CONSIDERATIONS IN APPLICATION AND SELECTION OF UNIT SUBSTATION TRANSFORMERS

Charles J. Nochumson
Member, IEEE
Application Engineer
601 Oakmont Lane, Suite 310
Westmont, IL 60559

Abstract **- This paper will discuss Secondary Unit Substations Transformers (USTs) ranging from 300 kVA up through 2500 kVA with 34.5 kV maximum primary voltages and with secondary voltages 600 volts and below. Pad-Mounted (compartmentalized) transformers are not considered in this paper. The first part of this paper will discuss USTs belonging to two general categories, Liquid-Type and Dry-type (non-liquid type). Liquid types will include a discussion of the presently available insulating fluids: Mineral Oil, High Temperature Hydrocarbon Fluid, Silicone Fluids and the new Vegetable Based Fluids. Dry types will include a discussion of VPI Polyester, VPE Silicone, Partial Cast and Full Cast insulation systems. National Electric Code (NEC) 1999 requirements as they effect both Liquid and Dry Type USTs for both outdoor and indoor locations will be considered. The second part of the paper will discuss the relative advantages of each UST within each category with respect to 1) First Cost, 2) Operating Costs (Losses), 3) Overload Capability, 4) Fan Cooling, 5) Space Factor, 6) Environmental Factors, 7) Sound Levels and 8) Maintenance.**

I. INTRODUCTION

This paper will discuss Secondary Unit Substation Transformers (USTs) as utilized indoors and outdoors. The UST primary is normally close coupled to one of the following: 1) an Air Terminal Chamber suitable for conduit and cable connection to a remote primary protective device, 2) Primary Non-Fused Switch, 3) Primary Fused Switch, 4) Combination Primary Switch with Vacuum Breaker, or 5) Draw-out Vacuum Breaker. The UST secondary is normally connected through a bus transition (including a short length of flexible conductor to isolate vibration & noise) to 1) Low Voltage Metal Enclosed Switchgear, 2) Low Voltage Switchboard, or in some cases to 3) Motor Control Center. This paper will cover UST typical ratings, construction features and variations available; however, specific manufacturers should be consulted regarding available alternate ratings and construction details. Part I will first discuss NEC requirements as they affect location considerations and will briefly discuss the various fluids and insulation systems available. Part II will review other consideration factors for the correct selection of the best type of UST for a given application. These factors include initial transformer cost, installation costs, operating costs, maintenance costs and special design features and options. Consideration of the type of facility, industrial versus commercial, the magnitude, length of time and type of loading on the transformer will play a big factor in the economically correct UST selection.

II. PART I – NEC LOCATION & INSULATION CONSIDERATIONS

A. NEC Location Considerations

The following are some applicable comments regarding the 1999 National Electric Code (NEC) Article 450-B which provides requirements regarding the general location requirements for each category of transformer. These NEC location requirements can significantly effect the installation first cost of the selected UST.

1) Indoor Use – Dry Type (Non-Liquid) USTs:

NEC Article 450-21 (b): Transformers over 112-1/2 kVA are to be installed in a transformer room of fire-resistant 1-hour fire rating construction. The following exceptions allow for indoor use without a fire-resistant room: (1) Transformers with Class 155 or higher insulation systems and which are separated from combustible material by a fire-resistant, heat insulating barrier or by not less than 6 ft horizontally and 12 feet vertically. (2) Transformers with Class 155 or higher insulation systems and completely enclosed except for ventilating openings.

Dry Type UST transformers of the VPE/VPI type are normally built with Class H insulation materials, which are Class 220 insulation systems. Dry Type UST transformers of the Cast Type are normally available depending on manufacturer built with Class B and F insulation materials which are Class 150 and Class 185 rated insulation systems respectively. Thus Dry Type USTs if correctly specified with minimum Class H 220 or Class F 185 fully rated insulation systems in their metal enclosure could be installed indoors without a fire-resistant room per 450-21 (b) Exception (2).

2) Indoor Use – Liquid USTs:

NEC Article 450-23: Less Flammable Liquid-Insulated Transformers (Sometimes referred to as High Fire Point or High Flash Point Fluids) – These transformers must be insulated with a <u>listed</u> less flammable liquid that has a fire point of not less than 300°C. For the USTs under discussion, NEC permits indoor locations <u>without</u> a vault for the following two options: (1) In Type I or Type II buildings, in areas, where no combustible materials are stored, liquid confinement area is provided, and the installation complies with all the restrictions provided for in the listing of the liquid; or (2) Any type of building with automatic fire extinguishing system and

Presented at the 2001 IEEE IAS Pulp and Paper Industry Conference in Portland, OR:

liquid confinement area. Otherwise a code –approved vault per Part C as described for Oil-Insulated transformers is required.

Typical examples of Less Flammable transformers available today meeting minimum 300°C fire point requirement are filled with listed either High Temperature Hydrocarbon (HTM) Fluid - typical fire point of 312°C, Silicone fluid - typical fire point of 330°C, or new vegetable based fluid - a typical fire point of 360°C.

NEC Article 450-24: Nonflammable Fluid-Insulated Transformers - At present, there is no commercially available Non-Flammable Fluid that also complies with EPA guidelines.

NEC Article 450-25: Askarel-Insulated Transformers – Although NEC still discusses this type of transformer, they are no longer available because of Environmental Protection Agency (EPA) rulings against Askarel fluids which contain PCBs.

NEC Article 450-26: Oil Insulated Transformers (Flammable Fluid with Fire Point typically 160°C) – This section applies to USTs with mineral oil insulating fluid and they must be located in a code-approved vault covered under Part C – Transformer Vaults, which generally has a minimum of 3 hour fire rating. An exception allows the transformer vault to have 1-hour fire rating when automatic sprinklers, water spray carbon dioxide, or halon is provided. [Note: Halon is similar to Freon and is considered an environmental pollutant causing depletion of the ozone layer.] Exception 5 permits the UST to be located in a detached building not complying with Part C if the building or its contents would not present a fire hazard to other buildings or property and it is used only in supplying electric service. This exception would be applicable to buildings specifically designed to house coordinated factory connection of various different assemblies of electrical distribution and control equipment.

3) Outdoor - Dry Type (Non-Liquid) USTs:

NEC Article 450-22: Dry Type USTs installed outdoors must have a weatherproof enclosure. Typically Dry Type USTs should be specified with a UL listed or other Nationally Recognized Testing Laboratory listed NEMA 3R enclosure. In addition, the UST must not be located within 12 inches of combustible materials of buildings unless the transformer has Class 155 insulation systems or higher and is completely enclosed except for ventilating openings.

4) Outdoor – Liquid USTs:

NEC Article 450-23 (b): Less Flammable Liquid Transformers with Listed less-flammable fluids (fire point not less than 300°C) are permitted to be installed outdoors attached to, adjacent to, or on the roof of buildings, where installed in accordance with either (1) For Type I or Type II buildings, the installation shall comply with all restrictions provided for in the listing of the liquid or (2) the same as indicated below for 450-27.

NEC Article 450-27: Oil Insulated Transformers installed outdoors – Combustible material, combustible buildings, and parts of buildings, fire escapes, and door and window openings shall be safeguarded from fires originating in oil insulated transformers installed on roofs, attached to or adjacent to a building or combustible material. Space separations, fire-resistant barriers, automatic water spray systems, and enclosures that confine the oil of a ruptured transformer tank are recognized safeguards. One or more of these safeguards shall be applied according to the degree of hazard involved in cases where the transformer installation presents a fire hazard. Oil enclosures shall be permitted to consist of fire resistant dikes, curbed areas or basins, or trenches filled with coarse, crushed stone. Oil enclosures shall be provided with trapped drains where the exposure and quantity of oil involved are such that removal of the oil is important – this almost always applies to USTs.

B. Dielectric Oil, Insulation, & Construction Features

1) Liquid Transformers – Temperature Rise Considerations: Although NEMA TR1 and ANSI C37.12.00 differ to some extent on definitions of insulation classes, the following is typical in the industry for USTs. Typical liquid transformers are designed with insulation systems to operate at a continuous 65°C rise plus 40°C ambient (average temperature of 30°C over a 24-hour period), plus 15°C hot spot for at total insulation rating of 120°C. Thus the standard specified temperature rise of 65°C rise. However, liquid transformers can be specified with an optional 55°C rise, suitable to be operated up to a 65°C rise with an increase of 12% of base kVA rating continuously. For example, a 1500 kVA transformer specified with a 55°C temperature rise could then be operated continuously at 1500 kVA x 1.12 or 1680 kVA. This optional 55°C rise rating usually costs approximately 5% additional over the base price of the standard 65°C temperature rise unit. This extra 12% rating may be utilized for:

- Unknown future load growth
- Obtaining kVA ratings slightly above standard ratings
- Double-ended unit substation applications to obtain increased kVA capacity when operating on only one transformer.
- When higher than the standard 40°C ambient conditions are expected, but not to exceed 50°C.

2) Liquid Transformers – Insulation Systems & Fluids: Essentially, the core & coil construction and insulation systems of mineral oil, high flash point silicone, hydrocarbon, or the new vegetable-based fluids (and previous non-flammable filled transformers) are similar. In most cases core & coil is of the rectangular design with the secondary coil made of sheet wound copper or aluminum and insulated with thermally upgraded insulating paper. However, some of the actual insulation materials, gaskets, and bushings may vary to ensure chemical compatibility with the fluid being utilized. Also in many cases, the basic dielectric fluids have various other chemicals, such as antioxidants to act as stabilizers under different operating conditions.

The new vegetable-based (edible seed-oil) fluids are available as UL listed and Factory Mutual approved as a less-flammable fluid. Even though the vegetable based fluids are highly biodegradable, at the present time the Federal Government has not proposed any new less stringent standards compared to mineral oil for compliance threshold volumes or spill response time. However, EPA is allowing differences in the area of spill remediation on a case by case basis. Thus they must be treated similar to other transformer fluids. These standards may be further reduced for vegetable-based fluids in the future based on testing in this area.

Some of the new vegetable-based fluids are compatible with mineral oil and hydrocarbon fluids and can be utilized to "top off" or refill existing mineral oil and hydrocarbon fluid units. The vegetable oil fluids are more suitable for transformers having internal switching or fusing (similar to what is done in Pad-Mounted transformers) than silicone which forms a silicone ash under these conditions. Vegetable oil based fluids under arcing conditions provide only approximately 20% of the gas and combustion products of mineral oil and less gas and combustion products than silicone or hydrocarbon fluids. Silicone oil is typically limited to 34.5 kV and 200 kV BIL applications, where as the new vegetable oil fluid and high molecular weight hydrocarbon fluids are suitable for much higher voltages including 69 kV and above. There is presently testing by some of the transformer manufacturers indicating that vegetable based fluid will allow the transformers to be overloaded with less loss of life than presently available with other fluids. This is based on the fluid inhibiting insulating paper degradation and it being able to absorb significant moisture from the insulating paper and still meet dielectric requirements. Some brands of new vegetable based fluids can meet the oxidation stability protocol limits for mineral oil as outlined in ASTM Standard D 2440. Thus under breathing conditions, pressure relief valve operation, or other situations which continuously introduce oxygen, some of the new vegetable based fluid can meet the same standard requirement limits as mineral oil in the area of reduced dielectric loss, reduced gelling, and reduced acidity if required.

Field servicing and testing of vegetable oil based transformers is essentially the same as other fluid transformers including requirements regarding minimizing exposure time to the atmosphere.

3) Dry-Type Transformers (Non-liquid filled) Noncast Designs: Typical types of non-liquid transformers are ventilated dry-type transformers or cast transformers, utilizing Class B-80°C rise, Class F-115°C rise or Class H-150°C rise insulation systems. Today, in UST, most dry-type noncast transformers are constructed of Class H materials suitable for a total temperature of 220°C which is composed of 150°C rise plus 40°C maximum ambient (average temperature of 30°C over a 24-hour period), plus 30°C hot spot. The 30°C hot spot allows for differences in temperature at various location points within the windings, because of uneven heating and cooling of the windings. Transformers can be specified to be constructed of all Class H-220°C materials, but with an optional winding temperature rise of either 115°C or 80°C rise. This optional 115°C or 80°C rise will result in a larger core and coil assembly having typically 15% and 35% <u>continuous</u> overload capability respectively. These transformers with optional 115°C or 80°C winding temperature rise will typically have <u>lower total losses</u> and slightly <u>higher no-load losses</u> than standard 150°C rise units. Their X/R ratio is slightly higher than standard units.

Previously, conventional ventilated dry type Class H transformers utilized NOMEX paper and a dip-and- bake process. Due to the increasing demand for use of dry-type transformers in moisture-latent or harsh service conditions and chemically –polluted environments, vacuum pressure impregnated (VPI) or vacuum pressure encapsulated (VPE) transformers have become the standard of many manufacturers.

The VPI transformers are constructed of Class H-220°C materials and then are given additional environmental protection by means of vacuum pressure impregnation of polyester varnish suitable for a minimum of 220°C total temperature. These VPI units have become common for use in normal applications indoors. The VPI process consists of drying the completed core and coil assembly at atmospheric pressure in an oven through which hot air is continuously circulated. After the coil is preheated and dried, it is vacuum impregnated with high temperature varnish. The varnish is then cured following an established temperature versus time baking cycle. Many times, the impregnation is done with a polyester-type varnish material. Indoor units usually receive as standard one cycle of the above process, whereas outdoor units as standard receive two of the above cycles.

The VPE transformers are also constructed with Class H-220°C materials and then are given additional environmental protection by means of a vacuum pressure encapsulation of silicone resin suitable for a minimum of 220°C total temperature. This premium VPE silicone encapsulation systems is often specified for use in possible heavy moisture conditions or outdoor locations, or indoors in industrial locations where harsh chemical atmospheres exist. The VPE silicone process consists of drying the completed coils and then placing them through four cycles of vacuum encapsulation with silicone resin. The core and clamping structure receives a minimum of two cycles of vacuum encapsulation with a silicone resin. Because of the inherent bonding strength of the resin, the finished coating remains smooth and gives superior environmental surface protection. The silicone resin is a 220°C insulation material tested to a minimum of 250°C. The silicone resin offers excellent dielectric strength and remains pliable even after severe thermal aging. It is suitable to operate at low temperatures and does not require allowance for degradation at hot spots on the coils. The silicone resin has been tested, after immersion in water for 24 hours and still maintains a dielectric strength of 1500 volts per mil. When cured, the silicone resin meets or exceeds UL 94 VO flammability tests and has a rating of 39 when coated over NOMEX paper. In addition, the VPE process by some manufacturers has been approved by the Navy for shipboard use and meets MIL-1-24092.

Both the VPI and VPE insulation system essentially can meet all ANSI, NEMA, and IEEE tests including Basic Impulse Level (BIL) tests <u>before</u> the environmental protection vacuum impregnation process. The VPI or VPE process is not used for mechanical support. The glass polyester or silicone insulation systems are compatible with the thermal expansion of either copper or aluminum windings.

4) Dry-Type Transformers (Non-liquid filled) Cast Designs: Cast transformers can be supplied in full cast designs or partial cast designs. In both designs, the high voltage winding conductors are insulated with high strength, high temperature insulation before being wound. Then the coil is wrapped in heavy glass fiber blankets on each side before being molded. Coils are then put into molds, where they are heated and then dried in a vacuum chamber. Special mineral-filled epoxy is then mixed and degassed in a vacuum tank above the coil vacuum chamber. The epoxy is then run through vacuum-tight connection to be poured to the proper height within the coil vacuum chamber. The coils, still in their mold, are then cured in time-temperature controlled ovens. The low voltage windings for full cast units are made of sheet or heavy “foil” conductor, which is interleaved, with full-width epoxy or polyester vacuum-impregnated insulation. The coils are then vacuum-pressure impregnated to seal the conductor similar to the high voltage coils. The low voltage windings for a partial cast are wound with epoxy pre-impregnated NOMEX insulation, heated, and coil margins (ends) are later sealed with epoxy.

The epoxy insulation utilized in many of the cast transformer designs has an available temperature rise of 80°C, 100°C, or maximum 115°C rise. Thus the standard epoxy insulation systems are available with a 155°C total temperature. One available optional epoxy system has a 115°C rise + 40°C ambient + 30°C hot spot = <u>maximum total temperature of 185°C</u>. Standard cast transformers are typically available with an 80°C temperature rise and a 155°C total temperature insulation system. As an option, transformers are available with an 80°C temperature rise and with the optional 185°C total temperature insulation system, which would have a continuous overload capability of 17%. . Another option available is a 100°C temperature rise and with the optional 185°C total temperature insulation system, which would have a continuous overload capability of 6%. Transformers could also be supplied with an 115°C rise and a 185°C total temperature insulation system which would not have any continuous overload capability, since when fully loaded, it would be operating at the maximum allowed temperature rise. In addition, some manufacturers have introduced cast epoxy insulation systems which are UL-recognized for a total temperature of 200°C. However, the transformer itself utilizing this 200°C cast epoxy system may not be available with a UL label for 200°C application.

Another alternate epoxy cast design dry type transformer is available with high voltage winding reinforced with multi-directional glass fiber. The glass fiber to epoxy ratio is a minimum of 70:30 based on insulation width and is uniformly distributed throughout the coil. The low voltage winding is wound using epoxy resin impregnated insulation with foil or sheet conductors. This type of transformer offers lower first cost than full cast coil designed transformers.

All cast transformer designs because they are of solid epoxy-cast material have greater inherent short circuit strength than any other dry-type of transformer. The cast must be uniform and without voids to minimize partial discharge. The dielectric quality of a solid cast transformer is related to the quality of the cast. Properly manufactured cast transformers can be subjected to severe load cycles (cold start to maximum load) and can be exposed to harsh climates (freezing, heat, chemicals, and moisture).

It should be noted that VPI, VPE and cast transformers are more resistant to humidity than conventional dry-types and are suitable for both indoor and outdoor service when located in an appropriate NEMA 3R enclosure. All three types are resistive to most normal chemicals and in addition, VPE silicone and epoxy-cast transformers are resistive to caustic and very acidic chemicals.

All information discussed above for liquid and dry type USTs is applicable from 0 to 3300 feet. Above 3300 feet, typically de-rating of transformer continuous kVA rating and in some cases short time overload rating must be made

5) Amorphous Core Transformers: New technology is available for Liquid and Cast Transformers, which utilizes amorphous magnetic core materials. Amorphous magnetic steel alloys are formed through the use of a manufacturing process that results in a material which exhibits no magneto-crystalline anisotropy and has electrical resistivities two to three times higher than silicon metal alloys. Furthermore, the magnetic properties can be further improved by stress relief annealing. The amorphous magnetic alloys with stress annealing process have approximately 75% lower loss (watts/lb) properties than conventional M4 grain oriented silicon steel. This does not mean that for transformer applications, amorphous steel cores would reduce the average core loss by 75%. The following should be noted: 1) The use of amorphous core material usually results in a much larger core and therefore, typically a larger transformer. 2) Some manufacturing processes result in problems such as a very brittle end product which when cut tends to cause the cut ends to roll up. In addition, in some instances when the amorphous steel material is cut and formed to make the core for a transformer, stress can be introduced into the material which can cause localized heating and increased core loss; stress relief annealing process is a method used to reduce this situation. However, because of the larger size cores in USTs, and the assembly of the coils on the core the stress relief annealing process is not always an option to eliminate the stress introduced into the core material during the transformer manufacturing process. Thus the amorphous steel core usually results in increased size and cost over conventional transformer units and to date in UST applications does not have the long term proven reliability of conventional grain oriented steel cores.

Conventional UST designs transmit short circuit forces through the core steel stack to the core clamp structure. Amorphous steel is very brittle compared to conventional silicon steel and may not tolerate the forces that occur during the short circuit interval. Therefore, short circuit certification tests should be made on basic similar designs and ratings of amorphous core transformers before acceptance.

As an alternate to amorphous steel, there are many refined grain oriented silicon steels available, which have loss characteristics that are approximately 50% less than traditional core materials. The use of these materials along with optimized designs and manufacturing processes can result in 50% reduction of transformer core loss levels from standards. USTs utilizing optimized grain oriented steel designs can be furnished with guaranteed no-load losses of approximately 0.15% of nameplate rating, however these would result in approximately 35% increase in transformer first cost over standard transformer units.

For heavy industry with large continuous loads and with ever-increasing utility rates, the trade-off of lower than standard core losses versus increased first costs is an area that should be explored. The user should take steps to insure the specified performance is achieved, whether lower no-load and/or total losses are specified. Certified Test Reports should be required with testing in strict accord with the applicable ANSI test standards. It should be required that the actual test data is to be taken from the purchased transformers. It should also be specified that the measurements should be taken using calibrated test equipment with records of calibration traceable back to NIST Standards and certified by a third party.

III. PART II - OTHER TRANSFOMER CONSIDERATIONS

A. First Cost Considerations

1) Initial Transformer Cost: The first cost of each type of transformer will vary significantly for a specific rating, if either non-standard electrical ratings are specified, non-standard physical dimensions are required, or special options are selected. Table 1 below provides an approximate first cost comparison of standard units built to ANSI standards, with a 15 kV class primary and 480Y/277-volt secondary. Table 1 indicates standard temperature rise for each of these units. Besides first cost for each unit, the table also indicates the relative cost of other types of transformers when compared to mineral oil transformers of the same kVA, and approximate dollars per kVA cost for each unit. NOTE: The table is based on standard typical Basic Impulse Level (BIL), sound levels, and 5.75% impedance (+/- 7-1/2% tolerance). For these 15 kV primary transformers, the VPI and VPE transformers have 60 kV BIL and the Cast and liquid transformers have 95 kV BIL. Actual pricing will vary from manufacturer to manufacturer based on material, labor, overhead costs and factory loading at the time of bid.

2) Transformer Direct and Indirect Installation Cost: Transformer direct installation costs will vary depending on NEC and local code special location requirements previously discussed in this paper. For example, a mineral oil insulated transformer installed indoors requires a code-approved transformer vault. A vault could add 40% to 80% or higher of the first cost of the transformer to the installation costs for mineral oil insulated transformers installed indoors. Less flammable fluid insulated transformers, such as silicone, hydrocarbon and the new vegetable based fluids would require liquid confinement (curbing) adding approximately 1 to 10% or higher of the first cost to the indoor installation cost of these transformers. While dry-type transformers would not normally have any of these extra installation costs, they may have added cost over liquid filled transformers for increased air conditioning and soundproofing.

TABLE 1
APPROXIMATE FIRST COST COMPARISON

DESCRIPTION	kVA -->	500	750	1000	1500	2000	2500	AVERAGE $/kVA
MINERAL OIL	**$-- 65C rise**	**$13,500**	**$16,000**	**$17,300**	**$19,300**	**$22,500**	**$25,300**	
(FLAMMABLE)-160C	ratio to oil	1	1	1	1	1	1	
	$ / kVA	$27	$21	$17	$13	$11	$10	$16.6
LESS FLAMMABLE	**$--65 C rise**	**$16,200**	**$19,000**	**$21,500**	**$25,000**	**$26,300**	**$27,500**	
HYDROCARBON-308C	ratio to oil	$1.20	$1.19	$1.24	$1.30	$1.17	$1.09	
	$ / kVA	$32	$25	$22	$17	$13	$11	$20.0
LESS FLAMMABLE	**$--65 C rise**	**$17,700**	**$21,000**	**$23,000**	**$26,000**	**$29,200**	**$32,500**	
VEGETABLE -360C	ratio to oil	$1.31	$1.31	$1.33	$1.35	$1.30	$1.28	
	$ / kVA	$35	$28	$23	$17	$15	$13	$21.9
LESS FLAMMABLE	**$--65 C rise**	**$18,900**	**$22,000**	**$24,000**	**$27,300**	**$30,000**	**$34,000**	
SILICONE-330C	ratio to oil	$1.40	$1.38	$1.39	$1.41	$1.33	$1.34	
	$ / kVA	$38	$29	$24	$18	$15	$14	$23.0
DRY TYPE - VPI	**$--150 C rise**	**$15,900**	**$20,000**	**$22,000**	**$26,000**	**$30,500**	**$36,000**	
POLYESTER	ratio to oil	$1.18	$1.25	$1.27	$1.35	$1.36	$1.42	
	$ / kVA	$32	$27	$22	$17	$15	$14	$21.2
DRY TYPE - VPE	**$--150 C rise**	**$19,000**	**$22,500**	**$25,000**	**$32,000**	**$36,500**	**$41,000**	
SILICONE	ratio to oil	$1.41	$1.41	$1.45	$1.66	$1.62	$1.62	
	$ / kVA	$38	$30	$25	$21	$18	$16	$24.8
DRY TYPE - EPOXY	**$--80 C rise**	**$35,000**	**$32,000**	**$35,500**	**$39,000**	**$48,000**	**$57,000**	
FULL CAST	ratio to oil	$2.59	$2.00	$2.05	$2.02	$2.13	$2.25	
	$ / kVA	$70	$43	$36	26.00	24.00	22.80	$36.8

TABLE 2 APPROXIMATE DIMENSIONS & WEIGHT COMPARISON												
Based on Secondary Unit substations with 15kV (Std BIL) HV and LV of under 600V (Std BIL)												
TRANSFORMER TYPE - TEMP RISE	500 kVA				1500kVA				2500 kVA			
	WIDTH (INCHES)	DEPTH (INCHES)	SQUARE FEET	**WEIGHT (LBS)**	WIDTH (INCHES)	DEPTH (INCHES)	SQUARE FEET	**WEIGHT (LBS)**	WIDTH (INCHES)	DEPTH (INCHES)	SQUARE FEET	**WEIGHT (LBS)**
Liquid 65C												
MANUFACTURER 1	61	75	31.8	**6,000**	65	130	58.7	**9,800**	68	135	63.8	**13,000**
MANUFACTURER 2	50	59	20.5	**6,300**	78	75	40.6	**9,800**	67	99	46.1	**14,680**
Dry Type VPI/VPE - 150C Rise												
MANUFACTURER 1	90	60	37.5	**4,600**	112	66	51.3	**9,300**	124	66	56.8	**13,000**
Dry Type Cast - 80C Rise												
MANUFACTURER 1	96	66	44	**7,100**	114	66	52.25	**14,000**	132	66	60.5	**18,000**
MANUFACTURER 3	84	54	31.5	**5,400**	96	54	36	**10,800**	108	60	45	**16,100**

Transformer indirect installation costs include the labor to handle and install the various types of USTs that will vary with the weight and size of the transformer. Table 2 above shows approximate dimensions, floor space in square feet and weight of the various types of standard designs of some major transformer manufacturers. Typically a liquid insulated transformer requires less square feet than a dry-type transformer, however, may actually require a larger room for the total unit substation because of the front to rear depth of the radiators. Note: The dimensions and weights can vary significantly from one manufacturer to another as shown in the table or if special electrical characteristics are specified or certain options are selected. For example, the size and weight of a standard design 2000 kVA dry-type VPI or VPE UST with 5 kV primary and Class H insulation system having a 150°C rise for Manufacturer 1 would have dimensions of 90 inches high, by 102 inches wide, by 66 inches deep, and a weight of 9400 lbs. The same transformer except specified with 80°C or 115°C rise for Manufacturer 1 would have increased dimensions of 102 inches high, by 112 inches wide, by 66 inches deep, and would have an increased weight of 12,000 lbs.

The square feet shown in Table 2, along with the addition of code required clearances, would have to be considered in relationship to building cost per square foot. In some cases, especially on modifications to existing facilities, existing openings, elevator weight capacity, etc., could be an evaluation criteria in UST selection.

B. Operating Cost Considerations

1) Loss Evaluation: There are many specialized computer programs for performing transformer loss evaluation which are capable of considering the multitude of available utility rate structures, varying first costs as lower losses are specified, customer loading criteria, and economic evaluation of customer cost of money. This article will consider only an abbreviated approximate method of loss evaluation. Table 3 gives a relative comparison of standard approximate losses

TABLE 3 STANDARD DESIGN TRANSFORMER APPROXIMATE LOSSES (WATTS)												
Note: Losses Based on Secondary Unit substations with 15kv HV (Std BIL) and under 600v LV (Std BIL) and based on Standard ANSI impedance.												
TRANSFORMER TYPE - TEMP RISE	**500 kVA**		**750 kVA**		**1000 kVA**		**1500 kVA**		**2000 kVA**		**2500 kVA**	
	NL	TL	NL	TL	NL	TL	NL	TL	NL	TL	NL	TL
LIQUID ALL - 65C												
MANUFACTURER 1	1,200	8,700	1,600	12,160	1,800	15,100	3,000	19,800	4,000	22,600	4,500	26,000
MANUFACTURER 2	1,200	7,000	1,690	8,800	2,230	11,000	2,350	15,000	3,150	18,600	3,650	24,000
DRY TYPE VPI/VPE - 150C												
MANUFACTURER 1	1,900	15,200	2,700	21,200	3,400	25,000	4,500	32,600	5,700	44,200	7,300	50,800
DRY TYPE - VPI/VPE - 80C												
MANUFACTURER 1	2,300	9,500	3,400	13,000	4,200	13,500	5,900	19,000	6,900	20,000	7,200	21,200
DRY TYPE CAST - 80C												
MANUFACTURER 1	2,275	7,800	2,950	10,025	3,575	12,000	4,650	15,425	5,600	18,450	6,475	21,175
MANUFACTURER 3	2,400	7,400	2,800	11,800	3,500	13,100	5,000	18,600	6,500	22,000	7,200	25,700
DRY TYPE CAST - 100C												
MANUFACTURER 1	2,250	9,025	2,900	11,600	3,550	13,850	4,600	17,800	5,600	21,275	6,450	24,425

for various types of USTs at different kVA ratings for different manufacturers. The table is based on transformers having 15 kV primaries and 480Y/277-volt secondary built to ANSI standards. It should be noted that losses would vary significantly depending on types, grades, and quantities of materials utilized in the core and coil, as well as manufacturing techniques utilized in the construction of the core and coil.

In addition, if special lower than standard temperature rises are specified (which will normally result in higher first cost), normally no-load losses will increase slightly and total losses will decrease significantly. It should also be noted that dry-type VPI and VPE transformers, designed with special higher than standard BIL to make them equivalent to liquid transformer BIL, will generally have slightly higher no-load and slightly higher total losses. In most cases, it is more cost-effective to apply a special low spark-over distribution class arrester at the primary terminals of the VPI or VPE transformer to reduce the need to obtain equivalent BIL to that of liquid transformers.

Utilizing some abbreviated formulas for cost analysis and approximate evaluation of differences between the various transformers, comparisons can be performed.

Key formulas are:

I^2R Losses = Total Losses (TL) – No Load Losses (NL)

I^2R Losses are Proportional to the load Factor (L) Squared - $(L)^2$

$$\text{The Load Factor LF} = \frac{\text{Actual Load kVA}}{\text{Total Rated Base Nameplate kVA}}$$

Operating Losses = No Load Losses + I^2R loss at the appropriate LF

Example A: A commercial customer with only one utility rate R1 = 4 cents per kWHR, compares a 1000 kVA UST of the following types (1) liquid 65°C rise, (2) VPI dry-type transformer 150°C rise and (3) cast dry-type 80°C rise, all under the following operating conditions. Facility is open 5 days a week for 8 working hours each day. With 800 kVA load during working hours and 100 kVA load for all other times.

For working hours LF1 = 800 kVA/ 1000 kVA = 0.8

For non-working hours LF2 = 100 kVA / 1000 kVA = 0.1

Then Table 4A shown below can be derived utilizing the formulas above and data of Table 3 for Manufacturer 1.

Table 4A indicates the approximate yearly operating costs for the various units for the given conditions. Changing the transformer size, loading factors, the amount of time the unit is loaded at the various load levels and the cost of energy will change the relative analysis of savings. [See Example B for an industrial continuous process type customer such as in the Pulp and Paper industry]

For Example A, if we analyze first cost and operating loss expense between the three types of transformer for Manufacturer 1, we obtain data shown in Table 5A on the following page.

For Example A with the given first costs, load factor and losses, the liquid transformer is the least expensive if located outdoors as part of a unit substation. (Liquid confinement would have to be considered in the evaluation). For indoor applications, the difference in yearly operating costs between the VPI and cast unit is $676 per year, while the first cost difference is $13,500, or it would take over 19 years to pay back the additional cost of the cast unit (without interest).

TABLE 4A

SIMPLIFIED CALCULATION FOR LOAD LOSSES EXAMPLE A - MANUFACTURER 1

LINE #	DESCRIPTION	Description	INPUT DATA	LIQUID 65C RISE	DRY TYPE VPI-150C	DRY TYPE CAST-80C
	TRANSFORMER kVA =		1000			
{1}	TOTAL LOAD LOSSES (WATTS) - From Table 3	TL losses		15100	25000	12000
{2}	NO-LOAD LOSSES (WATTS) - From Table 3	NL losses		1800	3400	3575
{3}	I2R LOSSES at FULL LOAD (LF=1.0): **{1}** - **{2}** (WATTS)			13300	21600	8425
{4}	For LF1: I2R LOSSES = **{3}** x (LF1)2	LF1 =	0.80	8512	13824	5392
{5}	For LF1: TOTAL LOSSES =**{2}** + **{4}**	LF1 Total Losses		10312	17224	8967
{6}	For LF2: I2R LOSSES = **{3}** x (LF2)2	LF2 =	0.10	133	216	84
{7}	For LF2: TOTAL LOSSES = **{2}** + **{6}**	LF2 Total Losses		1933	3616	3659
	Rate 1 Dollars/kwhr	R1: $/kwhr =	$0.0400			
{8}	[**{5}** /1000] x [LF1 hrs/yr @ R1/yr] x [$R1/kwhr]	LF1 hrs/yr @R1=	2080	$858	$1,433	$746
{9}	[**{7}** /1000] x [LF2 hrs/yr @ R1/yr] x [$R1/kwhr]	LF2 hrs/yr @R1=	6656	$515	$963	$974
{10}	TOTAL YEARLY OPERATING COSTS = **{8}** + **{9}**	Total Operating Costs		**$1,373**	**$2,396**	**$1,720**

The availability of money or alternate uses of money in regards to first cost purchase of the transformer plus installation costs as previously discussed, versus the operating loss savings in terms of payback needs to be considered along with the specific project requirements.

TABLE 5A
FIRST COST VERSUS OPERATING COST FOR 1000 kVA
EXAMPLE A - MANUFACTURER 1

COST	LIQUID OIL-65C	DRY TYPE VPI-150C	DRY-TYPE CAST-80C
FIRST COST	$17,300	$22,000	$35,500
YEARLY OPERATING COST (Total Losses)	$1,373	$2,396	$1,720

Example B: An industrial continuous process customer has two utility rates. At peak times R1 = 4.0 Cents/kWHR for 10 hours per weekday and at off peak rate R2 = 3.5 cents per kWHR for all other times. They are comparing 2000 kVA USTs of the following types (1) liquid 65°C rise, (2) VPI dry-type transformer 150°C rise and (3) cast dry-type 80°C rise, all under the following operating conditions. Facility open 7 days a week for 24 working hours each day of the year with 1300 kVA load during working hours except for 2 weeks of shut down for maintenance having 200 kVA load.

For working hours LF1 = 1300 kVA/ 2000 kVA = 0.65

For non-working hours LF2 = 400 kVA / 2000 kVA = 0.2

Then Table 4B can be derived utilizing the formulas above and data of Table 3 for Manufacturer 1.

For Example B if we analyze first cost and operating loss expense between the three types of transformers for Manufacturer 1, we obtain data shown in Table 5B. In this case, based on standard losses, the cast or liquid transformer results in significantly lower operating costs than the VPI transformer. Even though the Dry-Type Cast transformer has slightly lower operating loss costs per year than the Liquid transformer, the substantial first cost difference between the units could not be justified by operating loss savings evaluation. On the other hand, if only a Dry-Type transformer were under consideration with the indicated data, the cast transformer lower annual operating costs of $3,366 ($6,821-$3,455) would pay back the first cost difference of $17,500 in approximately 5.2 years (without interest).

TABLE 5B
FIRST COST VERSUS OPERATING COST FOR 2000 kVA
EXAMPLE B - MANUFACTURER 1

COST	LIQUID OIL-65C	DRY TYPE VPI-150C	DRY-TYPE CAST-80C
FIRST COST	$22,500	$30,500	$48,000
YEARLY OPERATING COST (Total Losses)	$3,693	$6,821	$3,455

TABLE 4B
SIMPLIFIED CALCULATION FOR LOAD LOSSES EXAMPLE B - MANUFACTURER 1

LINE #	DESCRIPTION	Description	INPUT DATA	LIQUID 65C RISE	DRY TYPE VPI-150C	DRY TYPE CAST-80C
	TRANSFORMER kVA =		2000			
{1}	TOTAL LOAD LOSSES (WATTS) - From Table 3	TL losses		22600	44200	18450
{2}	NO-LOAD LOSSES (WATTS) - From Table 3	NL losses		4000	5700	5600
{3}	I2R LOSSES at FULL LOAD (LF=1.0): **{1}** - **{2}** (WATTS)			18600	38500	12850
{4}	For LF1: I2R LOSSES = **{3}** x (LF1)2	LF1 =	0.65	7859	16266	5429
{5}	For (LF1) TOTAL LOSSES =**{2}** + **{4}**	LF1 Total Losses		11859	21966	11029
{6}	For LF2: I2R LOSSES = **{3}** x (LF2)2	LF2 =	0.20	744	1540	514
{7}	For LF2: TOTAL LOSSES = **{2}** + **{6}**	LF2 Total Losses		4744	7240	6114
	Rate 1 Dollars/kwhr (On Peak-10 hours/week day)	R1: $/kwhr =	$0.040			
	Rate 2 Dollars/kwhr (Off Peak - all times except peak)	R2: $/kwr=	$0.035			
{8}	[**{5}** /1000] x [LF1 hrs/yr @ R1/yr] x [$R1/kwhr]	LF1 hrs/yr @R1=	2500	$1,186	$2,197	$1,103
{9}	[**{5}** /1000] x [LF1 hrs/yr @ R2/yr] x [$R2/kwhr]	LF1 hrs/yr @R2=	5900	$2,449	$4,536	$2,278
{10}	COST OF LOSSES FOR LF1 = **{8}** + **{9}**	LF1 Total Costs		**$3,635**	**$6,733**	**$3,380**
{11}	[**{7}** /1000] x [LF2 hrs/yr @ R1/yr] x [$R1/kwhr]	LF2 hrs/yr @R1=	100	$19	$29	$24
{12}	[**{7}** /1000] x [LF2 hrs/yr @ R2/yr] x [$R2/kwhr]	LF2 hrs/yr @R2=	236	$39	$60	$51
{13}	COST OF LOSSES FOR LF2 = **{11}** + **{12}**	LF2 Total Costs		**$58**	**$89**	**$75**
{14}	TOTAL YEARLY OPERATING COSTS = **{10}** + **{13}**	Total Operating Costs		**$3,693**	**$6,821**	**$3,455**

<u>NOTE:</u> ANY OF THE VARIOUS TYPES OF TRANSFORMERS CAN BE DESIGNED TO HAVE LOWER THAN STANDARD LOSSES, HOWEVER, THEY WILL HAVE HIGHER FIRST COST. NO MATTER WHICH TYPE OF TRANSFORMER IS SELECTED TO MEET PROJECT NEEDS, IT IS RECOMMENDED TOTAL OWNING COST INVESTIGATION SHOULD BE MADE OF THE TRADE OFF BETWEEN PURCHASING USTs OF THAT TYPE WITH LOWER LOSSES VERSUS INCREASED FIRST COST.

The availability of money or alternate uses of money in regards to the first cost purchase of the transformer plus installation costs as previously discussed, versus the operating loss savings in terms of payback needs to be considered. It should also be noted that consideration must be given to the heat (BTUs) generated by the transformer, which will vary directly in relationship to <u>total losses at a given load.</u> This heat and possible cost of removal must be considered for indoor applications. (Number of watt-hours of losses x 3.143 = number of BTUs).

2) Maintenance: The availability and cost of experienced qualified maintenance personnel within the owner's organization or the cost of purchasing outside maintenance services must be considered. Most dry-type USTs normally require very little maintenance other than cleaning dust and dirt accumulation from the core and coil assembly and any exposed bushings or bus work. In addition, bus bar joints should be checked for tightness. Typically most liquid-type transformers require no cleaning (except exposed bushings) and when furnished with liquid level gauges, winding temperature gauges, and pressure vacuum gauges can be monitored for proper transformer performance. It is recommended that these gauges be inspected on a periodic basis (normally once a month the first year and once a year thereafter) to make sure proper liquid level, temperature, and pressure are being maintained. Readings should be recorded at each inspection and saved for future comparison. In addition for liquid transformers preventative maintenance testing using Dissolved Gas Analysis (DGA) and key properties value analysis can also be used to monitor transformer performance. This testing of periodic oil sampling can alert the user of a potential problem before it gets worse enabling the user to schedule an outage when needed. In addition on both Liquid and Dry-Type transformers, partial discharge readings can be taken to monitor the primary winding insulation condition and predict problems before they arise. In order to take Partial Discharge readings, this requires capacitive tap primary bushings. For liquid transformers used in heavy industries, such as Pulp and Paper Mills, where power faults are common, oil samples should be taken after each fault condition to help access the transformer condition.

C. Special Design Features and Options.

1) Lower than Standard Temperature Rise: As discussed previously, transformers can be furnished with lower than standard temperature rises for a first cost price increase. The lower temperature rise generally results in higher than standard no-load losses, but significantly lower total losses. Lower temperature rise increases the size of the core and coil and generally increases outside dimensions and weights. A few conditions which should be considered for selecting lower than standard transformer temperature rises are: 1) applications in higher than standard ambient conditions, 2) continuous overload capability desired (typical of double ended UST applications, 3) requirement for lower losses (helps reduce air conditioning load). It should again be noted that typically specifying lower than standard temperature rise transformer units usually results in significantly higher first costs.

For example, a standard dry-type transformer utilizing an insulation system composed of all Class H materials suitable for 150°C rise, 40°C maximum ambient and 30°C hot spot for a 220°C total temperature system could be specified with an optional 80°C rise. In those cases where the manufacturer derates the next higher kVA 150°C rise design rating to obtain an 80°C rise design, the total losses will decrease and the core watts will increase (See Table 3). For a 1000 kVA transformer (VPI) the price would increase approximately 20% from the $22,000 price indicated in Table 1 to $26,400. The losses could be expected to change from the 150°C rise value of 3,400 watts no-load and 25,000 watts total load to 80°C rise losses of 4,200 watts no-load and 13,500 watts total load (see Table 3). The size and weight probably would be increased to the dimensions and weights of a standard 1500 kVA transformer. Thus consideration of the operating loss cost savings for a particular application (based on expected loading conditions, utility rates, etc. versus the increased first cost (and increased size) taking into account the cost of money must be considered when making a decision as to which type of unit to utilize.

2) Basic Impulse Level (BIL): If system requirements dictate the need to increase standard indoor dry-type VPI and VPE transformers to equivalent liquid or cast transformer BILs, this normally results in approximately 10 to 15 percent price increase over standard unit base price for primaries 15 kV and below. In most cases, the addition of distribution or intermediate class surge arresters to achieve a comparable over-all BIL is more economical. When dry-type transformers are part of outdoor unit substations, station class arresters should be considered because of their higher energy capability and should be selected with lower discharge voltages at various discharge current values (based on 8 x 20 Microsecond wave) and lower front of wave spark over values. Although this is an economical alternative, it is not as reliable as designing the transformer with higher BIL rating or utilizing both surge arresters and higher BIL ratings.

3) Sound Level: Table 6 lists the standard NEMA TR-1 sound levels for self-cooled transformers in average dB. Per NEMA standards, liquid-type transformers are about 5 to 6 dB quieter than comparable dry-type transformers. Both liquid and dry-type transformers can be built quieter than the indicated NEMA standards. Approximate cost of sound level reduction is 2 to 4 percent of the transformer price for every dB below NEMA standard for a range of 3 to 4 dB below standard. Lower than 5 dB below NEMA standard requires much special design and associated increased costs. The addition of fan cooling generally raises the sound level 3 to 7 dB above the self cooled rating on dry-types and up to a maximum of 67 dB on all liquid ratings (See Table 6).

TABLE 6 NEMA TR-1 MAXIMUM SOUND LEVEL COMPARISON USTs				
kVA	LIQUID-TYPES (All Fluids)		DRY-TYPES VPI,VPE,CAST	
	OA	OA/FA	AA	AA/FA
301 to 500	56	67	60	67
501 to 700	57	67	62	67
701 to 1000	58	67	64	67
1001 to 1500	60	67	65	68
1501 to 2000	61	67	66	69
2001 to 2500	62	67	68	71
2501 to 3000	63	67	68	71

4) Fan Cooling: Fan cooling or provisions for fan cooling is available on both Liquid USTs and Dry-Type USTs. The addition of fan cooling to Liquid Transformers up to 2499 kVA results in 15% increase continuously over base kVA rating and for Liquid Transformers 2500 kVA and above results in 25% increase continuously over base kVA rating. Optional fan increased fan ratings beyond the ANSI 15% or 25% values for liquid-filled transformers are also available from UST manufacturers. For Dry Type Transformers, the addition of fan cooling results in 33% increase continuously over base kVA nameplate rating. Many cast transformer USTs can be furnished with optional fan cooling resulting in 50% continuous increase over base kVA rating. Since the addition of fans including winding or liquid temperature detection device, fan-control and display panel and fans results in only about 10% increase in price, this is usually an excellent option to select. Selecting provisions only for fans usually results in much higher field installation costs if the fans are added later. Fan cooling is normally selected on double-ended unit substation applications, where the fans are utilized when one of the transformers is out of service. Control power for the fans is normally obtained from a secondary Control Power Transformer throw-over scheme or other reliable source. The addition of fans provides for increases in continuous and short time overload ratings of the transformer, without increasing the available short circuit current through the transformer.

5) Overload Capacity: The ANSI/IEEE C57 Standards have allowed significant higher overload capacity for liquid-filled transformers than dry types. Using the tables provided by the standards (IEEE Guide for Loading Mineral-Oil Immersed Power Transformers Up to and Including 100MVA with 55°C or 65°C Average Winding Rise C57.92-1981 Table 5A versus IEEE Guide for Loading Dry-Type Distribution and Power Transformers C57.96-1989 Table 6), a liquid-filled transformer with a 50% continuous base load at 30°C ambient temperature can be loaded up to 120% of full load nameplate rating for eight hours without excessive loss of insulation life. Under identical base loading and ambient temperature, a dry-type transformer can only provide approximately one-hour at 120% without excessive loss of life. For a peak load duration of four hours, liquid-filled transformers are allowed as much as 38% peak overload, while dry-type transformers are limited to only 10%. As discussed previously, one means to improve overload rating (and/or continuous rating) is to specify an optional temperature rise rating below the thermal rating of the insulation system (at increased cost). However, designs in non-supervised locations per NEC Table 450-3(a) require secondary protection sized at 125% of transformer full load amperes, which effectively prevents the use of much of the transformer short time overload capacity. In supervised locations, NEC Table 450-3(a) allows generally up to 250% secondary protection (or 250% primary fuse or 300 % primary breaker protection if secondary protection is not required) which allows for more use of transformer short time overload capacity.

IV. CONCLUSION

In conclusion, the specifier and/or user must establish a set of specific criteria for each project to properly evaluate the type of transformer and special features desired. These criteria should include considerations, such as NEC requirements regarding location, first cost, cost of losses in relationship to operating load profile, maintenance, and disposal costs. Special transformer design requirements, i.e., temperature rise, BIL, sound level, impedance, as well as options such as fan cooling, must also be evaluated. These items have to be evaluated in terms of the cost and capital expenditure budget. This paper discussed some of these considerations and points out that most of these factors are interrelated. Once specific project criteria are established, the manufacturer should be consulted for specific transformer technical data, sizes, and cost factors.