# Built-in-Place Substations

## *Beauty and Brains at the Right Price— TriMet's Traction Power Substations Evolve to a Higher Level*

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Light rail traction power substations (TPSs) do not have to be unsightly and hidden in the most remote recesses of the project. The large painted metal boxes surrounded by cyclone fence that have become the familiar norm for many projects are being replaced by built-in-place buildings in Portland, Oregon, where the Tri-County Metropolitan Transportation District of Oregon (TriMet) and the community are concerned with aesthetics and have made the TPS an important and prominent design element.

The general design, construction, costs, contract packaging, advantages and disadvantages, and features of the TriMet built-in-place substation buildings are discussed, and they are compared to similar packaged units.

Built-in-place TPSs are far more likely to be accepted by their neighboring community. This acceptance allows them to be an important part of the architectural design of the stations, platforms, and other design sensitive locations. Field constructed TPSs using built-in-place buildings are a cost effective alternative to packaged traction power substations. Built-in-place TPS substations can offer more working space around equipment and better access to equipment, compared to packaged substations.

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## INTRODUCTION

The Portland TriMet light rail system is comprised of approximately 39 mi of line serving the greater Portland Area, with another 6 mi currently under construction. The original Banfield line has operated since 1986; the Westside and Hillsboro extensions have operated since 1998; and the Airport Extension began service late in 2001. The Interstate line will open in 2004.

Supporting the load are 38 mainline traction power substations (TPSs), one yard TPS at Elmonica Maintenance Facility, and two small TPSs feeding the overhead catenary system (OCS) inside the operation and maintenance buildings. Six additional mainline TPSs and one new yard TPS at Ruby Junction Maintenance Facility will be added by the Interstate project. Characteristics of the TPSs are summarized in Table 1.

**TABLE 1 TriMet Substations**

| | Banfield | Westside | Airport | Interstate MAX |
|---|---|---|---|---|
| Length of Line (mi) | 15 | 18 | 6 | 6 |
| Number of TPS (mainline) | 15 | 18 | 5 | 6 |
| TPS Full Load Voltage (Vdc) | 825 | 750 | 825 | 825 |
| TPSS Rated 100% Output Power (kW) | 750 | 750 | 1000 | 1000 |

## HISTORY

The Banfield substations were factory “packaged” units, featuring traction electrification equipment installed in prefabricated gray metal boxes at the factory. The packaged units were then installed on concrete foundations with crawl spaces for cable installation. The Westside and Airport substations were constructed in place. The Westside buildings used either brick or concrete masonry unit (CMU) construction. The Airport line substations were constructed from precast concrete panels. The Interstate MAX (IMAX) substations are the latest CMU design with glass block lights and metal roof, and are presently under construction. Installation of traction power equipment at the new Ruby Yard TPS is nearly completed.

After using typical prefabricated traction power substations on its first LRT project in the 1980s, at the beginning of the design of the Westside Light Rail (*1*), TriMet decided to locate many of the substations at passenger station platforms with the intention of building a brick façade around a packaged TPS. Additionally, several TPS were intended to be constructed in place within larger structures. The architectural treatment was in response to community desires for more aesthetically pleasing structures and to support urban design goals.

Preliminary cost analysis indicated that the cost for constructing a building and installing the traction electrification equipment in a follow-on contract was economical and feasible, and to be preferred over the alternative of attempting to construct a façade after the installation of the prefabricated TPS. The engineers managing the design and construction of the traction electrification contract, since all the substations would be constructed in the same manner, also favored this approach and the location at stations generally provided the best electrical performance.

Thus, beginning with the Westside LRT and continuing to the present, TPS buildings have been integrated with the station platforms wherever permitted by right of way or property availability. Otherwise TPS buildings have to be carefully integrated within the surrounding neighborhood. This consolidation of real estate reduces initial cost, and gives the urban designers and local artists enhanced opportunities for design and artwork. This approach has been well endorsed by the community, project architects, urban designers, and systems engineers. The larger working space and rear access to equipment incorporated into the latest IMAX design have been well received by TriMet operation and maintenance staff.

## ARCHITECTURAL PERSPECTIVE

### Building Features

In order to maximize the benefits of site built substations, it is important to address the scope of the total building.

### Building Location and Context

In order to maximize energy efficiencies and reduce costs, it is imperative to locate the TPS as close to the LRT station as possible. When the station area is limited, a well-designed TPS can be successfully integrated into the neighborhood, or be an attractive feature along the alignment. In the Portland metropolitan area the typical off-station site is a 50 by 100 ft plot. The building will need to comply with each city's urban design guidelines and community aesthetic concerns. The IMAX TPS building form is a response to local neighborhood and adjacent property owner requests to fit into the scale of residential and urban streets. In either at-station or off-station site locations, the site plan needs to be carefully considered and carefully situated for its specific location.

### Building Design and Materials

The new TriMet standard for TPS buildings features include a clearly recognizable triangle roof form, which is carefully detailed at the gable ends and eave lines. The building's design and materials were chosen to harmonize the scale of the substation in relation to its neighbors. By using careful, quality design, modest yet durable materials can be utilized. The interior floor plan is 19 ft 1 in. by 41 ft 10 in. by 13 ft 3.5 in. high. This incorporates a narrow access space along the rear of the traction power equipment. This layout allows for easily access to all the equipment round the clock, and in all seasons. All materials are noncombustible. Some of the substation building attributes are

- Metal galvanized roof coating that is a muted silver or gray over a waterproof sheathing and fire treated plywood diaphragm.
- Roof structure is premanufactured light gauge trusses anchored to wall plates.
- Exterior walls are a honed face, load bearing, concrete masonry system in a stack bond.
- Ballistic rated clear glass bricks are interspersed under the roof line, and along the street facing elevation.
- Antigraffiti coating is applied to CMU.
- Exterior paint is an abrasion resistant coating system.
- Interior walls are gypsum wall board with 4 in. metal studs, rigid insulation, and vertical metal framing channels at 4 ft on center.
- Gutters are deleted to minimize maintenance and allow storm water to recharge the local groundwater.
- Landscaping is provided to blend into the neighborhood vernacular.

## Mechanical and Electrical Systems

TriMet's goal was to use cost effective, durable, low energy use, and easily maintained ventilation, heating, and lighting systems. The lighting is positioned to enhance security and safety during the evenings. A modest amount of interior illumination radiates through the glass bricks to give the appearance of the building being occupied. Fluorescent lighting is used inside and outside. Exterior light fixtures are located at each door and on the gable roof ends for security and safety. Heating is provided by a ceiling mounted, 10 kW electric heater. The cooling system utilizes two 4100 CFM attic ventilation fan units with back-draft dampers that draw filtered air through door louvers. The attic space is insulated.

Table 2 provides building specifications for IMAX TPS.

## Contracting Methodology

TriMet has learned that the contractor that constructs the TPS building must be experienced in *building* construction. A *civil* contractor that coordinates packaged TPS building site requirements might be satisfactory, but in our experience, utilizing the knowledge and skills of a builder subcontractor can help overcome many concerns of site, mechanical elements, codes, and material coordination. A building contractor tends to monitor the construction process more closely, and understands how to manage the coordination of equipment, materials and products, and schedule. We also encourage the use of local subcontractors, trades, and product suppliers. It builds local capacity in the community, and reduces transportation costs and environmental impacts.

## Built-In-Place Versus Prefabricated Buildings and Packaged TPS

When the TriMet IMAX built-in-place TPS buildings are compared with Airport MAX prefabricated buildings or the Banfield packaged units, there are a number of similar features:

- Weatherproof enclosures,
- Site built foundations,
- Ground mats,
- Site fence enclosures, and
- Landscaping.

However, there are also many significant differences that the prefabricated Airport building design or Banfield packaged units did not provide. They had

- No interior rear equipment access aisle.
- No interior to exterior security illumination.
- No exterior form or materials that would meet city requirements.

## TABLE 2 IMAX TPS Building Specifications

| | |
|---|---|
| **Architectural Specifications** | |
| Building Dimensions | Interior: 19 ft, 1 in. by 41 ft, 10 in. by 13 ft, 3.5 in. high |
| Walls | Load bearing, honed-faced CMU, with 4-in. metal studs, vapor barrier, R-19 rigid insulation, and 5/8 in. Type X sheetrock. 1 5/8 in. x 1 5/8 in. 'Super-strut' metal framing channels. Interior Latex paint. |
| Ceiling | 5/8 in. Type X sheetrock, insulated R-30 batt insulation. 1 5/8 in. by 1 5/8 in. Super-strut metal framing channels |
| Ceiling Trusses | Prefabricated and engineered light gage steel trusses |
| Roof System | Pre-finished 'Zincalume' 24 gage metal roofing, over 30# felt, fireproofed plywood |
| Floor | Reinforced concrete slab-on-grade, 6 in. minimum, with polyethylene membrane. Sealed with acrylic, dustproof liquid membrane. |
| Doors | Steel, insulated, with stainless hardware and panic bars |
| **Mechanical Specifications** | |
| Cooling | Filtered exhaust air ventilation only (no air conditioning) designed for interior temperature using actual equipment full load losses. Two stage thermostat controlling both fans and unit heater. Heater will come on at 40° falling and off at 50° rising. One fan shall turn on at 85° rising, the second fan shall come on at 95° rising. Fans will turn off at 80° falling. |
| Heating | Chromolux 10 kW unit heater |
| Motors | (2) 1 H.P. Propeller Sidewall Exhaust Fans; drip proof, open type, with back draft dampers. |
| Control | Two stage, automatic/manual |
| Filters and Dampers | Door mounted |
| **Electrical Specifications** | |
| Interior Lighting | Fixtures are 4 ft length with 4 F32T8 fluorescent lamps, designed to provide adequate illumination for detailed maintenance; Emergency lighting provided by battery back-up "wall packs" for emergency egress only |
| Exterior | Fluorescent, 39 W wall packs, designed for each installation with automatic control (photocell or time clock) |
| Receptacles | 120-V receptacles provided for maintenance only |
| Power | 120/240 Vac panel installed prior to the Traction Electrification contract and temporary service provided by the utility (Converted in the TE contract) |
| Provisions for TE | Exterior NEMA 4x Emergency Shutdown Enclosures, ground mats, and substation ground buses, ductbank |

**Traction Electrification Design Parameters**

- National Electrical Code compliance; inspected by local and state of Oregon electrical authority
- Building sized to accommodate all potential suppliers
- DC feeder trench allows versatility in suppliers' equipment arrangement
- Equipment doors and access allows for quick equipment removal and replacement if necessary
- Ventilation system designed for optimum cooling while removing ionized or potentially explosive gases from inside the substation.

- Not easily incorporated into station design.

Other factors that make a built-in-place building desirable over a prefabricated building or a packaged TPS building are

- Easy incorporation of art features.
- Floor plan flexibility that can respond to a variety of site conditions.
- The option to incorporate into the station, which reduces real estate costs.
- The ease of conduit, duct bank, and cable installations.
- The ease of operation and maintenance, which means low agency costs.
- Q assurance and quality control inspections that are local versus factory visits.
- Project dollars that stay in the local economy.

## ENGINEERING PERSPECTIVE

The advantages and disadvantages of built-in-place traction power substations buildings will be discussed from the perspective of the traction power engineer for the three separate phases of the project: 1) preliminary design; 2) final design and procurement; and 3) construction.

### Preliminary Design

Ideally, when the preliminary alignment and preliminary design criteria for the light rail line have first been decided, the traction power engineer will be involved in the process of determining the locations of TPSs, and will have the opportunity to run multiple train simulations to assist in the process of deciding the locations. Past experience has shown that in order to minimize voltage drop and hence the cost of the OCS and parallel feeders, as well as minimize the number of substations required to meet the criteria, the substations should be located near the points of maximum acceleration—which is usually at passenger stations and major grades. The community and project acceptance of architecturally pleasing buildings allows integration of the buildings into the stations where the placement is electrically optimum. In contrast, on projects where prefabricated buildings or packaged TPSs have been used, community acceptance was much less forthcoming, and the project strategy was to conceal the substations and place them at a distance from areas of architectural sensitivity. Therefore, acceptance of the appearance of the substations by the community creates restrictions upon the electrical performance of the system to some degree by determining substation placement. In this respect, the use of built-in-place buildings over prefabricated or packaged TPSs affords the design engineer the opportunity to place the substations optimally.

During preliminary design, opportunities should be identified for co-location of the TPS with other facilities such as parking lots for park and ride facilities, where the land use and cost can be minimized—for example, locating the substation ground mat under an asphalt parking lot.

Consideration should also be given during preliminary design to the number of substations that will have to be constructed in place, sometimes in existing structures or buildings. The administration of the traction electrification (TE) construction contract is easier if all the substations are of one kind—either all built-in-place, or all packaged units. Table 3 compares built-in-place TPS buildings to prefabricated substations.

**TABLE 3 Built-in-Place TPS Buildings Versus Prefabricated Steel TPS Building Used for Packaged TPS**

| | Built-in-Place Building | Prefabricated TPS Steel Building |
|---|---|---|
| Initial Cost | Higher | Lower |
| Transportation/ Install Costs | None | May be high |
| Community Acceptance | Can be integrated with platform design and made architecturally pleasing | Poor, especially in central business district |
| Watertight Integrity | Few seams, water intrusion is normally not a problem even under maximum ventilation | Metal buildings are constructed with many seams which may not be waterproof. Water intrusion a possible problem, especially with maximum ventilation |
| Thermal Insulation and Sweating | Easy to achieve, and nonmetallic surfaces typically do not sweat | Difficult to achieve thermal insulation since interior walls are metal |
| Maintenance | CMU exterior does not require maintenance | Painting required to preserve metal |
| Design Limitations | Typically None | Shipping dimensions limit design and equipment arrangement; difficulty in obtaining NEC working clearances (Art 110 and 250-110) |
| Access to Equipment for Maintenance | All equipment maintenance can be performed indoors in any weather | Rear of the equipment is usually accessible by removing outside panels or opening doors |
| Site Restrictions | Vehicle and forklift access must be allowed to equipment, double doors only | Vehicle access must be allowed to entire rear wall of substation to remove panels and maintain equipment |
| Future Modification of Equipment or Building | Space for future expansion be provided without great expense | Space is at a premium |
| NEC Compliance | On-site building inspection ensures compliance prior to installation of TE equipment | Not inspected until after installation of TE equipment and installed on site |
| TE Equipment Installers | NEC qualified State Licensed Electricians | Factory workers |

## Final Design and Procurement

Final design marks the beginning of a process of design refinement and property procurement that will affect the substation placement and ultimately, can affect the decision of whether to build the substations in place, or procure packaged units. At the beginning of TE final design, the TPSs are placed in electrically ideal locations, with performance assured by running a computer simulation. We have found that built-in-place substations that have been placed as a part of an architectural design will remain in place, at least on the same site, and this stability is of benefit to the designer since it minimizes design changes. Packaged TPSs may move as the project attempts to hide them, or move them into less architecturally sensitive locations and this can destabilize the design effort.

To complicate the design process, the TE design involves both provisions in multiple “civil” contracts for the traction electrification, and the installation of the TPS equipment and OCS in the TE contract itself. Usually, the design schedule is organized so that the designs run concurrently, with the civil designs preceding the TE design. Generally, the work in the civil contract entails all underground work, or work in tunnels or on structures, including all underground conduit work and ground mat construction. The civil contracts also include either a foundation for a packaged TPS or a complete TPS building. It is absolutely essential from the TE design standpoint that the TPSs be located and stable at the beginning of final design, because TE designers may be involved in every civil contract. Changes in substation location are very difficult to accommodate at this stage and involve a second simulation; they may involve extensive changes to both the TE package and the civil contract packages. These factors favor the built-in-place buildings over the packaged TPS buildings.

Other design considerations include compliance of the finished TPS with the National Electrical Code (NEC), organization of the TE construction contract and contract interfaces, and cost.

## Construction

Whether substations are packaged, built-in-place, or prefabricated, the TE work will extend to the civil contracts as noted above.

The construction phase of the project is when the electrical inspection authority will become involved in the project for the first time. The State of Oregon has written into law that TPSs and TPS buildings are subject to electrical inspection up to the DC equipment. For built-in-place buildings, the first inspection occurs before the TE equipment is installed, and includes all AC low voltage lighting and power, heat, and motor starters for the ventilation. The buildings pass inspection without a problem since the wiring is done by Oregon-state licensed electricians and contractors knowledgeable in the NEC. A second and final inspection then takes place after installation of the TE equipment.

In contrast, for packaged buildings, maximum shipping dimensions determine the maximum allowable width which can lead to working clearances about equipment less than those recommended by Article 110 of the NEC, and therefore, issues with the electrical inspection authority arise. There has also been a misconception by manufacturers that they are exempt from the NEC requirements as stated in Article 90, which can conflict with state law. Construction contracts now require that all field wiring be done by licensed electricians and conform to the NEC. These requirements are easily met by building in place, but may not be easily met with packaged substations. It is important to recognize that dealing with the inspection issues during construction can be taxing on both the project budget and manpower resources, and so there is an indirect cost savings by minimizing inspection issues. For TriMet, part of the solution to minimizing inspection issues is to build the TPSs in place.

Another factor affecting both quality and cost is contract organization. If the choice is made to procure packaged TPSs, then agency oversight should be established at the factory, which usually involves one inspector at the factory during installation of the TE equipment in the prefabricated buildings. In addition, another inspector will be required to oversee the installation of the packaged units on the foundations, and witness start-up and field tests. These tasks may overlap. If the choice is made to construct buildings in place, the administration of the TE contract is simplified by the elimination of the ongoing factory inspection. After approval of shop drawings and submittals, witnessing of design tests, and first article inspections, the need for factory inspection is greatly reduced, and only one TE substation inspector is required. However, it is essential that the manufacturer provide an on-site engineer to supervise installation every step of the way so the completed product is to the satisfaction of both the agency and the manufacturer.

## OPERATION AND MAINTENANCE PERSPECTIVE

The decision whether to procure packaged substations or build the substations in place determines to a large extent how easily and successful the follow-on operation and maintenance program can be executed during revenue service. Maintenance-of-way has set several priorities for maintenance, which we attempt to accommodate in the design:

- Easy and ready access to the traction power transformer coils, and bolted bus connections;
- Maintenance not dependent upon weather;
- Adequate working space around switchgear; and
- Adequate floor space to accommodate and work on circuit breaker trucks.

These considerations are easily accommodated in the design of substation buildings. For example, all maintenance is performed from the inside of the substations, except when a component must be removed and replaced. Packaged substations, in contrast, are much more compact and the traction power transformers and switchgear are usually accessed through panels and openings in the building from the outside, where weather is a factor. Also, packaged substations may have bolt-on removable steel access panels that require a forklift or heavy piece of equipment to remove, which complicates the maintenance process.

## COST COMPARISONS

### Overview

The TriMet buildings can be categorized into the following types with the associated costs:

- Banfield—Packaged TPS with metal buildings and factory installed equipment, cost undetermined.
- Westside MAX—Brick exterior veneer steel frame building, constructed in place, $274,000.
- Airport MAX—Precast concrete building, constructed in place, $217,000.
- IMAX—CMU building, constructed in place, $240,000.

The above building costs are expressed in 2002 U.S. dollars and include costs to transport materials and equipment to the site, site work, foundation slab, ground mat, and complete building electrical and mechanical systems. (An itemized cost breakdown is not available for the Banfield packaged substations.)

### Built-in-Place Substation Cost

The average building cost for a substation building is about $240,000. This average figure is based on the recent bid for the TriMet IMAX Civil Construction Contract LS-10A/B, May 14, 2001 (*2*). This building cost includes site preparation, ground mat, foundation slabs, wall systems, concrete unit masonry, doors, coatings, and complete building electrical and mechanical systems. Cost for the transporting, furnishing, installation, and testing of the TE equipment for a typical 1MW substation is about $328,000. The installation cost includes 2 kV outgoing DC feeder and negative return cables. This is the average cost obtained from the recent bid on the IMAX Traction Electrification Contract, November 6, 2001 (*3*). Since the site work, substation foundation slab, and ground mat are also required for prefabricated or packaged substation building, this cost(estimated at about $50,000) will be deducted from the unit cost for built-in-place substation building. The average cost for a completed, furnished, installed, and tested of a built-in-place substation is, therefore, equal to $518,000.

### Prefabricated Built-in-Place Substation Cost

At first glance, it appears that a slight savings may be realized by using precast concrete construction. However, numerous disadvantages in precast construction—such as restrictions on size and placement of door openings, and the absence of an attic space for ventilation—favor other methods of construction. Also, the Airport MAX substations were approximately 15 ft by 39 ft, or 585 sq ft. The IMAX TPS, by comparison, were 20 ft by 42 ft, or 840 sq ft, so on a square foot basis the Airport MAX TPS building cost $370 per square foot, whereas the IMAX TPS building cost $285 per square foot—a significant savings.

**Packaged Substation Cost**

Cost for furnishing, installing and testing of a typical packaged substation building is itemized below:

| *Items* | *Cost* |
|---|---|
| TPS | $450,000 |
| Field Install | $25,000 |
| Field Testing | $10,000 |
| TPS Field Engineer | $10,000 |
| Factory inspections | $10,000 |
| Architectural Treatment | $5,000 |
| *Total Cost* | **$510,000** |

The installation cost includes receiving, off-loading, installing the TPS onto the slab, connecting AC service and outgoing positive feeder and negative return cables, and field testing. A representative from the TPS manufacturer is required at the site during the installation of the substation. Assume that four factory visits are needed for quality assurance inspection during the manufacturing of the substation equipment and building. The cost for the architectural treatment to the building enclosure varies, and a figure of $5,000 was used for this estimate.

Cost for a complete, furnished, installed, and tested built-in-place substation is only about 5% higher than that of a packaged unit. If savings in real estate cost and shorter conduit/ductbank runs for built-in-place substations are included in the total TPS cost, the costs appear to equalize, or favor the built-in-place over other methods of construction. Furthermore, the built-in place substation building clearly offers more advantages. Table 4 compares the costs of built-in-place substations to prefabricated substations.

**Comparison of Total TPS Costs**

In summary, the total costs for a 1 MW TPS, installed, complete, are

- IMAX CMU built-in-place, $518,000;
- Airport MAX prefabricated built-in-place, $495,000; and
- Typical Packaged TPS, $510,000.

## SUMMARY AND RECOMMENDATIONS

- Built-in-place TPSs are far more likely to be accepted by their neighboring community. This acceptance allows them to be an important part of the architectural design of the stations, platforms, and other design sensitive locations.
- Field constructed TPSs using built-in-place buildings are a cost effective alternative to packaged traction power substations.
- Built-in-place TPSs can offer more working space about equipment and better access to equipment when compared with packaged substations.

**TABLE 4 Cost Comparison of Built-in-Place TE Substations Versus Packaged TE Substations**

| | Built-in-Place | Packaged |
|---|---|---|
| Land | Real estate cost savings with TPS building integrated with station platform | No Saving |
| Inspection | Organize TE contract for continuous on-site inspection | Organize TE contract for continuous at-factory inspection |
| NEC Compliance Issues | None | Possible expense of dealing with electrical authority |
| Architectural Treatment | No extra cost | Extra cost is required |
| Off-loading, Handling with Cranes | Not required | Required |
| Ductbank/Cable Installation | Cost savings due to shorter ductbank runs | Extra cost for longer ductbank runs |

The following are recommended TE design parameters:

- NEC compliant, and inspected by local and State of Oregon electrical authority.
- Building sized to accommodate all potential suppliers.
- DC feeder trench included that allows versatility in suppliers' equipment arrangement.
- Equipment doors and access allows for quick equipment removal and replacement if necessary.
- Ventilation system designed for optimum cooling while removing ionized or potentially explosive gases from inside the substation.

Figures 1 through 10 provide photographs of IMAX substations throughout Portland. Tables 2 and 3 compare the elements and cost of built-in-place TPSs and prefabricated substations.

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**FIGURE 1 TriMet Banfield LRT Project Lloyd Center Substation, 1986.**

**FIGURE 2 TriMet Westside LRT Expansion Millikan Substation, 1998.**

**FIGURE 3 TriMet Westside LRT Expansion Civic Stadium Substation, 1998.**

**FIGURE 4 TriMet Westside LRT Expansion 170th Street Substation, 1998.**

**FIGURE 5 TriMet Hillsboro LRT Extension Government Center Substation, 1998.**

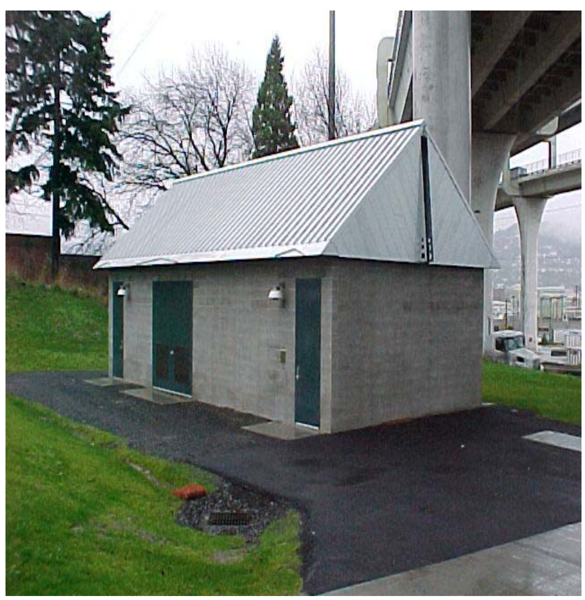

**FIGURE 6 TriMet Interstate MAX LRT Graham Street Substation, 2003.**

**FIGURE 7 TriMet Interstate MAX LRT Killingsworth Station Substation, 2003.**

**FIGURE 8 TriMet Interstate MAX LRT Failing Street Substation, 2003.**

**FIGURE 9 TriMet Interstate MAX LRT Expo Substation, 2003.**

**FIGURE 10 TriMet Interstate MAX LRT Expo Substation, 2003.**

## REFERENCES

1. Pham, K. D., and R. S. Thomas. Traction Power Supply for TriMet Portland Westside and Hillsboro Light Rail Extensions., *Proc., 1999 IEEE/ASME Joint Rail Conference*.
2. TriMet. Substation Building Costs, Civil Construction Contract LS-10A/B, IMAX LRT Extension, May 2001.
3. TriMet. Substation Equipment and Installation Costs, Traction Electrification Contract LS-10F, IMAX LRT Ext., Nov. 2001.

## BIOGRAPHICAL SKETCHES

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