recessed within insulated supports. Sufficient cross section of Copper to permit removal of heat from fingers and studs, to avoid localized high loads, to maintain high conductivity	7.2.5	COMPLIES
11. Drawout mechanism	Manual, horizontal. Shall move from connected... to disconnect positions and back w/ cubicle door open or closed. Crank inserted thru limited size hole in door or front panel	7.2.7	COMPLIES
12. Drawout mechanism	May be fully racked in or out in 1 minute by 1 man.	7.2.7	COMPLIES
13. Drawout mechanism	At end of travel drawout mech. shall automatically disengage. Over-travel prevented by positive stops	7.2.7	COMPLIES
14. Hand operated (Main bus, incomer, grounding)	Pad-lockable in any position. Clearly labeled open and closed indicators	7.3.10	COMPLIES
15. Motor operated (Transfer & test bus, test cubicle)	Remote or local operation. Sufficient torque, HP rating, RPM and gear ratio. DC operated from station battery (130 VDC nominal, 100 VDC min, 136 VDC max.)	7.3.10	COMPLIES

* Source of requirement is "SEPTA Technical Spec. for 12 kV and 24 kV Switchgear" unless otherwise noted

Table 5-1: Bus Structure Requirements/Compliance Summary

Feature	Source of Requirement*	Compliance Assessment
Busbars shall be made of solid, high electrical conductivity copper with silver plated contact surfaces	7.1	SPD Design Complies
The busbar continuos, overload and short circuit ratings shall be compatible with the switchgear ratings	7.1	SPD Design Complies
Maximum current density of the busbars shall not exceed 1,200 A/inch^2 at 200%% SFC overload	7.1	SPD Design Complies
Busbars at end cubicles shall be designed to permit future expansion	7.1	SPD Design Complies
The bus runs shall be completely insulated by rugged heat-shrinkable insulation sleeve, Raychem or equivalent	7.1	SPD Design Complies
Busbars shall be supported by molded supports that serve as barrier insulation	7.1	SPD Design Complies
Each bus run will be located in its own compartment and shall be insulated to the switchgear BIL level	7.1	SPD Design Complies

* Source of requirement is "SEPTA Technical Specification for 12 kV and 24 kV Switchgear" unless otherwise noted

Table 5-2: Junction Coupler Comparison

Criterion	Alternate junction Coupler	Assessment	Spherical Junction Coupler
Transportation Impact	Reduced complexity due to height decrease of 13%	←	Cubicle height increases complexity due to required overpass clearances
Fabrication Issues	Simple investment casting similar to off-the-shelf castings in production	←	Complex investment casting
Assembly Issues	Insulation application is similar to current methods	←	Insulation application will be difficult due to spherical shape
Logistical Issues	Multiple designs required to accomodate all possible conductor arrangements	→	One design will accomodate all possible conductor arrangements
Thermal Issues	Meets all thermal requirements with careful attention to the mass of the coupler	●—●	Spherical shape provides the optimal surface area for convective heat dissipation
Electro-Statc Issues	Meets all electro-static requirements with careful attention to sharp edges	→	Spherical shape represents the ideal for ensuring the uniformity of th electro-static field generated
Structural Issues	Split clamp provides good structural joint	●—●	Split clamp in conjunction with spherical shape provides good structural joint

Table 6-1: Switchgear Requirements/Compliance Summary

Feature	Source of requirement *	Compliance Assessment
1. Indoor, dead-front, floor-mounted, free-standing, metal-clad, rigid enclosures	6.2 7.20.1	SPD design complies
2. Grounded 11 gauge steel barriers between compartments and 7 gauge steel floor pans	6.3	SPD design complies
3. Cubicle door serves as relay and instrument panel	6.3	SPD design complies
4. Guide rails to be provided for power component trucks	7.2.4	SPD design complies
5. Circuit Breaker position can be changed with door closed	7.2.7	SPD design complies
6. Power component truck can be withdrawn from cubicle	7.2.7	SPD design complies
7. Access doors to disconnect switches interlocked for door opening	7.8.3.8	To be addressed in Phase II
8. Protective raceways and terminal blocks to be used for secondary control wires	7.11.2.4	To be addressed in Phase II
9. Structural frame to support eq'pt during shipping and installation and during short circuit conditions	7.20.1	SPD design complies
10. Provisions for anchoring to substation floor	7.20.1	SPD design complies
11. Provide adequate ventilation	7.20.1	SPD design complies
12. Front access by hinged doors	7.20.2	SPD design complies
13. Top access by bolted panels	7.20.2	SPD design complies
14. Rear access by hinged or bolted panels	7.20.2	SPD design complies
15. Doors of 14 gauge steel minimum with stiffeners	7.20.2	SPD design complies
16. Doors must have handles, locks, keys and padlocks (approved by SEPTA)	7.20.2	To be addressed in Phase II
17. Power cable entry from cubicle bottom	7.20.3.1	SPD design complies
18. Bus compartments to have removable covers	7.20.3.5	SPD design complies
19. Painted or powder coated in/outside	7.23	SPD design complies
20. Hardware to be zinc or cadmium plated	7.24	To be addressed in Phase II
21. All metric **or** all inch fasteners	8.4.1	SPD design complies
22. Captive access panel screws	8.4.2	SPD design complies

* Source of requirement is "SEPTA Technical Spec. for 12 kV and 24 kV Switchgear" unless otherwise noted

Table 6-2: Switchgear Cubicle Analysis Summary

Loading Conditions	Analysis to be Performed	Objective	Pass/Fail Criteria	Requirement Origin
ANSI certification	Apply an inward 100# load, with a 1/2" x 1/2" square rod, to each wall of the enclosure individually	Determine static deflections, strains and stresses associated with this type of loading in preparation for the actual testing during phase II	The resulting deflections are elastic and do not impair the dielectric or mechanical performance of the power components	ANSI C37.20.3-1987 A3.6.2 "Deflection Test"
ANSI certification	With base of enclosure fixed, apply an inward 200# load to an upper corner of the enclosure enducing a torsional load	Determine static deflections and strains associated with this type of loading in preparation for the actual testing during phase II	The resulting deflections are elastic and do not impair the dielectric or mechanical performance of the power components	ANSI C37.20.3-1987 A3.6.3 "Torsion Test"
Normal operation	With base of enclosure fixed, apply loads to the component-to-enclosure interfaces to simulate their weights	Determine static deflections and stresses associated with this type of loading to ensure rigidity of enclosure	The resulting deflections are elastic and do not impair the dielectric or mechanical performance of the power components	SEPTA 317/LTK 2294-1993 section 7.20
Short-Circuit operation	In addition to the loads applied under the normal operating conditions, the electro-magnetic forces exerted on the components should be applied to the same interfaces	Determine static deflections and stresses above/beyond the normal operating conditions to ensure rigidity of enclosure	The resulting deflections are elastic and do not impair the dielectric or mechanical performance of the power components	SEPTA 317/LTK 2294-1993 section 7.20
Tractor-trailer transport	With the cubicles fastened together to form a transportable switchgear section and fixed at the base as if fastened to a trailer, apply a 2G lateral acceleration (or static equivalent)	Determine dynamic deflections and stresses associated with this type of loading to ensure safety of equipment during transport	The resulting deflections are elastic and do not damage or move the mechanical interfaces of the power components and do not present a hazard to transport personnel	SEPTA 317/LTK 2294-1993 section 10.3
Tractor-trailer transport	With the cubicles fastened together to form a transportable switchgear section and fixed at the base as if fastened to a trailer, apply a 12G vertical acceleration (or static equivalent)	Determine dynamic deflections and stresses associated with this type of loading to ensure safety of equipment during transport	The resulting deflections are elastic and do not damage or move the mechanical interfaces of the power components and do not present a hazard to transport personnel	SEPTA 317/LTK 2294-1993 section 10.3
Fork-lift/machinery mover transport	With the cubicles fastened together to form a transportable switchgear section and fixed at the base as if supported by the fork-lift, apply a 2G vertical acceleration (or static equivalent)	Determine static deflections and stresses associated with this type of loading to ensure safety of equipment during transport	The resulting deflections are elastic and do not damage or move the mechanical interfaces of the power components and do not present a hazard to transport personnel	SEPTA 317/LTK 2294-1993 section 10.3
Hoisting with crane	With the cubicles fastened together to form a transportable switchgear section and supported only at designated lift points, apply a 2G vertical acceleration (or static equivalent)	Determine dynamic deflections and stresses associated with this type of loading to ensure safety of equipment during transport	The resulting deflections are elastic and do not damage or move the mechanical interfaces of the power components and do not present a hazard to transport personnel	SEPTA 317/LTK 2294-1993 section 10.3
Maintenance operations	With base of enclosure fixedand the extension rails installed on the ends of the guide rails, apply loads to the guide rails to simulate the weight of a fully withdrawn component	Determine static deflections and stresses associated with this type of loading to ensure safety of equipment and personnel during maintenance operations	The resulting deflections are elastic and do not present a hazard to maintenance personnel	SPD

Table 7-1: Projected Number of Switchgear Shipments

	12 kV Switchgear			24 kV Switchgear			
Substations	**Shipment Segmentation**	**Shipment Length (Meters)**	**Shipment Weight (Tons)**	**Shipment Segmentation**	**Shipment Length (Meters)**	**Shipment Weight (Tons)**	**QTY of Trailers Required**
Wayne Junction	3 Sections	11.6	14	3 Sections	9.4	12	6
Bethayers	3 Sections	6.9	7	3 Sections	7.9	9	6
Jenkintown	2 Sections	8.1	9	2 Sections	8.6	11	4
Ambler	Full Line-up	10.2	12	Full Line-up	11.6	14	2
Lansdale	Full Line-up	10.2	12	Full Line-up	11.6	14	2
Neshaminy	Full Line-up	10.2	12	Full Line-up	11.6	14	2
Woodburne	Full Line-up	10.2	12	Full Line-up	11.6	14	2
Norristown	Full Line-up	5.0	5	Full Line-up	5.0	7	1
Yardley	Full Line-up	5.0	5	Full Line-up	5.0	7	1
Warminster	Full Line-up	5.0	5	Full Line-up	5.0	7	1
Doylestown	Full Line-up	5.0	5	Full Line-up	5.0	7	1
Green St.	Full Line-up	5.0	5	Full Line-up	5.0	7	1
Allens Ln.	Full Line-up	5.0	5	Full Line-up	5.0	7	1
Newtown	Full Line-up	3.3	4	Full Line-up	3.6	5	1
				Total number of trailers required =			31

assuming 12.19 of available space on each trailer

Table 7-2: Site Survey Results Summary

	Off-Site access issues				On-Site access issues		Unloading issues	
Substations	**Tractor trailer Accessible**	**Rail Accessible**	**Bridge Underpass in Surrounding Area**	**Low Overhead Lines in Surrounding Area**	**Access Road Improvements Required**	**Bridge Underpass on Site**	**Low Overhead Lines on Site**	**Space Available for Crane**
Wayne Junction	⬭	⬭	▷	▷				⬭
Bethayers	⬭	⬭		▷			▷	⬭
Jenkintown	⬭	⬭		▷	▷			⬭
Ambler	⬭	⬭						⬭
Lansdale	⬭	⬭						⬭
Neshaminy	⬭	⬭	▷	▷	▷			⬭
Woodburne	⬭	⬭	▷		▷	□		⬭
Norristown	⬭	⬭	▷			□		⬭
Yardley	⬭	⬭		▷				⬭
Warminster	⬭	⬭						⬭
Doylestown	⬭	⬭	▷		▷		▷	
Green St.	⬭		▷					
Allens Ln.	⬭	⬭	▷	▷	▷		▷	
Newtown	⬭	⬭		▷				⬭

Solution: Careful route planning (Bridge Underpass in Surrounding Area)

Solution: Coordinate with PECO, Bell Tel., Cable TV Co, etc. (Low Overhead Lines in Surrounding Area)

Solution: Coordinate with TPDC building construction (Access Road Improvements Required)

Solution: Temporarily relocate (Low Overhead Lines on Site)

⬭ **Positive Attribute**

□ **Impact is part of detailed study to be conducted later**

▷ **Negative Attribute**

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Table 8-1: Switchgear Rating Table

6.8 MINIMUM SWITCHGEAR RATINGS

The minimum required switchgear ratings are summarized in Table 6-3. Remainder of the switchgear ratings shall be in accordance with ANSI C37 series of Standards.

Table 6-3 - Minimum Switchgear Ratings

No.	Operating Characteristic	12 kV Line-up	24 kV Line-up
1	Nominal Voltage	12 kV	24 kV
2	Rated maximum voltage	13 kV	26 kV
3	Number of phases	1	
4	Rated frequency	25 Hz	
5	Voltage class - 3-phase equivalent	27 kV	48.3 kV
6	Normal frequency withstand voltage	60 kV	105 kV
7	Rated full wave impulse withstand voltage - Basic insulation level (BIL) across contact gap and to ground	150 kV	250 kV
8	Rated voltage range factor K	1.0	
9	Rated standard operating duty	CO - 15 s - CO	
10.1	Rated continuous current, trolley/feeder circuit breakers	1,200 A	
10.2	Rated continuous current, transfer bus circuit breakers	1,200 A	
10.3	Rated continuous current, bus-tie breakers	2,000 A	
11.1	Rated continuous current, transfer bus disconnect switches	1,200 A	
11.2	Rated continuous current, test bus disconnect switches	Compatible with the bus rating	
11.3	Rated continuous current, bus incomer disconnect switches	2,000 A	
11.4	Rated continuous current, horn-gap disconnect switches	1,200 A	
12	Overload rating	Refer to Section 6.9	
13.1	Rated short circuit current, trolley to ground, 12 kV fault	25 kA	
13.2	Rated short circuit current, feeder to ground, 24 kV fault		12 kA
13.3	Rated short circuit current, feeder to trolley, 36 kV fault		8 kA

Table 8-2: Harmonic Content Table

Table 5-1 - Harmonic Content of the Power System Currents for One SFC

Frequency (Hz)	Current Harmonics (A)	
	Converter Load 15 MVA	Converter Load 30 MVA
25	1,456	2,686
75	269	367
125	444	633
175	100	144
225	41.7	52.8
240	5.6	11.1
275	16.7	44.5
290	5.6	11.1
325	8.8	33.32
340	5.6	11.1
375	5.6	27.8
390	19.4	50.0
425	5.6	8.3
440	36.1	61.1
475	5.6	5.6
490	63.9	80.6
525	5.6	5.6
540	75.0	55.6
575	5.6	2.8
590	33.3	41.7
640	5.6	5.6
690	19.4	5.6
740	2.8	11.1
790	16.7	5.6
840	33.3	5.6
890	30.6	5.6
940	19.4	5.6

Table 8-3: Temperature Allowables per ANSI

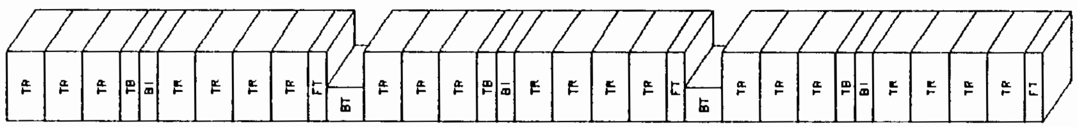
Elements	Allowable Temperature
Insulation	Class 90/105/130/155/180/220
Heat Shrink Tube	Class 90
Epoxy	Class 105
Buses	105 C
Connections w/ plated joints:	
Bus to Bus connection	105 C
Bus to Cable connection	85 C
Ambient inside Cubicle	Not cause the device to run at excessive Temp.
Ambient surrounding Insulated Power Cable	65 C
Ambient surrounding Cubicle	40 C
Parts subject to contact by personnel:	
Operating parts	50 C
Ext. Surfaces accessible to operator	70 C
Ext. Surfaces not accessible to opterator	110 C

Table 9-1: Design Status Summary

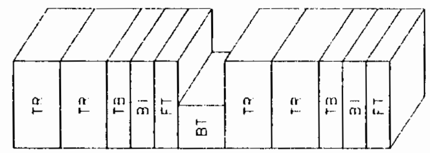
Component	Item	Status
Vacuum Circuit Breakers	1200A	Complies
	2000A	Complies
Switches	Test	Complies
	Transfer	Complies
	Incomer	Complies
	TR/FD Ground	Needs Refinement
	Main Bus Ground	Needs Refinement
Bus Structure	Fixed Wall Bushings	Complies
	Disconnect Wall Bushings	Complies
	Bus Conductors	Complies
	Conductor Insulation	Complies
	Junction Coupler	Complies
Switchgear	Enclosures	Complies

Appendix C

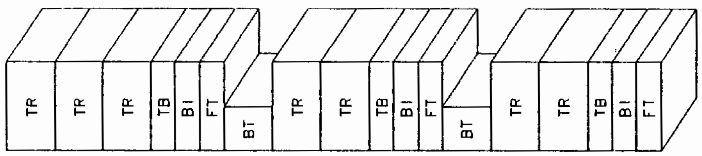
Switchgear Line-ups by Substation



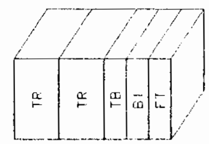
Wayne Junction
Footprint: 77 m^2
Height: 2.5 m, Width: 40.5 m, Depth 1.9 m



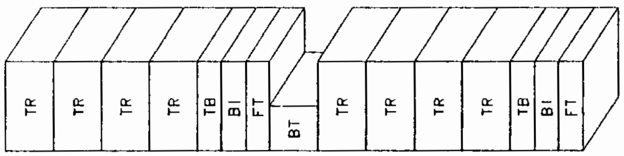
Ambler, Lansdale, Neshaminy, Woodburne
Footprint: 21.7 m^2
Height: 2.5 m, Width: 11.4 m, Depth 1.9 m



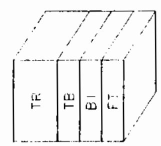
Bethayres
Footprint: 37.8 m^2
Height: 2.5 m, Width: 19.9 m, Depth 1.9 m



Norristown, Yardley, Warminster, Green St., Doylestown, Allens Lane
Footprint: 9.5 m^2
Height: 2.5 m, Width: 5 m, Depth 1.9 m

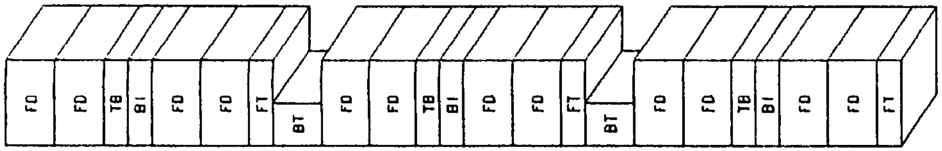


Jenkintown
Footprint: 36.3 m^2
Height: 2.5 m, Width: 19.1 m, Depth 1.9 m

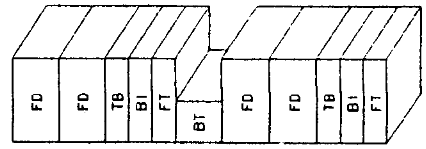


Newtown
Footprint: 6.7 m^2
Height: 2.5 m, Width: 3.5 m, Depth 1.9 m

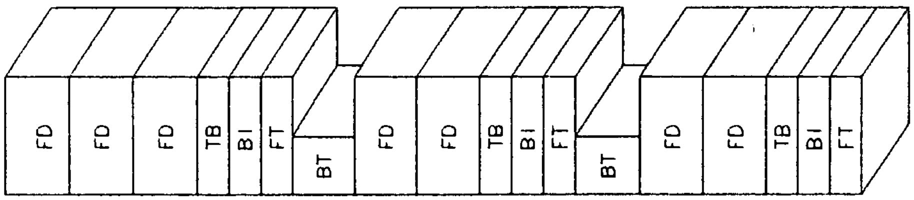
Figure C-1: 12 kV Line-up Arrangements by Substation



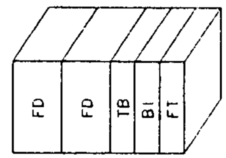
Wayne Junction
Footprint: 68.3 m²
Height: 3.5 m, Width: 27.3 m, Depth 2.5 m



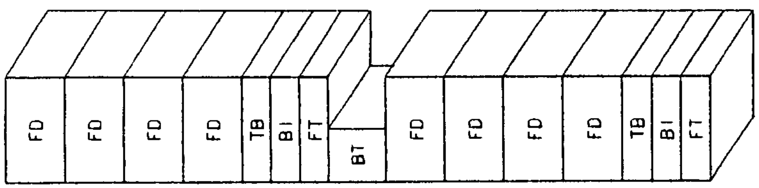
Ambler, Lansdale, Neshaminy, Woodburne
Footprint: 30.5 m²
Height: 3.5 m, Width: 12.2 m, Depth 2.5 m



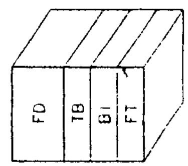
Bethayres
Footprint: 51.4 m²
Height: 3.5 m, Width: 20.6 m, Depth 2.5 m



Norristown, Yardley, Warminster, Green St., Doylestown, Allens Lane
Footprint: 13.3 m²
Height: 3.5 m, Width: 5.3 m, Depth 2.5 m



Jenkintown
Footprint: 41.9 m²
Height: 3.5 m, Width: 16.8 m, Depth 2.5 m



Newtown
Footprint: 9.5 m²
Height: 3.5 m, Width: 3.8 m, Depth 2.5 m

Figure C-2: 24 kV Line-up Arrangements by Substation