

DESIGN AND PERFORMANCE EXPERIENCE OF FOUNDATIONS STABILIZED WITH THERMOSYPHONS

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Abstract

Stable, on-grade foundations for heated structures located on ice-rich permafrost are possible, if the top of the permafrost is maintained within a thaw-stable gravel fill placed below the structure's floor. ARCO Alaska, Inc. has had experience with twenty-nine passive subgrade-cooling systems at the Prudhoe Bay and Kuparuk oil fields on the North Slope of Alaska. The passively cooled foundations include new and retrofit installations. Twenty of these installations use a thermosyphon made by one manufacturer. The design and operational experience for several ARCO buildings, structures and heated tanks, using the thermosyphons from this manufacturer, are described.

Résumé

Il est possible d'établir des fondations stables d'édifices chauffés sur du pergélisol riche en glace à condition de maintenir le plafond du pergélisol dans un radier de gravier étendu sous le plancher de l'édifice. ARCO Alaska Inc. a acquis de l'expérience avec vingt-neuf systèmes passifs de refroidissement du sol de fondation à Prudhoe Bay et au champ pétrolier de Kuparuk sur le versant nord de l'Alaska. Certains équipement de refroidissement ont été implantés lors de la construction, d'autres à *posteriori*. Vingt de ces installations utilisent un modèle de thermosyphon acquis chez un seul manufacturier. Nous décrivons la conception et l'expérience acquise chez ARCO pour des bâtiments, des structures et des réservoirs chauffés, équipés de ce modèle de thermosyphon.

Introduction

The discovery of oil at Prudhoe Bay on the North Slope of Alaska created a need for support facilities for the development of North America's largest oil field. Because this area is underlain with continuous ice-rich "cold" permafrost, approximately 600 m (2,000 ft) thick, heated buildings required special foundation designs to avoid thaw of the ice rich soils and subsequent settlement. Two design techniques are commonly used to avoid this problem: (1) elevated pile foundations which isolate the building from the ground, or (2) subgrade cooling systems which limit heat transfer to the permafrost using subgrade cooling, insulation and NFS fill (Fig. 1). Cooling techniques for the latter method include active (mechanical refrigeration) and passive (air duct or thermosyphon) systems. Passive systems depend upon enough cooling of the NFS gravel fill below the building slab and insulation during the winter months so that summer thawing will not extend to the ice-rich permafrost. This paper will discuss the application of one manufacturer's thermosyphon to ARCO Alaska's passively cooled on-grade structures at Prudhoe Bay and the nearby Kuparuk River field.

Thermosyphons

A two-phase thermosyphon (often called "wickless heat pipe") consists of a sealed tube filled with a two-phase

working fluid. A portion of the fluid is in the liquid phase but most of it is in the vapor phase. If the lower end of the tube is heated, additional liquid will vaporize. If the upper end is cooled, a portion of the vapor will condense. This temperature difference sets up a pressure differential causing vapor to flow from the heated section to the cooled section. The liquid returns to the heated section by gravity flow. The continuous evaporation and condensation of the working fluid gives rise to a very high heat transfer rate. The McDonnell-Douglas "Cryo-Anchor" thermosyphons used in the applications described in this paper are charged with anhydrous ammonia as the working fluid.

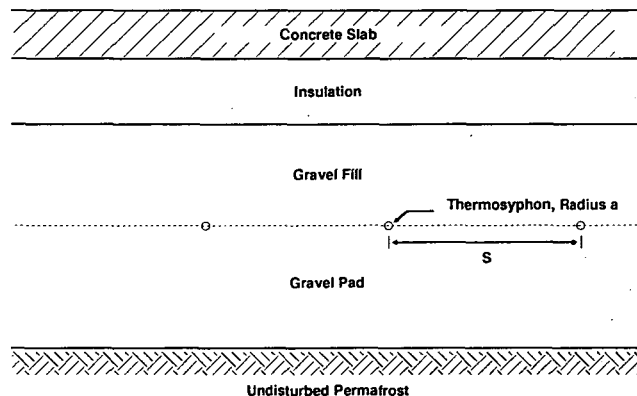


Figure 1. Sketch showing building foundation and thermosyphons.

The heat transfer rate of two-phase thermosyphons is a function of many variables. Vapor and liquid densities, specific heats and viscosities, liquid thermal conductivity, and heat of vaporization are the main working fluid variables affecting performance. Lengths of heated and cooled sections, tube diameter and material type, fin design, and material, installation slope and surface treatment are the variables associated with the vessel. When the thermosyphon is installed, the ambient temperature, wind speed and soil properties further determine the amount of heat transferred.

Haynes and Zarling (1988) have conducted performance tests on a McDonnell-Douglas "Cryo-Anchor" Model 800 thermosyphon. The tested unit is similar to those described in the case studies section of this paper. The McDonnell-Douglas thermosyphon is made of 38 mm (1.5 in) i.d. steel tubing with a 6 mm (0.25 in) wall thickness for the below-ground section and 19 mm (0.75 in) wall thickness for the above-ground section. Twenty extruded longitudinal aluminum fins form the radiator section. Each fin varies in thickness from 3.2 mm (0.125 in) at its root to 1.6 mm (0.062 in) at its tip, and extends outward 95 mm (3.75 in) from its root. The length of the fin is typically 1.8 m (6 ft). The extruded aluminum fin assembly is press-fitted onto the steel tube. A typical performance curve for a McDonnell-Douglas thermosyphon is presented in Figure 2. Shown is conductance as a function of wind speed for the evaporator section tilted at 0°, 3° and 6° from the horizontal. Conductance, the inverse of thermal resistance, includes the effects of tube wall, properties of the working fluid, and the convective and radiation resistances at the fin surface.

ON-GRADE FOUNDATIONS

On-grade foundations built over ice rich permafrost require three key elements: insulation, a cooling system, and nonfrost susceptible gravel fill. The performance of the foundation system depends on the insulation's thermal resistance; thermosyphon conductance, horizontal spacing and vertical placement; indoor temperature and climatic conditions; and the gravel fill's moisture content, dry density

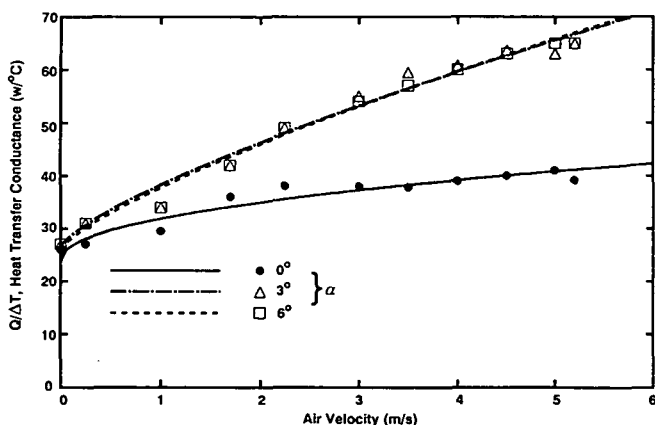


Figure 2. Heat transfer conductance of mcdonnell-douglas thermosyphon with evaporator section tilted at 0° to 6° from horizontal.

and thickness. A given combination of these parameters, which restricts the annual cyclic freezing and thawing zone to the gravel fill, can be viewed as a successful design.

Thermal analysis

The symmetrical distribution of thermosyphons below a building's floor allows the thermal domain to be reduced to a two-dimensional strip. Vertical boundaries of the strip represent lines of symmetry and, as such, experience zero heat flow. One vertical edge of the strip is centered on a thermosyphon and the other edge is defined as the midline between adjacent thermosyphons. The boundary condition at the top of the strip is a prescribed surface or air temperature, and the boundary condition along the bottom is specified either as a uniform temperature or temperature gradient.

During the summer months, thermal energy from the building flows through the floor and insulation, and warms and thaws the gravel fill. With the commencement of winter, the thermosyphons become operational, refreezing the thawed gravel fill and cooling the subgrade materials as well as intercepting the heat from the floor. Two thermal design approaches are commonly used to design on-grade foundation systems: quasi-steady or transient analysis.

A quasi-steady analysis first requires estimating the design thaw season length and index for the building air or floor. These data are then used to determine the minimum gravel fill and insulation thickness required to contain the active layer. Next, the heat flow rate from the slab and the subgrade is estimated. The quantity of thermal energy needed to be removed to refreeze the gravel fill is calculated. These three thermal loads are then used to determine the size and spacing of the thermosyphons. Larger spacing yields higher thermal loads requiring increased conductance or larger thermosyphons.

A transient analysis, using two-dimensional finite difference or finite element computer programs, can be used to improve the precision of the design. The previously described strip is divided into elements with a node along the strip boundary in the gravel fill specified as a heat extraction node or the thermosyphon. A conductance is specified for the thermosyphon and the simulation is run for several years to attain a periodic steady-state condition. The winter ambient outdoor temperature serves as the heat sink for the thermosyphon. An acceptable design is one in which the thaw front does not penetrate beyond the base of the gravel fill.

THERMOSYPHON INSTALLATIONS ON THE NORTH SLOPE

Thermosyphons have been installed at some 25 facilities built on-grade in the Prudhoe Bay and Kuparuk oil fields on Alaska's North Slope during the last ten years. The installations, which total about 28,000 m² (300,000 sq ft) in area, include mostly new buildings and retrofits of existing buildings up to 2,500 m² (27,000 sq ft) in size. More recently, thermosyphons have been used to stabilize the

foundations below four new tanks that store hot crude oil. The authors have participated in most of these installations which have generally performed well. The use of thermosyphons, where appropriate, has resulted in significant cost savings over conventional pile-supported structures. Eighteen of the 25 installations use McDonnell-Douglas "Cryo-Anchor" (nearly all Model 800) thermosyphons, Table I. Figure 3 shows a typical installation detail for new construction.

Three varied installations will be described briefly: a retrofit application (U9A Utility Building), a new building (CPF-3 Work Area/Office Building), and new hot-oil storage tanks (CPF-1 and CPF-2 Divert Tanks). In addition, several performance problems encountered among the installations will be discussed.

U9A UTILITY BUILDING

The U9A Utility Building is located on a 1.5 m (5 ft) gravel pad behind ARCO's Main Construction Camp at Prudhoe Bay. It is one of twenty buildings constructed in 1976 to support construction of the original oil production facilities. The structure, measuring 18.3 m by 48.8 m (60 ft by 160 ft) with 6.1 m (20 ft) eaves, consists of a rigid-frame, pre-engineered metal building supported by a 0.5 m by 0.6 m (1.7 ft by 2 ft) perimeter concrete grade beam, which in turn rests on timber piles slurried about 6.1 m (20 ft) into permafrost. The grade beam and piles also support a large overhead crane. Originally, gravel covered about 60% of the building floor area with the remainder covered by a concrete slab underlain by 50 mm (2 in) of urethane insulation buried in the 1.3 m (4.3 ft) thick gravel fill.

No subgrade cooling system was installed because the building was designed for a life span of three years and an

Table I. Summary of prudhoe and kuparuk structures with subgrade cooling systems using mcdonnell-douglas thermosyphons. structure location category.

Heavy Equipment Storage Building	Prudhoe	New
Field Exploratory Warehouse	Prudhoe	New
U-5A	Prudhoe	New
Communications Module Parking Garage	Prudhoe	New
Co-User Camp Firewater Tank Building	Prudhoe	New
Co-User Camp Elevator Area	Prudhoe	New
C Pad Warehouse Addition	Prudhoe	New
U-4B	Prudhoe	Retrofit
U-7	Prudhoe	Retrofit
U-8	Prudhoe	Retrofit
U-9	Prudhoe	Retrofit
U-13	Prudhoe	Retrofit
U-14	Prudhoe	Retrofit
C & D Warehouse	Kuparuk	New
CPF-3 Work Area/Office Building	Kuparuk	New
Fire Station	Kuparuk	New
Olitok Point STP Shop	Kuparuk	New
CPF-1 Divert Tanks	Kuparuk	New
CPF-2 Divert Tanks	Kuparuk	New
Kuparuk River Bridge	Kuparuk	New

interior temperature of 4.4 °C (40 °F). By 1982, however, the building was still being used for its original purpose, pipe fabrication, and the interior temperature had been kept at 21 °C (70 °F) and above for some time. Parts of the floor had subsided up to 0.6 m (2 ft) and the thaw depth had reached 4.0 m (13 ft) in the center of the building. A further problem was poor drainage of the gravel pad surrounding the building. During spring and summer, the floor was often covered with several centimeters of water.

In late 1982, a decision was made to retrofit the building with thermosyphons and extruded polystyrene insulation. The design was based upon a finite-element thermal model analysis. During February - March, 1983, the concrete slab and insulation, which had deteriorated mostly to a pulp, were removed. The excavation was dry, requiring no stabilization of the working surface. The subgrade was excavated and 22 thermosyphons with a nominal 1.8 m (6 ft) radiator section and 19 m (63 ft) length were placed in the bottom of the excavation spaced 3 m (10 ft) on center at a slope of 6°, followed by gravel backfill and 200 mm (8 in) of extruded polystyrene insulation.

The thermal model had predicted that refreezing the existing thaw bulb would take two years; however, it required only two months based on recorded thermocouple temperature measurements. The difference was attributed to the model not considering low interior temperatures during the two-month construction period and to the manufacturer's conservative rating of the thermosyphon conductance. In general, the published values of differential temperature versus heat removal for these units appear to be minimums. Actual ground temperature data from other ARCO Alaska installations indicate that thermal models using published performance values will tend to predict warmer ground temperatures than actually occur.

The building has been used heavily for over six years since the retrofit, with the subgrade cooling system performing better than predicted. Measured floor temperatures have been 10 °C (50 °F) during that time. The greatest recorded summer thaw depth was 1.4 m (4.5 ft), still within the gravel pad. Within two months of fall freeze-up each year, the gravel pad below the insulation is completely frozen. No elevation changes in the new gravel floor have been detected; infrared thermal monitoring of the radiators has shown that the thermosyphons are working well, with no detectable problems.

CPF-3 WORK AREA/OFFICE BUILDING

The CPF-3 Work Area/Office Building is a support building attached to a major production facility at the Kuparuk oil field. It consists of a shop area with overhead cranes, a drive-in bay, and offices, totalling 1,600 m² (17,000 sq ft). The 24.4 m x 30.5 m (80 ft x 100 ft) building (Fig. 4) is a pre-engineered steel structure with insulated metal panels. It is located on a 1.5 m (5 ft) gravel pad overlying the tundra mat and ice-rich permafrost. Its subgrade cooling system consists of 18 thermosyphons 13.7 m (45 ft) long spaced 3.7 m (12 ft) on center at a 6°

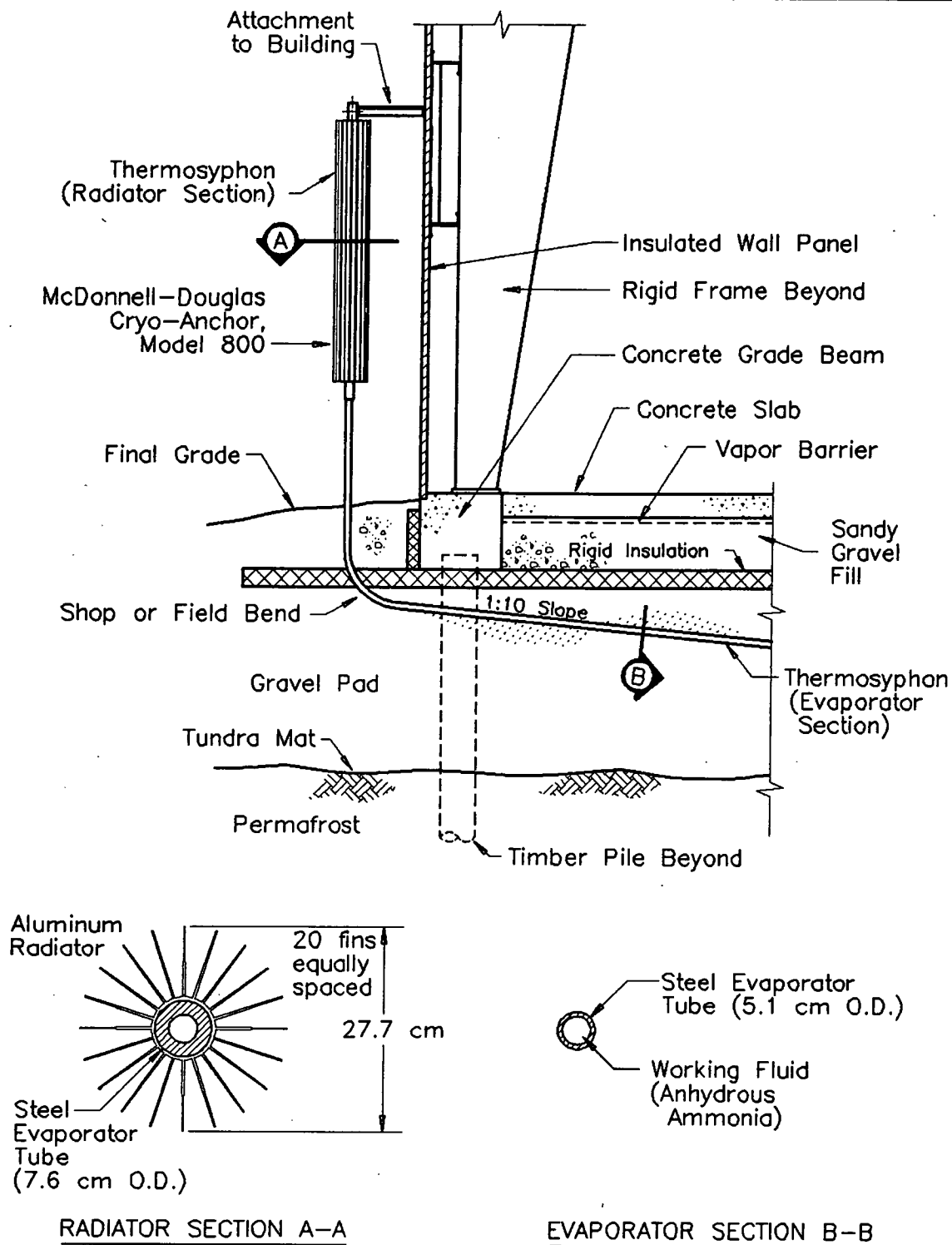


FIGURE 3. TYPICAL THERMOSYPHON INSTALLATION
FOR NEW CONSTRUCTION
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Figure 3. Typical thermosyphon installation for new construction.

slope. Rigid plastic foam insulation of 150 mm (6 in) thickness was installed below the floor.

The unusual aspect of the building design is that half the building consists of high-quality office space, which is susceptible to damage if the slab moves. The use of thermosyphons for this office building is different than most other applications, which generally consist of warehouses, garages and other open-bay buildings which will not suffer distress from minor movements of the slab or gravel floor should frost heaving or thaw settlement occur.

This building was completed in 1986 and has been in service for over three years with no detectable subsidence. During winter, the slab heaves up to 6 mm (1/4 in); however, the building was constructed with extensive architectural expansion joints that have worked as designed to accommodate differential movement. No cracks have been detected to date in any drywall or other architectural finishes.

CPF-1 AND CPF-2 DIVERT TANKS

Four insulated steel tanks were constructed at Kuparuk during 1986 for temporary storage of crude oil maintained at 54 °C (130 °F), with temperature excursions to 74 °C (165 °F). The four identical 8,900 cubic meter (56,000 bbl) tanks, each 30 m (100 ft) in diameter by 12.2 m (40 ft) high (Fig. 5), are located at two different production facilities. The walls of each tank are located on a 0.6 m x 0.9 m (2 ft by 3 ft) concrete ring foundation. The tank center is supported by a gravel pad. There are no piles. The gravel pad below the tank was raised 3.3 m (11 ft) above the existing 1.5 m (5 ft) thick gravel pad. Each tank has 20 thermosyphons spaced 2.4 m (8 ft) on center at a slope of 6° and about 0.3 m (12 in) of extruded polystyrene insulation. Because of the critical nature of the storage tanks, the thermosyphon design assumed that every other thermosyphon would fail, providing an additional safety factor.

The tanks have been in service for over three years, with no problems due to subsidence. An extensive survey was performed to detect movement as small as 0.3 mm (0.001 ft)



Figure 4. Cpf-3 work area/office building (thermosyphons are not visible).

or less in the tank rings. It was found that movement due to seasonal freezing and thawing occurs, but was limited to 3 mm (0.125 in), an insignificant amount. The only problem noted has been "cold-topping" of the thermosyphons at both CPF-1 tanks. This condition lowers conductance, which is caused by an accumulation of noncondensable gas in the radiator section of the thermosyphons. The identical CPF-2 tanks, which use thermosyphons from the same production run and were installed at the same time, have shown no indication of cold-topping to date. It is anticipated that cold-topping will likely occur at CPF-2 as well.

Special problems

Of 18 McDonnell-Douglas thermosyphon installations, only three have experienced detectable problems. Some practical lessons can be learned from these problems.

The first of two buildings to suffer any subsidence was the Heavy Equipment Storage Building at Prudhoe Bay. This building, built in 1981, was among the first thermosyphon installations. It contains a 460 m² (5,000 sq ft) shop with a concrete slab, and a 2,000 m² (22,000 sq ft) garage area with a gravel floor. By 1986, a 370 m² (4,000 sq ft) gravel floor area at one end of the garage had subsided nearly one

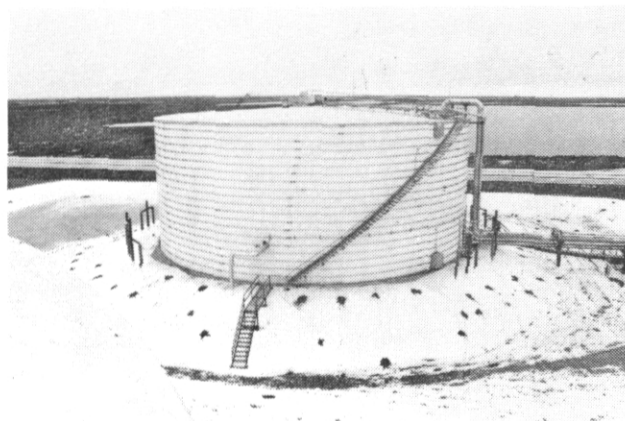


Figure 5. Divert tank with thermosyphons and supports shown.

meter but the building itself was not affected because it was supported by a grade beam resting on piles. The subsidence was attributed to a combination of: 1) water in the gravel pad absorbed by the installed expanded polystyrene insulation caused a loss of thermal resistance or R value; 2) the thermosyphons were less effective because they were installed in diesel-filled sleeves (to allow removal of defective thermosyphons); and 3) deleterious material in the gravel pad as a result of earlier activities. The problem was repaired by overexcavating the deleterious material, replacing gravel fill and extruded polystyrene insulation, and reburying the thermosyphons without the sleeves. Since the 1986 repairs, the floor has been stable.

The second building to experience subsidence was the U5A Warehouse at Prudhoe Bay. Like the previous building, U5A was among the first thermosyphon installations in 1981. The building is 24.4 m by 76.2 m (80 ft by 250 ft) in size and contains a concrete slab added in 1984. By early 1989, the slab had subsided up to 0.3 m (1 ft) in places but the building itself was not affected because of its pile supported grade beam foundation. The cause of subsidence is still under investigation, but may be due to: 1) shallow water in the gravel pad being absorbed by the inferior insulation installed, causing a loss of thermal resistance, or R value; 2) watering of the gravel floor for dust control before 1984 causing the same effect; 3) the thermosyphons not being effective because the diesel-filled sleeves leaked at the end caps; and 4) the thermosyphons working at a lower efficiency because of the diesel oil's lower conductance. Repairs to the slab and subgrade repair system are scheduled for 1989 - 1990.

Besides subsidence, the second problem has been cold-topping of the thermosyphons at the CPF-1 Divert Tanks. The presence of cold-topping at one site suggests that the source of the noncondensable gas is the surrounding soil.

The presence of hydrogen, the suspected gas, may be a by-product of exterior corrosion. It is hypothesized that the hydrogen diffuses through the steel pipe wall of the thermosyphon and collects in the condenser (radiator) section as a noncondensable gas. The thermosyphons for this installation were not coated or otherwise protected against corrosion, although many other installations were. Future thermosyphons will likely be coated prior to installation to reduce the likelihood of cold-topping. In the past, a zinc rich primer coat with an epoxy top coat has been used.

These cases lead to the following recommendations:

- Design the building's floor to be .6 m - .9 m (2-3 feet) above the surrounding gravel pad so that the buried insulation remains dry.
- Use only extruded polystyrene insulation, not expanded polystyrene "beadboard" or urethane which may absorb water and disintegrate.
- Protect units against corrosion with proper coatings.
- Coat the thermosyphons and avoid making metal-to-metal contact which could allow galvanic action.
- Direct-bury the thermosyphons in the gravel pad for higher performance, without the use of sleeves.

Research recommendations

Areas of research suggested to improve the design and performance of thermosyphon stabilized foundations are:

- Cause(s) of and retrofit(s) for cold-topping of thermosyphons.
- Effect of evaporator installation angle on performance.
- Detailed comparisons of design versus field performance of thermosyphon stabilized foundations.

References

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