RECLAMATION

Managing Water in the West

Facilities Instructions, Standards, and Techniques
Volume 3-32

Transformer Fire Protection

U.S. Department of the Interior
Bureau of Reclamation
Denver, Colorado

~~January 2005~~
Updated September 2016

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE *(DD-MM-YYYY)* January 2005	**2. REPORT TYPE** Final	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE
FIST 3-32, Transformer Fire Protection

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Bureau of Reclamation
Hydroelectric Research and Technical Services Group
Denver, Colorado

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Bureau of Reclamation
Denver Federal Center
P.O. Box 25007
Denver, CO 80225-0007

8. PERFORMING ORGANIZATION REPORT NUMBER
FIST 3-32

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Hydroelectric Research and Technical Services Group
Bureau of Reclamation
Mail Code D-8450
PO Box 25007
Denver CO 80225-0007

10. SPONSOR/MONITOR'S ACRONYM(S)
DIBR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Available from the National Technical Information Service, Operations Division,
5285 Port Royal Road, Springfield, Virginia 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Large, oil-filled transformers pose the risk of explosion and fire should the transformer fail and the insulating oil ignite. Fire suppression systems have been used at Reclamation plants for many years, but there have been inconsistencies in applications of these systems and in their operation and maintenance procedures. This volume establishes consistent practices for use across the organization and provides technical background and references, as well.

15. SUBJECT TERMS
Transformers, fire suppression, fire protection, insulating oil, mineral-based insulating oil, ester-based insulating fluid.

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Gary Osburn
a. REPORT UL	**b. ABSTRACT** UL	**c. THIS PAGE** UL	UL	36	**19b. TELEPHONE NUMBER** *(include area code)* 303-445-2297

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. 239-18

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1. Introduction

Bureau of Reclamation (Reclamation) facilities have hundreds of mineral-oil-filled power transformers. Most of these are large, generator step-up (GSU) transformers whose purpose is to connect medium-voltage generators to the high-voltage power system.

Many of these transformers are accompanied by water spray fixed systems, commonly called transformer "deluge" or "fire water" systems, intended to extinguish a transformer fire.

The need for and use of transformer fire protection systems have been discussed for many years in Reclamation and a variety of practices have evolved. Some facilities have been constructed with fire suppression systems while others have no fire suppression systems installed. In light of current industry practices, designs of some existing systems may be adequate while others need to be rehabilitated. A few existing fire suppression systems have been abandoned or may need improvements in their maintenance and testing practices. In some cases, plant staff may not understand fully what the system was intended to do when implemented or how it currently works. And finally, plants originally designed for full-time operators may now be unattended, thus changing the way fire suppression systems must be monitored and operated.

Also, since most Reclamation plants were built, environmental laws have become much more stringent. Oil and water containment systems related to transformer fire protection systems may have become obsolete and the new emphasis on protecting the environment must be taken into account.

Transformer fires are rare but the impact is great. Even though a transformer involved in a fire likely will be destroyed almost immediately, the fire's effect on adjacent equipment and structures can be mitigated and therefore must be considered. An uncontained fire can do a significant amount of damage and result in a prolonged, unscheduled outage.

Fire suppression systems can be effective in minimizing damage caused by a transformer fire but only if properly designed, constructed, operated, maintained, and tested.

Reclamation requires the use of active fire suppression systems for ~~large,~~ mineral-oil-filled unit step-up transformers where structures and other equipment are at risk from a fire. Such systems must be evaluated carefully to ensure they meet all current codes and standards including environmental laws and regulation. ~~Fire suppression should be considered for smaller, mineral-oil-filled transformers where the risk and/or consequences of fire are unacceptable.~~

~~Recent developments and experience with ester-based insulating fluids show great promise for reducing the likelihood of transformer fires, and thus the need for suppression and containment while minimizing environmental effects from the~~

~~insulating medium. This volume entitled, Facilities Instructions, Standards, and Techniques (FIST), Volume 3-32, Transformer Fire Protection, includes a discussion of this alternative.~~

2. Scope

This volume outlines basic considerations and requirements for fire protection of ~~large,~~ mineral-oil-filled, GSU transformers at Reclamation powerplants. ~~However, smaller transformers should also be considered for fire protection where the risks and/or consequences of fire to other equipment and structures are unacceptable.~~

It is beyond the scope of this volume to provide design details. Each installation is unique and must be evaluated for the best type of fire suppression and water-oil containment systems. For specific design requirements, qualified designers, the latest codes and standards, and experienced contractors must be consulted.

It is also beyond the scope of this document to specify every inspection, test, and maintenance activity required. Reference is made to the appropriate industry codes and standards to provide guidance to the reader.

~~This volume also includes a discussion of an alternative to fire suppression using ester-based insulating fluids in lieu of traditional mineral-based oils.~~

3. Background

~~Documented history shows that Reclamation has had at least 23 power transformer failures in the last 25 years—including five fires. Industry transformer statistics indicate that one in five failures results in a fire.~~

~~With the exception of the Hoover Dam Nevada Powerplant, which uses a sprinkler system, Reclamation powerplants having outdoor fire suppression systems use a "water deluge" (open nozzles) system. Deluge systems simultaneously direct large volumes of water at the transformer from several angles, attempting to "drown" the fire.~~

Fire suppression systems are extremely effective in containing fires when properly designed, constructed, operated, maintained, and tested. Unfortunately, there are several concerns with these systems:

- Some facilities do not have transformer fire suppression systems.

- Many facilities do not have fire protection barriers (walls) to separate transformers or phases of a transformer to prevent adjacent equipment from becoming involved in a fire or damaged by debris thrown from an exploding transformer.

- Many deluge systems and containment structures are designed to allow burning oil to be washed off into the adjacent waterway. Release of ~~mineral~~ oil into the waters of the United States is a violation of the Clean Water Act and can result in penalties and high cleanup/restoration costs.

- Many suppression systems are activated manually even though some are automatic. Over the years, reductions in the number of people on the operations' staff could possibly mean these manually activated systems are no longer appropriate.

- Automatically activated systems must be turned off manually in most cases. Where a plant is unattended, this means thousands of gallons of water discharged on the fire may wash off spilled oil and overfill containment structures.

- Some plants have fire system components (piping, discharge nozzles, electrical wriring, etc) physically close to the transformer. These may melt in a fire before the suppression system is operated.

- Some existing deluge systems have been abandoned and no longer function.

- Some facilities, in light of current standards, may not have adequate inspection, testing, and maintenance of fire suppression systems and containment structures.

- Sometimes the staff's working knowledge of the purpose and operation of the deluge system and accompanying documentation, such as the Standing Operation Procedure (SOP), is inadequate.

Many new and stringent environmental laws and regulations have been enacted since most Reclamation powerplants were built. The U.S. Code of Federal Regulations, Title 40 (CFR 40), Parts 110 and 112, requires that appropriate oil containment and diversionary structures be provided to prevent discharged oil from reaching navigable waters if a facility reasonably could be expected to discharge oil in harmful quantities into or upon said navigable waterways. The term "navigable waterways" (see CFR 40, Part 110.1) is interpreted by the Environmental Protection Agency (EPA) very conservatively and applies to all waterways around Reclamation powerplants.

The need to comply with these requirements poses particular problems in regard to oil-filled transformers. Even where fire suppression systems do not exist, containment must be sufficient to meet the regulations since transformers can leak oil in normal operation or discharge large quantities in the case of a transformer fire or tank rupture due to internal fault. Compliance with containment requirements causes another problem: unless drained into containment away from the transformer, burning oil spilled in a transformer failure will be confined around the transformer, concentrating the heat poses a risk to an adjacent plant structure and nearby equipment. Given that containment is mandatory, in most cases suppressing the fire then becomes essential to minimize collateral damage. If the burning oil can be drained into a containment which is remote from the transformer, structures, and other equipment (or if the transformer itself is located away from the structure), suppression might be less important. However, allowing a transformer fire to burn unrestricted is not environmentally responsible because it causes air pollution.

Environmental problems become even more acute with the use of water-based fire suppression because the additional—and often large—volume of water can cause existing containment structures to be overtopped, allowing water and oil to flow into waterways. Disabling a fire suppression system to avoid this situation is not considered a long-term solution since oil still can be discharged into a waterway due to tank rupture, during a fire, or from leakage and rainfall, among other ways.

Therefore, a carefully designed transformer fire protection system is essential for minimizing fire and environmental damage with ~~large~~, ~~mineral-based~~ oil insulated transformers.

~~At initial publication of this volume, there are no large Reclamation transformers insulated with ester-based insulating fluids. However, these fluids are becoming available for large transformer applications as a viable way to reduce fire danger, minimize impact on the environment, and potentially increase the life of the insulation. This technology is well proven in smaller transformers and has recently been evaluated by the Electric Power Research Institute (EPRI) and is now a manufacturer-supplied option in many new, large power transformers. It is also suitable for retrofilling existing transformers. This is of interest to Reclamation facilities addressing fire protection concerns.~~

4. Transformer Fire Protection Goals

In accordance with National Fire Protection Association (NFPA) 851, *Fire Protection for Hydroelectric Generating Plants*, section 5-7, and Edison Electric Institute, *Fire Protection for Transformers*, Reclamation requires the use of active (automatic) fire suppression systems for ~~large~~, ~~mineral-~~oil-filled GSU transformers. (Note that NFPA 851 is now incorporated in NFPA 850)

The NFPA 851, section 5-7, states, pertaining to mineral oil: "Oil-filled main, station service, and startup transformers should be protected with automatic water spray or foam-water spray systems." Edison Electric Institute[1] *Fire Protection for Transformers*, recommends that highly important outdoor transformers be equipped with water spray and that where other equipment or transformers are exposed to the fire, water spray/barrier walls be used as follows:

1 General Electric Industrial Risk Insurers

Separation (feet)	Capacity (gallons)	
	> 500	**> 5,000**
25 to 50	Water Spray	Water Spray & Barrier Wall
10 to 25	Water Spray & Barrier Wall	Water Spray & Barrier Wall

The fire suppression requirement may be mitigated when the transformer is located, or the burning oil can be contained, remotely from the structure and other equipment. Protection of the plant structure and adjacent equipment, as well as reducing hazards to personnel, warrants fire suppression in most cases. In some cases, use of less-flammable ester-based insulating fluids may mitigate the need for fire suppression and should be considered as an alternative.

Although most fire suppression practices included in this document are directed at ~~large,~~ GSU transformers, local offices are advised strongly to apply these practices to other important ~~or risky~~ transformers as well. Industry standards and insurance requirements include fire suppression and barrier walls for transformers containing as little as 500 gallons of combustible oil where acceptable separation/barriers from buildings and other equipment cannot be achieved.[2] Non-GSU transformer fire protection (or retrofill with less-flammable fluid) therefore should be considered where transformers are located indoors (not in vaults); adjacent to other, larger transformers; or where personnel or the public may be at risk.

It is recognized that it may not be technically feasible or economically viable to retrofit existing plants to meet all the criteria of this document or to comply with all current industry standards. However, in the interest of protecting plant structures, other equipment, human health and safety, and the environment, conscientious efforts must be made to achieve as many of these goals and meet as many recognized industry practices as possible at existing facilities. At new facilities, the goals of this document and requirements of all codes and standards shall apply.

Therefore, either when an oil-filled transformer is replaced, or no **later than January 2007,** even if replacement is not planned, each existing transformer installation should be reviewed formally for the following:

- Need for active fire suppression system

- Adequacy of existing fire suppression system in light of current technology

[2] Institute of Electrical and Electronic Engineers (IEEE) © Standard 979 – 1994, Section 4.4.5. 2002 National Electric Code® (NEC®) Section 450.27. Edison Electric Institute, *Fire Protection for Transformers*, Table 2.

- Adequacy of oil and water containment systems to meet current environmental requirements

- Need for supplementary systems such as firewalls

- Needed revisions to electrical and control/alarm systems

- Compliance with current codes and standards

Engineering retrofit alternatives resulting from this review should be considered using benefit/cost analysis and all results and decisions should be documented.

Achieving desired transformer fire protection goals may be costly. However, this cost can be made predictable. It will be much more costly and unpredictable to repair plant structures, replace adjacent equipment, and clean up oil spills in waterways.

5. Transformer Fire Protection Practices

How the above goals are achieved at specific facilities depends on many factors. The basic principles follow:

- New facilities with ~~large, mineral~~ oil-filled transformers located near the plant structure or other equipment should include active transformer fire suppression systems to protect the structure and adjacent equipment and properly designed containment systems to protect the environment.

- For new facilities, and where justified at existing plants, serious consideration should be given to locating ~~mineral~~ oil-filled transformers away from the plant, other equipment, and waterways as a way of reducing fire and environmental risks. In these cases, active fire suppression may not be necessary if other considerations allow.

- Existing, functional fire suppression systems should continue to be used to protect plant structure and other equipment but should be reviewed for adequacy and compliance with current codes and standards.

- Inactive fire suppression systems should be reviewed for adequacy and compliance with current codes and standards and restored to service.

- Fire suppression systems should be added to existing facilities (where none currently exist) and where required to protect the plant structure or other equipment. Decision documents should be established if it is decided that fire protection is not going to be added. In this case, the SOP should note that fire suppression is not available.

- Transformers should have periodic condition assessments in addition to routine inspection, testing, and maintenance. Transformers with low condition indices should be programmed for rehabilitation or replacement.

- Fire barrier walls between adjacent transformers, between transformers and the plant structure, between single-phase transformers, or between transformers and other equipment should be added where feasible and appropriate to contain a fire and explosion, thus reducing collateral damage.

- Existing and new fire suppression systems should comply with the Design Considerations below and all applicable codes and standards.

- Fire suppression systems must be adequately operated, maintained, and tested.

- Conversion from manual to automatic discharge of fire protection should be implemented. Even where plants are staffed, automatic operation ensures better fire protection.

- Operation and maintenance documentation on fire systems—including the plant SOP—must be kept current and accurate. Training should be provided to operation and maintenance (O&M) personnel on fire suppression system O&M.

- Containment and oil-water separation structures must comply with all applicable laws, regulations, and standards.

- Spill Prevention, Control, and Countermeasure (SPCC) plans must incorporate provisions for transformer oil spill whether from fire or normal operation.

- Access to transformers will be limited only to those having official business in the area. Proximity of the public to transformers will be restricted.

- Applicable environmental laws must be accommodated.

6. Responsibility

Each office with ~~mineral~~ oil-filled transformers is responsible for ensuring the provisions of this document and applicable codes and standards are met.

Adequacy of suppression and containment system O&M practices are verified under the Reclamation Power Review of O&M Program. Adequacy of containment system design and operation may be subject to other review, as well.

7. Applicable Codes and Standards

The following codes and standards apply to transformer fire protection and associated systems:

- NFPA 15, Standard for Water Spray Fixed Systems for Fire Protection
- NFPA 25, Water-Based Fire Protection Systems
- NFPA 30, Flammable and Combustible Liquids Code
- NFPA 70, National Electrical Code
- NFPA 72, National Fire Alarm Code
- NFPA 101, Life Safety Code
- NFPA 255, Method of Test of Surface Burning Characteristics of Building Materials
- NFPA 495, Explosive Materials Code
- NFPA 750, Standard on Water Mist Fire Protection Systems
- NFPA 851, Fire Protection for Hydroelectric Generating Plants (Note that NFPA 851 is now incorporated in NFPA 850)
- Edison Electric Institute, *Fire Protection for Transformers*, March 2001
- IEEE Standard 979, Substation Fire Protection
- IEEE Standard 980, Guide for Containment and Control of Oil Spills in Substations
- CFR Title 40, Part 300 [B34] (Oil Fires)
- CFR Title 40, Part 110 (Discharge of Oil) and Part 112 (Oil Pollution Prevention)

8. Risk and Consequences

The risk of a catastrophic fire with a ***properly inspected, tested, and maintained*** transformer is small. Proper maintenance and thorough testing of the transformer will prevent or detect many events that could lead to explosion and/or fire.

However, unforeseen events such as design defects, voltage surges, lightning strikes, structural damage, rapid unexpected deterioration of insulation, sabotage, and even maintenance errors can and do lead to transformer fires and the consequences can be severe. A transformer fire that involves several thousand gallons of combustible insulating oil can result in severe damage to nearby powerplant structural components such as concrete walls and damage or destroy electrical components such as nearby transformers, buswork, and circuit breakers.

Although a transformer already involved in a fire generally cannot be saved for future use, suppression of the fire could save the plant structure and other equipment, avoid extended outages on other generating units, and reduce air and water pollution. If damage can be limited to only one unit, avoidance of outages on nearby units could save millions of dollars in forced outage losses. Fire suppression may be justified on this basis alone.

~~A transformer fire creates air pollution. In some locations, this environmental "cost" may be quantified because of potential fines. A suppression system not only suppresses fires early, it is a "good faith" demonstration in reducing air pollution. In some cases, a suppression system may be required by environmental laws.~~

Transformer water deluge fire suppression poses an environmental risk of its own. Water suppression in some plant configurations or water suppression if improperly applied, could increase pollution by washing spilled oil, burning oil, or other fire debris into the adjacent waterway. Properly designed and operating oil containment systems will reduce this risk~~ as will the use of low-volume water fire suppression (mist systems).~~

Transformers and other electrical equipment such as capacitors and bushings may contain polychlorinated biphenyls (PCB). Current regulations forbid spilling any amount of PCBs into waterways, emphasizing the need for effective containment. In addition, electrical equipment containing PCBs must be properly labeled, managed in accordance with applicable regulations, and removed from service as soon as practicable.

An exploding transformer initially may throw insulating oil great distances, causing contamination in nearby waterways and other locations. This is almost impossible to contain given existing plant arrangements. If this risk is to be eliminated, complete relocation of the transformer would be required.

Obviously, there is no way to eliminate all risk and consequences of operating oil-filled transformers. However, using fire suppression systems to protect adjacent structures and equipment, while applying effective containment systems to reduce the environmental risk, is a reasonable approach to reducing transformer operating risks and consequences.

9. Transformer Maintenance, Diagnostics, and Condition Assessment

Transformers should be inspected, tested, and maintained according to requirements of FIST Volume 3-30, Transformer Maintenance; Volume 3-31, Transformer Diagnostics; and Volume 4-1B, Maintenance Scheduling for Electrical Equipment. Proper maintenance and testing will reduce the risk of a transformer explosion and fire.

One of the most important preventive measures that will reduce the risk of a transformer explosion and fire is regularly scheduled dissolved gas analysis (DGA) sampling and evaluation. Detecting and reducing explosive gasses such as acetylene in the incipient stage of generation will greatly mitigate the risk of explosion. Gassing transformers must be watched especially close to avoid dangerous gas buildup. More frequent DGA sampling may be required and remedial action taken. Ideally, a gassing transformer that cannot be repaired or replaced immediately should be monitored by an on-line, continuous gas monitoring system. See FIST Volume 3-31, Transformer Diagnostics, for more information.

New transformers must be monitored carefully since they have not been loaded fully and operated in a plant environment. Several DGA samples are required in the first year of operation while under warranty to detect design and construction flaws.

Although transformer age alone does not determine transformer condition, it is an important factor. Aging transformers—particularly those not properly maintained—pose a greater risk for an explosion and fire. Transformer condition should be assessed periodically using the tools described in the Appendix to FIST Volume 3-31. Proactive replacement of a deteriorated transformer can help reduce the risk and consequences of a transformer fire.

Transformer maintenance documentation should exist in MAXIMO. Job plans and work orders specifying and verifying appropriate maintenance will ensure this important work is being accomplished. MAXIMO data will be accessed during a Power O&M Review to confirm maintenance adequacy.

10. Fire Suppression System Inspection, Testing, and Maintenance

Transformer fire protection systems comprise of mechanical and electrical equipment necessary to furnish water to extinguish the fire. Pumps, piping, motors, valves, solenoids, control and power circuits, and relays must be in good working order.

Transformer fire protection systems must be inspected, tested, and maintained in accordance with this volume, FIST Volume 4-1B (Maintenance Scheduling for Electrical Equipment), and the applicable standards:

Transformer Fire Protection System
Inspection, Testing, and Maintenance Requirements
Reference Guide

System/Equipment	Component	Standard	Chapter/ Section	Table
Water-Based System	Fire Pumps	NFPA 25	8	8.1 8.5.3
	Water Spray Fixed System		10	10.1
	Valves, Valve Components, Trim		12	12.1
Water Mist System	All	NFPA 750	13	13.2.2 13.3.4
All Systems	Alarms Detectors	NFPA 72	10	10.3.1 10.4.2.2 10.4.3

The principal tool for ensuring fire system preparedness is the annual functional test. **Annually**, each transformer fire suppression system should be tested functionally to ensure that:

- Detecting and initiating devices deenergize the transformer
- Detecting and initiating devices trigger a fire water release
- All components of the control circuitry operate correctly
- Motors, pumps, solenoids, and valves operate correctly
- Water is delivered to the discharge nozzles
- Nozzles are free of debris
- Containment system drain valves operate correctly
- Sump pumps are deactivated
- All alarms and indication function properly

On a frequency consistent with the NFPA standard applicable for the suppression system used, all piping should be flushed to clear debris and to verify the spray pattern is still effective.[3]

Maintenance of water-oil containment systems should be performed in accordance with section 7.8 of IEEE Standard 980, which includes regular inspections, cleanings, testing, and maintenance of equipment according to the manufacturer's instructions.
Fire suppression system maintenance documentation should exist in MAXIMO. Job plans and work orders specifying and verifying appropriate maintenance will ensure this important work is being accomplished. MAXIMO data will be accessed during a Power O&M Review to confirm maintenance adequacy.

11. Transformer and Fire Suppression System Operation

Transformers should be operated in accordance with the SOP, manufacturer's instructions, and FIST Volume 1-5, Permissible Loading of Oil-Immersed Transformers and Regulators. Transformers that are operated properly (not overloaded) are not as likely to suffer the kind of insulation damage that can lead to fires.

It is recommended that transformer fire suppression systems be activated automatically by fire and/or detectors even in facilities staffed full time. As described under "Control and Protection Systems," false activation can be eliminated assuring the operator that if the suppression system has activated, a fire is very likely. A person intervening in the situation is not as necessary as it was in the past. Automatic activation provides the best chance of suppressing a fire and reducing damage. Manual activation should be provided as a supplement to automatic activation and in some instances, remote activation (through the use of SCADA) may be warranted depending on local operating practices.

Fire suppression water should NOT ~~be discharged on an energized transformer, nor should it~~ be used as a cooling method. Water contains contaminants that if used extensively, will damage transformer external components and possibly cause flashover. The transformer should automatically be deenergized prior to water being discharged.

The plant SOP must include current and accurate information on fire suppression system operation. Training should be provided to all plant personnel on fire suppression O&M.

The fire suppression mechanical and electrical system should be covered in the plant Hazardous Energy Control Program.

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[3] Spraying water on the transformer more frequently is not recommended and water-based fire suppression systems should never be used to cool an overheating transformer because of the contaminating effects of water.

Some facilities were constructed with the capability to trap and contain spilled transformer insulating oil and fire suppression water in sumps or other containment structures. This reduces the risk of oil being discharged into the adjacent waterway. Where this type of containment exists, the system should be inspected **weekly** and maintained properly. Inspection and maintenance should be documented. Accumulating oil should be removed and water should be evacuated on a regular basis to allow for maximum capacity in the event of an oil spill and fire water discharge.

Some fire suppression designs provide for shutting off sump pumps in the event of fire water discharge to prevent oil from being discharged to the waterway. Manual operation of the sump pumps may be needed to keep the plant from flooding until the oil in the water has been removed. This should be documented in the SOP, and Emergency Action Plan, and training provided.

Similarly, containment structure drains may be designed to close when fire suppression operation is activated. Such systems must be documented and tested regularly.

Consideration should be given to including important transformers in the field of view of cameras used for security or supervisory control purposes. This could be of great use in determining the status of a fire or perhaps remote activation of fire suppression.

12. Design Considerations

Since every plant is unique, each facility must be evaluated individually to identify all design considerations. Fire suppression systems are complex and expensive. Likewise, containment and diversion structures are complex and costly.

The following design considerations should be included in new or retrofit installations and used as general guidance. Qualified designers and experienced contractors should be consulted for design details.

Controls and Protection Systems

Refer to Appendix A for a functional diagram of transformer fire protection.

Current industry practice does not recommend the use of most transformer protective devices for initiating fire suppression. Devices considered <u>not</u> appropriate include:

- ~~Transformer differential relay~~
- ~~Sudden (fault) pressure relay~~
- Winding temperature detector
- Oil temperature detector

- Low oil detector
- ~~Buchholz relay~~
- Bladder failure relay

It has been determined that inadvertent operation of these devices can initiate false operation of the suppression system, thus contaminating the surface of the transformer and bushings and flushing any spilled oil into waterways.

Since most of Reclamation's transformer fire suppression systems are activated directly or indirectly by these devices, review and modification of control systems is warranted.
The following devices should deenergize the transformer and trigger the transformer fire suppression system:

- Heat and/or fire sensors appropriately located near or on the transformer

- Manual discharge (control switch, pushbutton)

Depending on the type of sensors used and the details of the design, it may be desirable to require two sensors to operate before activating suppression to reduce false operation.

In addition, remote activation through the use of SCADA might be considered where operating practices permit and sufficient information is available to the remote operator.

~~Heat sensing fire detectors are the most reliable way of activating fire suppression for transformers. Techniques that should be considered include linear heat detectors (heat sensing cable) and infrared detectors. The appropriate method of detection is chosen when designing or re-designing the system.~~

Control system considerations include:

- Operation of the fire suppression system should deenergize the transformer to prevent water from discharging onto an energized transformer.

- Loss of power to fire suppression system pump motors, solenoids, and controls should be annunciated so the problem can be detected, diagnosed, and remedied.

- Activation of the suppression system should be annunciated and input to the SCADA system.

- Activation of the suppression system should block drains and pumping of oil-contaminated water from sumps into waterways.

- Activation of the suppression system should stop transformer fans and oil pumps that might feed the fire.

- Power the fire detection system from a reliable source, have continuous internal monitoring, and have sufficient output contacts for necessary alarm and control functions.

- Power the fire suppression system from a reliable source not affected by the loss of the transformer being protected.

- At unattended plants where high-volume deluge systems are retained, detection and control circuits should be designed to suppress the fire while reasonably minimizing the amount of water discharged. The purpose of this is to suppress the fire while limiting the risk of overtopping containment structures and contaminating waterways. It is reasonable to apply water for a limited time, temporarily shut down, and then reactivate water discharge to suppress any remaining fire. This might be accomplished through detectors that continue to sense fire, timers that cycle the system, or other means. In addition, high level detection in the containment structure is recommended to shut off fire suppression to prevent overflow. High level detection might be supplemented by video monitoring and remote deactivation through the use of SCADA.

Mechanical Systems

Each facility is unique and the type of fire suppression system most appropriate is dependent on several factors. Each facility must be evaluated individually to determine which system will be most effective.

Water Deluge Systems

Existing deluge systems (high volume at low pressure) at Reclamation plants have been effective in suppressing transformer fires but the large volume of water discharged easily can cause overtopping of the containment system and flush oil into waterways. On the other hand, existing piping and water supplies (penstock pressure, fire pumps) are designed for low pressure and high volume which makes retaining these systems attractive.

After adequate review, if it is appropriate to retain the deluge system, improvements must be made to avoid potential contamination problems. Adequate water-oil containment and control of discharge into waterways is essential. Controlled activation of the suppression system (timed release) is highly recommended.

~~*Water Mist Systems*~~

~~Water mist systems (low volume at high pressure) have been proven to be effective in suppressing transformer fires in certain situations. Because these systems discharge much less water, the risk of contaminating waterways is reduced and the containment system may need little modification. On the other hand, existing piping and water supply systems may have to be modified to provide the required high pressure. Despite these complications, water mist systems may be advantageous because of their environmental advantages.~~

Foam, Gas, and Dry Chemicals

~~These systems are not recommended at this time for fire protection at existing Reclamation facilities. Conversion to these systems would be very costly and they each present their own problems:~~

- ~~Foam has no documented history for use on outdoor transformer fires; leaves an environmentally unfriendly residue; provides no cooling action; and is extremely slippery.~~

- ~~Gases such as nitrogen or carbon dioxide are not effective outdoors where there is no containment and safety considerations due to toxicity are considerable.~~

- ~~Dry chemicals do not work well on large fires; are dependent on containment; and offer no cooling effect.~~

Regardless of the system used, suppression system piping, nozzles, and other mechanical components should be located so as to avoid damage from fire in the interval before the suppression system activates.

Containment Systems

Effective oil and water containment systems are essential in light of current environmental laws. The CFR 40, Parts 110 and 112, require that appropriate oil containment and diversionary structures be provided to prevent discharged oil from reaching navigable waters.

Transformers can leak oil under normal operation or during maintenance. Rain and snow can flush this oil into waterways if not contained. Release of larger amounts of oil is to be expected in the event of a transformer fire and tank rupture and must be contained consistent with the standards. Containment of oil and water that accumulates during a transformer fire being extinguished by the suppression system is the biggest challenge.

Designs of existing powerplants often do not readily provide or easily accommodate adequate containment. Yet, every reasonable effort should be made to provide adequate containment.~~ The use of water mist systems in lieu of deluge systems may make containment design easier.~~

Oil spill containment should be added or improved as needed at existing installations. Adequate containment should be included in designs of new installations. Provisions for containing burning oil in a location remote from the plant structure and other equipment should be considered.

Oil and water containment systems should be sized for containment of discharge during and after a transformer fire. Containment systems must be large enough to accommodate the volume of oil that might spill plus the expected amount of fire suppression water plus any accumulated rain or snowmelt. NFPA 851, section 3-6.5, states that curbed areas must contain a spill of the largest container (transformer) plus a minimum of 20 minutes of fire suppression operation at maximum discharge. See 40 CFR 112(A) for sizing containment for single and multiple tanks.

Provisions should be made to contain the oil and water in such a way to keep it from contaminating waterways. Ways of accomplishing this include:

- Oil-contaminated water can be prevented from draining to sumps in cases where sumps are inadequate. This is accomplished with drain valves that are automatically blocked when the fire suppression system activates. Such valves and their control systems must be maintained and tested regularly.

- Oil-contaminated water should be prevented from being evacuated to waterways from sumps. This is accomplished by shutting off sump pumps in the event of a transformer fire. Personnel responding to the incident should manually activate sump pumps as necessary to keep the plant from flooding until the oil has been removed.

- Separating oil from the water may allow for water discharge while preventing the oil from being evacuated to waterways.

- Containment may be accomplished by compacted soil, berms, and walls. Consideration should be given to improving this type of containment whenever transformer replacement or similar major modification is planned for existing installations. If berms are used, they must be able to withstand the expected hydraulic head and provide adequate fire rating. Earth and concrete berms may meet these requirements while metallic berms likely will not. Metallic berms are not recommended because of their susceptibility to failure when exposed to the extreme heat of a fire.

~~Containment system requirements are much reduced when using ester-based insulating fluids as described in Section 18.~~

Barrier Walls and Separation

NFPA 851, section 3-2.2.1, states: "Outdoor, oil-filled transformer should be separated from adjacent structures and from each other by firewalls, spatial separation, or other approved means for the purpose of limiting the damage and potential spread of fire from a transformer failure." This includes separating or firewalling individual phases of three-phase banks. (Note that NFPA 851 is now incorporated in NFPA 850)

Barrier walls should be considered when replacing transformers or when improving or installing a fire suppression system.

Barrier walls should be part of designs for new installations and must be constructed with noncombustible materials with appropriate fire ratings and mechanical ability to withstand exploding transformer bushings and lightning arrestors.

Barrier and separation requirements described above apply to minera~~l oil insulated transformers because of the combustible nature of the oil. These requirements are significantly red~~uced with the use of ester-based insulating fluids as described in Section 18, below.

13. Oil Spill Cleanup

Directive and Standard FAC 01-03, Hazardous Materials, requires facilities to have a written SPCC plan. This plan must be in compliance with CFR 40, Part 112 (Oil Pollution Prevention), and should include a contingency plan which commits manpower, equipment, and materials required to control and remove expeditiously any harmful quantity of oil discharged. The plan should be supplemented with a list of potential contractors who are qualified to assist with cleanup. Training must be provided to O&M staff on a recurring (annual) basis.

Ester-based insulating fluid cleanup is discussed in Section 18.

14. Firefighting

Firefighting policies and practices at Reclamation facilities are determined locally based on regional policy, staff capability, available equipment, and arrangements with alternative firefighting resources (municipal fire departments).

It is common practice in Reclamation not to use Reclamation employees to fight fires. In this case, an automatic transformer fire suppression system can help prevent unnecessary damage to plant and other equipment in the interim until outside firefighters arrive.

An automatic transformer fire suppression system will likely reduce hazards for firefighters since the fire may be out by the time they respond. In any case, firefighters should be informed of the hazards of fighting a transformer fire including the nature of the chemicals in the oil and smoke and the proximity of other energized equipment.

See FIST Volume 5-2, Firefighting and Fire Prevention, for more information.

15. Access and Proximity

Energized transformers are by their nature hazardous. High voltages and currents exist along with combustible insulating oil in a confined space. A transformer explosion and fire is a catastrophic event with a high probability of injury or death to anyone in the vicinity.

Access to transformers by plant personnel for O&M purposes is unavoidable. However, access should be restricted only to necessary activity to minimize risk to health and safety.

Exposure of the public to this risk is another matter. Energized transformers might be near the public who are touring the facility. Given the risks and consequences of a transformer explosion and fire, . . .

> ***. . . access and proximity of the public to energized transformers should be restricted, if not eliminated altogether.***

16. Incident Investigation

A transformer fire at a Reclamation facility is a Level 1 or Level 2 Incident as defined by the Power O&M Incident Evaluation and Reporting Program (Directive and Standard FAC 04-02). Any transformer fire must be investigated, documented, and reported in accordance with this program.

A transformer fire should also be reported immediately through the Reclamation Emergency Notification System.

17. Mitigation of Outages

Since transformer fires are catastrophic, destroying the transformer regardless of fire suppression, a recovery strategy should be defined as to how a unit outage caused by the fire could be mitigated. Spare transformers should be considered as a way to recover quickly. As an alternative, a preplanned strategy for acquiring a replacement as quickly as possible should be developed. ~~Several sources of replacement transformers exist:~~

- ~~A database of electrical equipment in Reclamation, including spare transformers, is found at <http://intra.do.usbr.gov/electrical_data_library/start.htm>~~

- ~~A list of replacement transformer contacts is found at <http://intranet.usbr.gov/~hydrores/>~~

~~18. Alternative Provisions to Fire Suppression and Containment~~

~~Transformer fire protection requirements described in this volume apply to mineral-based dielectric oil-filled transformers. Such transformers are subject to explosive failure and fire because of the combustible nature of the oil. In addition, this oil is environmentally unfriendly, being toxic and non-biodegradable. Fire suppression generally is required as well as barrier walls and possibly physical separation. Required containment may become complicated because it is necessary to contain fire suppression water in addition to spilled transformer oil. Meeting Reclamation fire protection requirements for mineral-based dielectric oil-type transformers can be expensive, time consuming, and complex.~~

~~In lieu of bringing existing installations up to the standards of this volume regarding fire suppression, barriers, separation, and oil/water containment for mineral-oil-insulated transformers, many transformers may be candidates for retrofill (or replacement) with ester-based insulating fluid. Use of ester-based fluids may mitigate the need for these extensive fire suppression and containment provisions.~~

~~Properly manufactured and applied ester-based insulating fluid is sufficiently less flammable than mineral-based oil that~~ **~~fire suppression can be eliminated altogether.~~** ~~The flash point and fire points are well above 300 degrees Centigrade (°C). Factory Mutual Insurance Company (Factory Mutual) has stated that using approved ester-based insulating fluid, water spray protection and barriers are not needed if minimum spacing is provided. This spacing, between transformers and buildings or between transformers and other equipment (including other transformers), is approximately 5 feet or less—much less than required for mineral-based oils. It is likely that the most recently installed transformers already meet this minimum space requirement.~~

~~In addition to eliminating fire suppression, barriers, and separation requirements; the environment, safety, and security can be enhanced with ester-based fluids. Environmental benefits include less impact in the event of a spill or fire and cleanup is non-toxic. Safety is improved since transformer explosion essentially is eliminated. Security is improved by providing a less volatile and therefore less attractive target.~~

~~By retrofilling an existing transformer with ester-based fluid, fire protection requirements or costs that may be eliminated include:~~

- ~~Active fire suppression is not needed since fire risk essentially is eliminated~~
- ~~Containment for water used to suppress a fire. Containment for transformer fluid is still required.~~
- ~~Fire wall barriers~~
- ~~Increased physical separation~~
- ~~Maintenance and replacement costs for fire suppression and containment systems~~
- ~~Toxic waste cleanup costs resulting from spill of mineral-based oils~~
- ~~Training and documentation required for fire suppression systems~~

~~Disadvantages of retrofilling transformers with ester-based fluids include:~~

- ~~Ester-based fluid is approximately 5 times as expensive as mineral-based oils~~
- ~~An outage is required~~
- ~~Disposal of the mineral-based oil~~
- ~~Modifications to dissolved gas analysis~~

~~For other considerations, see Appendix B.~~

~~In addition to retrofilling applications, ester-based fluids should be seriously considered when specifying a new transformer.~~

~~Ester-based insulating fluids are categorized as “natural,” being produced from edible seeds (vegetable oil) and “synthetic.” While either is superior to mineral-based oils in reduced combustibility, natural ester fluids are much less expensive than synthetic esters. Based on technical considerations and cost, natural ester-based insulating fluids are currently the best alternative to mineral-based oils.~~

~~Ester-based fluids have been proven to retard deterioration of insulating paper. Manufacturers claim that paper life can be extended by 500 percent in new transformers insulated with ester-based fluids. These claims are based on laboratory data. Given that this fluid has been in field service for less than 30 years, a conservative estimate of a 25-percent paper life increase is a reasonable~~

~~expectation until further field experience is gained and empirical data collected. Even this conservative estimate indicates a great savings potential.~~

~~Appendix B provides more detail on ester-based fluids and considerations for retrofilling.~~

~~An economic analysis must be performed to determine whether it is advantageous to continue operating a mineral-based-oil insulated transformer with accompanying fire suppression and containment measures or to retrofill the transformer with ester-based fluid. Each installation must be evaluated individually since there is great variance from site to site regarding transformer vicinity to the plant and other equipment, status of fire suppression systems, adequacy of containment systems, and other factors.~~

~~Appendix C includes an example of an economic analysis for comparing the alternative of operating an existing mineral-oil transformer in accordance with this volume to retrofilling a transformer with ester-based fluid.~~

~~This type of analysis is best performed using a life-cycle cost comparison based on present value calculations over a period approximately the expected life of the transformer (with extended insulating paper life made possible with ester-based fluid) in order to allow for one replacement cycle. The reader may choose to modify the assumptions in the example to suit local conditions. For assistance in performing site-specific economic analysis, contact the Technical Service Center's (TSC) Economics Group (D-8270) at 303-445-2724.~~

~~Based on the conclusions of this analysis and environmental, safety, and security considerations, retrofilling transformers with ester-based fluids should be seriously considered as an alternative in lieu of, or in addition to, other fire protection measures.~~

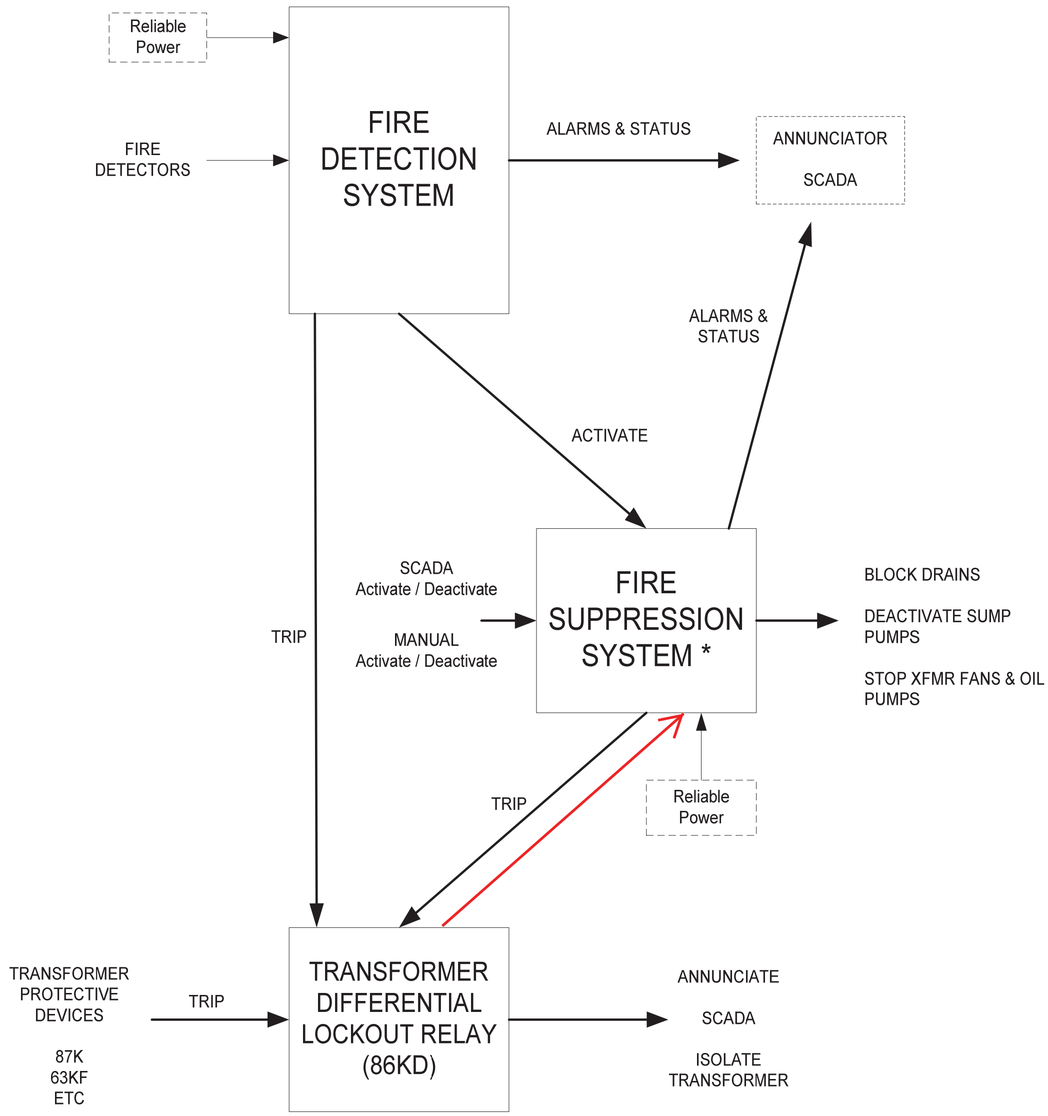
~~At the time of the initial publication of this volume, Reclamation has no direct experience with use of ester-based insulating fluids in larger power transformers. Industry experience with ester-based fluids in medium and large transformers is limited. Only recently have manufacturers of larger transformers begun offering ester-based fluids as an option to mineral oil. However, all indications are that ester-based fluids are fully satisfactory for large transformers and retrofills.~~

~~Therefore, it is recommended that each potential new or retrofill ester-based insulating fluid installation be considered on an individual basis and in coordination with fluid and transformer manufacturers. For more information on ester-based insulating fluids, contact the TSC's Hydroelectric Research and Technical Services Group (D-8450) at 303-445-2300, and the Electrical System Group at 303-445-2850.~~

Appendix A – Transformer Fire Protection Functional Diagram

Appendix A

TRANSFORMER FIRE PROTECTION
FUNCTIONAL DIAGRAM
April 6, 2004



* Includes electrical and mechanical equipment to discharge fire suppression water. Deluge type should cycle or use high level detection to limit water volume and overflow risk.

~~Appendix B – Ester-Based Transformer Dielectric Fluids~~

~~Background~~

~~Reclamation power transformers traditionally have been insulated with mineral-based insulating oils which have been in use in transformers since the late 1800s.~~

~~Mineral oils have proven reliable as an insulating medium but they have disadvantages:~~

- ~~Combustibility – explosion and fire cause collateral damage to adjacent equipment and buildings. Fire suppression, barrier walls, and large physical separation are now standard practice to reduce this risk.~~

- ~~Environmentally unfriendly – spilled oil must be treated as toxic waste. Mineral oil that escapes into water (such as rivers) is especially harmful. Mineral oil is non-biodegradable. Secondary containment must be used and if fire suppression water is applied, containment can be complicated and expensive.~~

- ~~Shortened insulating paper life – water trapped in the paper shortens the life of the paper and the transformer. Water is minimally soluble in mineral oil.~~[4]

~~Askarel oils were promoted years ago to address fire safety concerns but these fell out of favor and have been restricted because they contained PCBs which are perceived to pose health risks and are non-biodegradable. Askarels are no longer allowed in Reclamation transformers.~~

~~“Less-flammable transformer fluids” (minimum open-cup fire point of 300 °C) in the form of high molecular weight hydrocarbons (HMWH) have been used widely in the industry for many years. These successfully address fire safety concerns but since they are mineral-based oils, they are becoming more restricted by environmental regulation and spills must be reported and treated as toxic during cleanup.~~

~~Esters are a broad class of organic compounds available from agricultural products (natural esters) or chemically synthesized from organic precursors (synthetic esters). Synthetic ester dielectric fluids are a suitable insulating medium and are more biodegradable than mineral oil but their high cost limits their use to specialty applications.~~

~~Natural esters were previously thought unsuitable for transformer use because of their susceptibility to oxidation. The use of suitable fluid additives has eliminated~~

~~4 Mineral oil saturates with water at approximately 60 parts per million (ppm). Natural ester saturates at approximately 1,200 ppm, 20 times mineral oil saturation. This means that much more water will be in the ester fluid instead of the paper; thereby, extending paper life.~~

~~this concern. Based on research and development beginning in the early 1990s, natural esters have matured into suitable dielectrics with excellent fire safety properties while being non-toxic and biodegradable.~~

~~Characteristics and Comparisons~~

~~Ester-based fluid compared to mineral oil, silicone oil, HMWH, and synthetic esters, adapted from Table 1, IEEE Industry Applications Magazine, May/June 2002.~~

~~Comparison of Transformer Dielectric Fluids – Typical Values~~							
		~~**Mineral Oil**~~	~~**Silicone Oil**~~	~~**HMWH**~~	~~**Synthetic Ester**~~	~~**Natural Ester**~~	~~**Test Method**~~
~~Dielectric Breakdown (kV)~~	~~New~~	~~42~~	~~40~~	~~52~~	~~43~~	~~47~~	~~D-877~~
	~~After 50 switch opera-tions~~	~~41~~	~~<4~~	~~43~~	~~36~~	~~47~~	~~D-877~~
~~Viscosity (cS)~~	~~40°C~~	~~9.2~~	~~37~~	~~121~~	~~29~~	~~33~~	~~D-445~~
	~~100°C~~	~~2.3~~	~~15.5~~	~~12.5~~	~~5.6~~	~~7.9~~	~~D-88~~
~~Flash Point (°C)~~		~~147~~	~~300~~	~~276~~	~~270~~	~~328~~	~~D-92~~
~~Fire Point (°C)~~		~~165~~	~~343~~	~~312~~	~~306~~	~~357~~	~~D-92~~
~~Specific Heat (cal/gm/°C) at 25°C~~		~~0.39~~	~~0.36~~	~~0.45~~	~~0.45~~	~~0.45~~	~~D-2766~~
~~Pour Point (°C)~~		~~-50~~	~~-55~~	~~-21~~	~~-50~~	~~-21~~	~~D-97~~
~~Specific Gravity~~		~~0.87~~	~~0.96~~	~~0.87~~	~~0.97~~	~~0.92~~	~~D-1298~~
~~Biochemical Oxygen Demand (ppm)~~		~~6~~	~~0~~	~~6~~	~~24~~	~~250~~	~~5-day SM5210B~~
~~BOD/COD Ratio (percent)~~		~~7~~	~~0~~	~~17~~	~~--~~	~~45~~	~~--~~
~~Trout Fingerling Toxicity Mortality~~		~~N/A~~	~~N/A~~	~~N/A~~	~~N/A~~	~~0~~	~~OECD 203~~

~~BOD – biochemical oxygen demand~~
~~cal – calories~~
~~cS – Centistokes: A measure of dynamic viscosity; a lower value of cS means less resistance to flow at a given temperature.~~
~~COD – chemical oxygen demand~~
~~gm – gram~~
~~kV – kilovolt~~
~~OECD – oxygen ester chemical demand~~

~~Leading manufacturers' ester-based insulating fluids are:~~

- ~~Fully miscible with mineral oil~~
- ~~Resistant to coke and sludge formation~~

~~Industry Acceptance~~

~~Esters are classified as "less-flammable transformer fluids" by the NEC®.~~

~~Leading manufacturers' ester-based fluids are Factory Mutual approved and classified by Underwriters Laboratories™ (UL™).~~

~~In April 2004, Waukesha Electric Systems, Inc.—the largest manufacturer of medium-power transformers in the U.S.—announced that it has approved use of a leading brand of natural-ester dielectric fluid in its power transformers. Other manufacturers are sure to follow suit.~~

~~Alternative to Fire Suppression and Barrier Walls~~

~~Because of the very high flash and fire points of ester-based fluids, the need for active fire suppression and barrier walls essentially has been eliminated. Laboratory tests by manufacturers and decades of use in smaller transformers without fire or explosion incident renders fire suppression superfluous. Barrier walls are not needed in most cases since explosion hazard and exposure to fire by adjacent equipment is virtually non-existent.~~

~~In an April 29, 2004 letter to Reclamation regarding "approved less flammable transformer fluid," Factory Mutual stated:~~

~~"Water spray protection and barriers are not needed if the spacing is equal to or greater than that required in Table 2a or 2b, as applicable, of the above data sheet."~~

~~In other words, if minimal separation is maintained, neither fire suppression nor barrier walls are required to meet Factory Mutual standards. Separation distances cited by Factory Mutual are minimal (see Physical Separation).~~

~~Physical Separation~~

~~Factory Mutual Global Property Loss Prevention Data Sheet on transformers, revised May 2003, includes the following separation distance tables (modified to show only English units):~~

~~Table 2a. Separation Distances between Outdoor Liquid Insulated Transformers and Bushings~~						
~~Liquid~~	~~Approved Transformer or Equivalent~~	~~Liquid Volume (gallons)~~	~~Horizontal Distance (feet)~~			~~Vertical Distance (feet)~~
			~~2-hour Fire Resistant Construction~~	~~Non-combustible Construction~~	~~Combustible Construction~~	
~~Less Flammable (approved fluid)~~	~~Yes~~	~~N/A~~	~~3~~			~~5~~
	~~No~~	~~≤ 10,000~~ ~~> 10,000~~	~~5~~ ~~15~~		~~25~~ ~~50~~	~~25~~ ~~50~~
~~Mineral Oil or Unapproved Fluid~~	~~N/A~~	~~< 500~~ ~~500-5,000~~ ~~> 5,000~~	~~5~~ ~~15~~ ~~25~~	~~15~~ ~~25~~ ~~50~~	~~25~~ ~~50~~ ~~100~~	~~25~~ ~~50~~ ~~100~~

~~Table 2b. Outdoor Fluid Insulated Transformers Equipment Separation Distances~~			
~~Liquid~~	~~Approved Transformer or Equivalent~~	~~Fluid Volume (gallons)~~	~~Distance (feet)~~
~~Less Flammable (approved fluid)~~	~~Yes~~	~~N/A~~	~~3~~
	~~No~~	~~≤ 10,000~~ ~~> 10,000~~	~~5~~ ~~25~~
~~Mineral Oil or Unapproved Fluid~~	~~N/A~~	~~< 500~~ ~~500-5,000~~ ~~> 5,000~~	~~5~~ ~~25~~ ~~50~~

~~Factory Mutual's endorsement of these distances used in conjunction with approved less-flammable fluids such as ester-based insulating fluids, is strong assurance that such fluids can be used safely in Reclamation transformers without fire suppression and/or barrier walls, in most cases.~~

~~Environmental Benefits~~

~~Environmental benefits of using natural ester-based transformer insulating fluids are significant. Unlike mineral oil which is considered toxic and non-biodegradable, ester-based fluids are considered by EPA to be non-toxic and biodegradable.~~

~~Although transformers with ester-based fluids are required to have secondary containment, any spilled fluid can be disposed of through normal means and not treated as toxic waste.~~

~~Use of ester-based fluids has an additional environmental benefit: since ester-based fluid transformers do not require fire suppression, there is no risk of fire water overtopping secondary containment structures into nearby waterways. Containment can be sized only for the likely spill of fluid and not for fire water as well.~~

~~Insulating Paper Aging~~

~~In accelerated aging studies in a sealed environment at 170 °C, one manufacturer of natural ester-based fluids showed that paper in mineral oil had no tensile strength at 3,000 hours while paper in ester-based fluid still had 40-percent tensile strength. Paper in simulated retrofill mixture (2- to 4-percent mineral oil) still had 36-percent tensile strength.~~

~~Some estimates show that insulating paper in ester-based fluids may have 500 percent of the life of paper in mineral oil because moisture—one of the main deteriorating agents—is attracted from the paper to the ester-based fluid. Ester-based fluid introduced to an existing transformer from retrofilling will act as a drying agent for insulation that has become wet from aging. It is estimated from laboratory tests that the remaining life of transformer paper insulation will be doubled after having been retrofilled.~~

~~While retardation of paper aging has not been proven empirically in large ester-based fluid transformers, it has been proven in smaller transformers in service over the last 30 years.~~

~~Ester-based fluids do not provide the same level of cooling as mineral oil because of their higher viscosity. Ester-based fluid does not circulate as readily through the cooling system; therefore, heat is not removed as quickly. The operating temperature is thus slightly higher with ester-based fluid. However, natural-ester fluid chemically helps preserve the paper when exposed to heat. Accelerated aging studies verify that the paper will last well beyond the expectation for mineral oil.~~

~~Any increase in paper life has significant economic implications since deterioration of the paper determines transformer life, and thus the life-cycle cost of the transformer. An increase in transformer life will defer capital investment in replacement as well as the expensive outage required to replace the transformer.~~

~~Retrofilling Existing Transformers~~

~~New, ester-based transformers are endorsed for future installation to reduce fire risk and mitigation costs, minimize environmental risks, and extend the life expectancy of the transformer. Likewise, retrofilling existing transformers can provide these same benefits.~~

~~Experience in the industry shows that retrofilling is practical and cost effective. Transformers as large as 200-megavolt amperes have been retrofilled successfully.~~

~~Retrofilling procedures have been developed and tested. It is necessary to remove as much mineral oil from the transformer as possible before filling with ester-based fluid. It is recommended that once the transformer has been drained, that it be allowed to "drip" for at least 24 hours to remove more mineral oil. Applying a dry nitrogen head space pressure and/or flushing with hot flushing fluid may be~~

~~appropriate depending on transformer design and manufacturers' recommendations.~~

~~Also, since many drain valves are located several inches above the tank bottom, it is recommended that the remaining oil be pumped out of the bottom of the tank before filling. It may be necessary to remove the drain valve to accomplish this. The ester-based insulating fluid manufacturer should be consulted for recommended retrofilling procedures and precautions.~~

~~Using these procedures, it should be possible to get the retrofilled liquid volume between 2- to 4-percent mineral oil content. This is sufficient to get almost all the benefits of the ester-based fluid. Mineral oil contamination above 4 percent may reduce the fire point of the combined fluid below 300 °C, thus losing the "less flammable" rating.~~

~~Retrofilling procedures should be obtained from the ester-based insulating fluid manufacturer.~~

~~Handling and Storage~~

~~Natural ester-based fluid is more susceptible to oxidation than petroleum-based products, so exposure to air (and water) should be guarded against. Otherwise, handling and storage is similar to mineral oil.~~

~~Ester-based fluids are generally compatible with materials used in association with mineral oils. Compatibility with transformer, storage, and containment system materials should be verified with the manufacturer in a retrofit situation.~~

~~A dry nitrogen, vacuum, dry air headspace, or desiccant vent dryer may be required for optimum storage.~~

~~Handling and storage procedures should be obtained from the ester-based insulating fluid manufacturer.~~

~~Maintenance~~

~~Ester-based fluid testing is recommended to be conducted on the same schedule as mineral oil. Recommended testing includes:~~

- ~~Dielectric strength~~
- ~~Dissolved gas analysis~~
- ~~Dissipation factor~~
- ~~Neutralization number~~
- ~~Interfacial tension~~

~~Since water is much more soluble in ester-based fluids, water content in the sample should be expected to be higher than for mineral oil. At 25 °C, mineral oil~~

~~becomes saturated around 65 ppm of H_2O and concern begins about the dielectric strength of the oil at about 25 to 30 ppm depending on transformer voltage. At this point, a dryout or replacement of the oil may be appropriate. Ester-based fluid will not become saturated until about 1,200 ppm of H_2O. Dryout would not be recommended until about 400 ppm (ASTM D-1533B). This increased ability of ester-based fluid to hold water is a major factor in its ability to preserve paper life.~~

~~Dissolved gas analysis for ester-based fluid is conducted similar to mineral oil and may be conducted per FIST Volume 3-31 and ANSI/IEEE Guide C57.104. Higher levels of CO and CO_2 will be normal in DGA of ester fluids.~~

~~Maintenance procedure specifics should be obtained from the ester-based insulating fluid manufacturer.~~

~~References and Standards~~

- ~~FIST Volume 3-31, Transformer Maintenance~~
- ~~Factory Mutual Global Property Loss Prevention Data Sheet on Transformers, revised May 2003~~
- ~~Factory Mutual Research Corporation Approval Standard Class Number 3990 (Less and Nonflammable Liquid-Insulated Transformers)~~
- ~~NEC® Requirement Guidelines – 2002 Code Options for the Installation of Listed Less-Flammable Liquid-Filled Transformers (Cooper Power Systems Bulletin 92046 – Application Information)~~
- ~~UL™ Standard 340 – Standard For Safety For Tests For Comparative Flammability Of Liquids~~
- ~~NEC® – Section 450-23 – Less-Flammable Liquid-Insulated Transformers~~
- ~~National Electric Safety Code (IEEE C2-1997) – Section 15 – Transformers and Regulators~~
- ~~IEEE Standard C57.91 – Transformer Loading Guide~~
- ~~ANSI/IEEE Guide C57.104 – IEEE Guide to Interpretation of Gases Generated in Oil-Immersed Transformers~~
- ~~CFR Title 40, No. 270 – Federal Regulation of Used Oils~~
- ~~CFR Title 40, No. 279 – Federal Used Oil Regulation~~

- ~~Edible Oil Regulatory Reform Act (U.S. Public Law 104-55, 1995)~~
- ~~EPA OPPTS 835.3100 – Aerobic Aquatic Biodegradation~~
- ~~Toxic Substance Control Act (U.S. Public Law 94-469)~~
- ~~International Electrotechnical Commission (IEC) Standard 1099, Specifications for Unused Synthetic Organic Esters for Electrical Purposes*~~
- ~~IEC Standard 1203, Synthetic Organic Esters for Electrical Purposes – Guide for Maintenance of Transformer Esters in Equipment*~~

~~*Currently, there are no ASTM, IEEE, or IEC standards specifically for natural esters.~~

~~Appendix C – Economic Analysis Example~~

~~Retrofilling a Power Transformer with Ester-Based, Dielectric Coolant Fluid vs. Continuing Operation with Mineral Oil~~

~~Background~~

~~Reclamation power transformers are insulated and cooled with mineral-based oils that are subject to fire and are environmentally unfriendly. Modern ester-based, dielectric coolant fluids promise to provide superior insulating and cooling properties, extension of insulation life, higher flash point (less fire risk), and less environmental risk. Although ester-based fluids initially cost more than mineral oil, total cost of transformer ownership may be less with ester-based fluid, thus analysis is warranted. Major factors that affect this study include:~~

- ~~Cost of fire suppression for mineral-based oil-filled transformers~~
- ~~Cost of installing or expanding (rehabilitating) oil/water containment systems for fire suppression~~
- ~~Potential increase in life expectancy with ester-based fluids~~

~~Objective~~

~~The objective of this study is to assess the economic benefit, if any, using life cycle costs for a typical existing transformer, comparing continuing use of the transformer with mineral-based insulating oil to retrofilling it with ester-based dielectric coolant fluid. This is a hypothetical example.~~

~~Basic Data~~

~~Facility Name: ***Flaming Horse***~~
~~Transformer Designation: ***K1A***~~
~~KVA: ***100,000***~~
~~Voltage: ***12.0/230 kV***~~
~~Number of Phases: ***3***~~
~~Capacity (gallons): ***10,000***~~
~~Year Installed/Age: ***1994/10***~~
~~Original Life Expectancy: ***40 years***~~
~~Year of Study: ***2004***~~

~~Assumptions~~

~~Mineral-based oil transformer to be replaced at **40** years of age (30 years from study point in 2004).~~

~~Retrofill to take place at **10** year point in transformer life (e.g., 2004).~~

~~Expect **25** percent increase in life expectancy of the winding with ester-based fluid.[5] 10 years + 125 percent of remaining 30 years = 47.5 years or 37.5 years from retrofill point. Therefore, replacement of retrofilled transformer to take place **37.5** years from study point.~~

~~Retrofill outage length: **100** hours to drain, clean, retrofill, and test transformer~~

~~Transformer replacement outage length: **720** hours~~

~~Value of energy: $**50**/megawatt hour (MWH) (present value)~~

~~Energy lost during retrofill outage: **6,000** MWH (assumes 60-percent load for 100 hours)~~

~~Energy lost during transformer replacement outage: **43,200** MWH (assumes 60-percent load for 720 hours)~~

~~Cost of ester-based fluid installed: $**15**/gallon.~~
~~Cost of disposal of mineral-based oil: $**3**/gallon~~

~~Cost of new transformer (present value): $**1** million (furnish and install)~~
~~Federal Discount Rate: **4** percent~~

~~Transformer maintenance cost with and without retrofill assumed to be about the same at **$10,000/**year.~~

~~Fire suppression system:~~

- ~~Rehabilitation cost: $**50,000** (rehabilitated at 10-year point)~~
- ~~Maintenance cost: $**15,000**/year~~

~~Note: For mineral-based oil, fire suppression rehabilitation is needed per NFPA recommendations. Fire suppression system is not needed for ester-based system.[6] Suppression system rehabilitation will take place at the 10-year point and again at the end of the 40-year life of the transformer.~~

---

[5] ~~Manufacturers predict a doubling of remaining life from point of retrofill (and five-fold life expectancy in new transformers) based on laboratory tests. Since there is no empirical evidence to support this prediction, this study assumes a much smaller increase in life expectancy.~~

[6] ~~Factory Mutual has stated that ester-based fluids are equivalent to fire suppression provided that minimum spacing is provided.~~

~~Barriers and Separation:~~

~~For purposes of this analysis, it is assumed that fire barriers or increased physical separation are not required for either ester- or mineral-based alternatives. However, it is likely that many mineral-based oil installations will require new barrier walls or increased separation to meet NFPA requirements. Costs for these items will increase the cost of the mineral-based alternative. Addition of barriers or increasing separation is extremely unlikely for the ester-based fluid alternative.~~

~~Containment System:~~

~~Rehabilitation cost: $**100,000** (rehabilitated at the 10-year point)~~

~~Maintenance cost: $**5,000**/year for rehabilitated system needed for mineral oil~~

~~Maintenance cost: $**2,000**/year for existing system sufficient for ester-based~~

~~***Note***: For mineral-based oil, containment must be sufficient for 100 percent of the transformer oil and 10 minutes of fire suppression water. For ester-based fluid, containment is required for transformer oil only; fire suppression water containment not needed nor included in cost estimate.~~

~~It is assumed for this study that the existing containment is sufficient for the ester-based transformer fluid but that extensive rehabilitation would be required for mineral-based oil and fire suppression water.~~

~~Environmental Risk:~~

~~For purposes of this study, an oil spill and resulting environmental cleanup costs are not considered. If an oil spill were to be included, the cost of mineral oil cleanup would be significantly higher than ester-based fluid.~~[7]

~~Analysis~~

~~All costs are shown in present value over a **50**-year-life cycle (to include extended life using ester-based fluid).~~

[7] ~~Ester-based fluids have been determined to be non-toxic and biodegradable. Although cleanup is required, waste is not considered toxic. Mineral oil is considered toxic and non-biodegradable.~~

~~Life-Cycle Cost for Mineral-Based Transformer~~		
~~Category~~	~~Cost of Action [dollars ($)]~~	~~Present Value ($)~~
~~Transformer replacement at 30 years~~	~~1,000,000~~	~~308,319~~
~~Replacement outage cost at 30 years~~	~~2,160,000~~	~~665,968~~
~~Transformer maintenance-annual~~	~~10,000~~	~~214,822~~
~~Fire suppression rehabilitation-current item~~	~~50,000~~	~~50,000~~
~~Fire suppression rehabilitation in 30 years~~	~~50,000~~	~~15,416~~
~~Fire suppression maintenance-annual~~	~~15,000~~	~~322,233~~
~~Containment system rehabilitation-current item~~	~~100,000~~	~~100,000~~
~~Containment system maintenance-annual~~	~~5,000~~	~~107,411~~
~~Retrofill oil installed~~	~~0~~	~~0~~
~~Mineral oil disposal at 30 years~~	~~30,000~~	~~9,250~~
~~Retrofill outage production~~	~~0~~	~~0~~
~~Total cost~~		**~~$1,793,418~~**

~~Life-Cycle Cost for Ester-Based Transformer Retrofill~~		
~~Category~~	~~Cost of Action ($)~~	~~Present Value ($)~~
~~Transformer replacement at 37.5 years~~	~~1,000,000~~	~~229,747~~
~~Replacement outage cost at 37.5 years~~	~~2,160,000~~	~~496,253~~
~~Transformer maintenance-annual~~	~~10,000~~	~~214,822~~
~~Fire suppression rehabilitation-current item~~	~~0~~	~~0~~
~~Fire suppression system maintenance~~	~~0~~	~~0~~
~~Containment system rehabilitation~~	~~0~~	~~0~~
~~Containment system maintenance-annual~~	~~2,000~~	~~42,964~~
~~Retrofill oil purchase~~	~~150,000~~	~~150,000~~
~~Retrofill disposal-current item~~	~~30,000~~	~~30,000~~
~~Retrofill outage lost production-current item~~	~~300,000~~	~~300,000~~
~~Total cost~~		**~~$1,463,787~~**

~~Comparison of Costs ($)~~	
~~Mineral-based oil transformer~~	~~1,793,418~~
~~Ester-based oil transformer~~	~~1,463,787~~
~~Benefit of ester-based oil transformer~~	~~329,631~~
~~Ratio of ester- to mineral-based oil (percent)~~	~~81.6~~

~~Conclusions~~

~~In this example, the net benefit (reduced cost) of retrofilling transformers based on this example is about $330,000.~~

~~Recommendations~~

~~Based on the assumptions in this example, it is cost effective to retrofill transformers with ester-based fluids. In addition, there are indirect benefits to the environment, safety, and security which are not given a monetary value.~~

~~While this example is based on the above assumptions, the outcome is not sensitive to the interest rate, length of time to replacement, or length of life cycle.~~

~~Increases in the interest rate reduce the difference between the costs of the two alternatives, but it would require large interest rates (around 60 percent) to make the two alternatives comparable in cost.~~

~~Based on these assumptions, the length of time to replacement does not affect the overall conclusion as the ester-based retrofill always will be less expensive. This is because the fire suppression rehabilitation and containment system rehabilitation costs are offset substantially by the retrofill installation costs. But, the fire suppression system maintenance and the containment system maintenance costs are greater in the mineral oil alternative. These costs will always lead to higher net costs for the mineral oil alternative.~~

~~The length of the life cycle slightly affects the net difference between the alternatives, but would not affect the overall conclusion. The difference between assuming a 50-year-life cycle versus a 40-year-life cycle is due primarily to the difference in maintenance costs of the two alternatives. The net difference between the two alternatives remains substantial in favor of the ester-based simulation.~~