New Seawater Delivery Systems at the Natural Energy Laboratory of Hawaii

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ABSTRACT

The 30-cm diameter deep seawater supply system ("The 12-in System") at the Natural Energy Laboratory of Hawaii (NELH) at Keahole Point has been operating continuously since August 1982. The commercial potential of many projects which have used the cold, nutrient rich, clean seawater for research and demonstration projects at NELH has led to the installation of four new deep seawater systems since June 1987. Ocean Farms Hawaii (OFH - formerly Hawaiian Abalone Farms) has deployed two 38-cm pipelines, the State of Hawaii has deployed a 45-cm backup pipeline, and a 1-m pipeline now serves both the State's Hawaii Ocean Science and Technology (HOST) Park adjacent to NELH, and ocean thermal energy conversion (OTEC) research sponsored at NELH's Seacoast Test Facility (STF) by the U. S. Department of Energy (DOE) and the Pacific International Center for High Technology Research (PICHTR). This last system also includes a surface seawater supply for the OTEC research. All of the deep systems supply seawater through high density polyethylene (HDPE) pipe from approximately 600 m depth. Various design options have been employed for the pipeline deployments and for the pumping systems. These new systems bring the total deep seawater supply capacity at Keahole Point to about 1.3 m^3/s and the surface supply capacity to about .71 m^3/s.

The deep seawater is used for a wide range of projects, including closed- and open-cycle OTEC research; aquaculture of abalone, nori (the seaweed used for wrapping Japanese sushi), microalgae, Maine lobster, salmon, oysters, sea urchins, flounder, and opihi; air conditioning of laboratory buildings; production of cold freshwater condensate for temperate climate agriculture (e.g. strawberries, asparagus and alstroemeria flowers) in the tropics; and industrial process cooling.

INTRODUCTION

The Natural Energy Laboratory of Hawaii (NELH) at Keahole Point on the western coast of "The Big Island" of Hawaii has been pumping cold seawater ashore from 600 m depth since 1982. The deep water and warm surface water are being used for research and development of Ocean Thermal Energy Conversion (OTEC) and related technologies. From August 1982 until August 1987, a maximum of 0.069 m^3/s of cold deep seawater was pumped ashore through a 30 cm diameter pipeline installed by the State of Hawaii for aquaculture research.

Many useful results have been obtained using the water from this "12-in pipeline", which has been the only continuous source of deep seawater.

Since June of 1987, four new deep seawater pipelines have been deployed at NELH (Table 1, Fig. 1), each extending to approximately the same 600-m depth. Two of these were deployed by a private company, Hawaiian Abalone Farms (now Ocean Farms of Hawaii) which leases land and facilities from the State-owned NELH; one pipeline was deployed by the State of Hawaii as a backup to existing systems; and the largest pipe was deployed through a cooperative agreement between the State of Hawaii's new Hawaii Ocean Science and Technology (HOST) Park, the Federal Department of Energy (DOE) and the Pacific International Center for High Technology Research (PICHTR), a non-profit corporation founded by the State of Hawaii and funded by State, Federal and foreign sponsors to promote the development of appropriate technology for the Pacific island and Pacific rim nations. The DOE/PICHTR portion of this last system is part of the DOE's Seacoast Test Facility (STF) at NELH, and it also includes a new surface seawater supply.

At the end of 1988, negotiations are underway to combine administration of all of these pipelines under a new Keahole Point Ocean Development Authority which will oversee the operations of NELH and the adjacent Hawaii Ocean Science and Technology (HOST) Park.

The NELH 12-in Pipeline

The State of Hawaii deployed a 1.7 km long, 30-cm diameter deep seawater pipeline at NELH in December 1981. This unique system (9) has provided a continuous flow of cold seawater from a 600 m depth since it became operational in August 1982. The water has served a wide variety of research and development projects to be discussed below.

The 12-in pipeline design (Fig. 1), prepared by Makai Ocean Engineering, Inc. (MOE) of Waimanalo on the island of Oahu, incorporates a unique buoyant catenary to avoid the rough bathymetry which exists below the 160 m depth off Keahole Point. The high density polyethylene pipeline (HDPE) material is slightly buoyant in seawater and very strong and resilient, but also subject to abrasion. The nearshore pipeline section, to about 20 m depth, is fastened to the bottom using various clamps bolted to the basalt rock bottom. From 20-m to 160-m depth, 136 concrete anchors, each weighing about 225 kg are strapped to the pipe at 3-m to 5.5-m intervals and hold it securely about 30 cm off the bottom. Just below the "transition point" at 160 m depth, a series of wire pendants from a chain along the bottom serves as a strain relief, absorbing the large stresses on the pipe caused by currents acting on the 873-m long catenary section. The bottom of the catenary is fastened through a nylon bridle to two surplus 1360 kg danforth anchors.

The pipeline was assembled in two sections at Kawaihae Harbor, about 50 km north of Keahole Point. The concrete anchors were strapped to the nearshore section of the pipe which was pressurized with air and floated for towing to the deployment site. The nearshore end was chained to the bottom and a tug at the offshore end pulled the pipe section into position. Seawater pumped into the nearshore end then submerged the pipe progressively farther from shore. Regulation of the pumping rate allowed control of the submergence rate, while the tug offshore maintained sufficient tension to prevent the pipe from buckling. This nearshore section of the offshore pipe included a portion of the buoyant catenary, so that the offshore end was on the surface when the transition section was correctly deployed on the bottom. The second phase of the deployment (designed to be done at a later date in case weather changes made continuous operations impossible) involved towing the offshore pipe section from Kawaihae, flanging its nearshore end to the installed nearshore pipe section and lowering the bottom anchors to properly position the catenary. Since the inter-anchor distance between the two ends of the catenary was critical to the design, a wire rope was strung along the bottom from the transition anchor to the end anchors. The tug was required to keep this wire taught while lowering the bottom anchors.

Though this system was only designed as an interim pipeline to serve until a permanent line could be installed, it has far exceeded its initial two year design life. Even though the winch on the tug failed and was unable to keep the bottom inter-anchor wire taught so that the end anchor was deployed inshore of its intended position, the offshore portion has experienced no apparent degradation or damage. Though submersible observations have shown that a progressively larger number of the anchors above the transition point have lifted off the bottom as the slack inter-anchor wire has gradually been pulled upslope (six of the anchors were off the bottom in December 1987), these configuration changes have not compromised pipeline operations.

The portion of this pipeline between the shoreline and about 20 m depth has suffered significant wave damage several times. The original design called for the pipe to be anchored at approximately 3 m intervals by two 2.5 cm diameter "all-thread" galvanized steel rods epoxied into the basalt bottom and fastened to the pipe with galvanized steel saddles. In practice, the continuous water motion at the site washed away the concrete sacks specified to provide lateral stability at these anchor points before the cement could cure. Wave action has then caused fatigue failure of the all--thread rods, so that the steel anchoring system has failed several times even though the resilient polyethylene pipe has remained intact. A major redesign and rerouting of the nearshore portion of the pipeline in 1986 incorporates a new anchoring design (Fig. 2), which appears much better suited to the rigorous wave environment in the nearshore zone.

The initial design for the pumping system proposed that the pumps be submerged in a sump onshore. This would provide access to the pumps for maintenance while also providing the static head needed to overcome the positive suction head due to the length of intake pipe required to reach the deep water. The pipeline would have to be well below sealevel over the approach to this sump, necessitating a trench through the shoreline area to the sump. The trench, however, made the cost of such a design prohibitive.

The pumps for this pipeline are, therefore, placed about 30 m offshore at a depth of about 8 m. Three 15-hp submersible, in-line, axial turbine centrifugal pumps, arranged in parallel push up to 0.069 m^3/s to a total delivery head of 16 m. The pumps and electrical connections must be serviced by divers, and such service is only possible during suitable wave conditions. An average of 20-30 days per year have proven unsuitable for safe maintenance operations (Daniel, 1986).

The electrical cables to the pumps were initially routed through a PVC conduit which was quickly destroyed by the waves. Armored cables were then run individually from shore through the surf zone to the pumps. As the initial military surplus armored cables failed due to the pounding surf, they were replaced by a specially designed cable housing the three conductors and ground in a caged armor, the interstices of which were filled with a flexible polymer. Though these special armored cables lasted longer - 12-18 months - they too eventually failed. Initial designs called for connecting the cables to the pumps through permanent splices to be created on a boat anchored over the pump station. The usual rough conditions at the site and the frequency of pump changeouts necessitated by submersible motor failures made such splices impractical, so underwater pluggable connectors have been used.

A 4-in steel conduit, designed to contain three active electrical cables and a spare, was installed through the surf zone when the nearshore portion of the pipeline was upgraded in 1986, but this broke at the shoreline during relatively small waves in November 1988. The cables have now been routed from the shoreline to the pumps through the 12-in coldwater pipe itself.

Ocean Farms Hawaii Cold Water Pipelines

Ocean Farms Hawaii (OFH), formerly known as Hawaiian Abalone Farms, was one of the first users of the deep seawater from the NELH 12-in pipeline. The company soon found that the cold seawater from 600-m depth was ideally suited for the culture of abalone and the kelp on which these marine mollusks thrive. They immediately began planning to install their own deep seawater pipelines to serve their anticipated commercial expansion.

The company has developed a unique pipeline design. The high density polyethylene pipeline is welded together into one piece and placed on rollers along the one-mile portion of the NELH access road which parallels the ocean. Hydraulic driver and brake units, manufactured on site from scrap automobile wheel assemblies, control the pipe motion as it rolls into the ocean where it is positioned by a small fleet of fishing boats. A sleeve of epoxy-coated expanded metal, placed around the pipe during its assembly along the road, provides both anchoring weight and abrasion protection for the polyethylene. This sleeve is continuous throughout the nearshore zone and distributed as needed for anchoring weight in the deeper portions. The pipeline, with anchoring sleeve attached, passes easily over the rollers and through the driver and braking units. It is pressurized and floated into position, then flooded from the nearshore end so that it sinks progressively to the bottom. The design utilizes in-line submersible pumps similar to the 12-in system.

This design has some significant cost advantages over the buoyant catenary design of the 12-in system described earlier. First, the assembly on land at the deployment site reduces costs and logistics difficulties inherent in the alternative of assembly in the protected harbor at Kawaihae. Second, the need for large deployment vessels is obviated by avoiding the buoyant catenary and the large anchors which it requires.

Disadvantages include the requirement for moderate weather and currents throughout the deployment because the procedure cannot be reversed once it is started, and the significant potential for pipeline abrasion or damage inherent in laying the pipe directly on a rough steeply-sloping bottom. This latter impact may adversely affect the pipe's lifetime, but the cost savings noted above may more than offset this factor.

NELH 18-in Backup Pipeline

Following the large waves which demonstrated the fragility of the single 12-in pipeline in February 1986, the Hawaii State legislature appropriated funds for a backup deep water pipeline at NELH. The selected design (Fig. 3) represents a compromise between the buoyant catenary and the bottom deployment scheme developed by Ocean Farms Hawaii. It incorporates the logistics and cost savings inherent in on-site assembly and deployment with small vessels, while reducing the potential problems of abrasion from contact with the bottom.

The design, developed by Makai Ocean Engineering, uses multiple "pendant weights" distributed along the pipeline below the 160 m dropoff depth. As in the 12-in design discussed above, concrete anchors mounted on the pipe hold it near but clear of the bottom in the portion from 20 m depth to the 160 m dropoff depth. For deployment, an assembly line system with dollies on tracks permitted installation of the 85 727-kg concrete clamp-on anchors on the pipeline as it passed the shoreline off of the OFH roller system. The eleven 568-kg and 27 273-kg pendant weights were hung from coiled cables beneath the pipeline until the whole line was floating on the sea surface. Divers then cut the temporary ties, leaving the pendant weights supported at their design positions below the pipe by individual pendants and the preinstalled inter-anchor connecting wire.

This design required only a medium sized tug at the offshore end to maintain proper position. The on-site assembly reduced the required time and simplified the deployment logistics. The pendant-weighted design of the lower section keeps the pipeline well clear of the bottom and whatever obstacles it contains, while also significantly reducing the current loads along its length and distributing the weight required to keep it in place against those loads. On the other hand, weather and current constraints are also critical during this type of deployment, as noted above for the OFH design.

The pumps for this system are deployed offshore at 8.5 m depth. The electrical cables from shore to the pumps are routed through the seawater pipe itself, utilizing the system designed to protect the pipeline through the shoreline and the surf zone. This eliminates the need for armored cables or conduits through the surf zone, which has turned out to be the weakest link in our six years of experience with the 12-in system. The pump station itself, with four active pumps and one standby pump arranged in parallel, uses 45 degree angles throughout to reduce hydrodynamic losses. This proved to be no more costly nor difficult to manufacture or install than the right angle design used for the 12-in and the OFH systems, yet it appears that it will significantly increase pumping efficiency.

The 40-in Pipeline

Both the State of Hawaii and the Federal Department of Energy planned to install new deep seawater pipelines in 1986. The State's High Technology Development Corporation (HTDC) had contracted with Makai Ocean Engineering for the design of a 75-cm line to provide approximately 0.41 m^3/s to the new Hawaii Ocean Science and Technology (HOST) Park, a state-sponsored "high-tech" park designed to provide infrastructure for the nearby commercial expansion of successful research projects at NELH. The DOE had contracted with Gibbs and Cox for the design of a "Seacoast Test Facility Upgrade" which incorporated a very similar pipeline to provide approximately 0.42 m^3/s cold water for their planned open-cycle OTEC experiments, and in January 1986, they had selected a contractor and were negotiating the deployment contract.

Following passage of the Gramm-Rudman Act, the DOE modified their plans and negotiated an agreement with the State for the design and construction of a larger 1.0-m diameter pipeline to meet the needs of both projects. The Pacific International Center for High Technology Research (PICHTR) has also participated with DOE in the project, which is now referred to as either "the 40-in system" or "the STF System". The re-design process delayed construction until the summer of 1987, but the new design otherwise meets the requirements of all three sponsors. R.M. Towill Corporation of Honolulu, the designer of the HOST Park, designed the pumping and onshore delivery systems and MOE again designed the offshore pipeline and its installation (R. M. Towill Corp., 1986; Lewis et al., 1988).

The design (Fig. 5) incorporates a buoyant catenary very similar to the 12-in pipeline and features the first onshore deep water pumping system at Keahole Point. The pipeline deployment contractor, Kiewit Pacific, used a large tug at the offshore end and a 300,000-kg capacity barge-mounted crane for deploying the 62,500 kg (dry-weight) transition anchor at the top of the catenary. The original design used a heavy (1 5/8-in) chain from the transition anchor to absorb the current- and buoyancy-induced stresses on the pipeline. The bottom anchor was, however, deployed about 37 m downslope from the design position. This changed the shape of the catenary so that the bridle designed to take the load (b in Fig. 5c) is slack and the transition stresses are taken by two smaller bridles (c and d in Fig. 5c) which had been designed to handle loads during installation. Subsequent analysis has indicated that, if cathodic protection can be maintained on the smaller (1-in) chains of bridles c & d, the deployed configuration will provide adequate strain relief to achieve the 10 year design lifetime for the HDPE pipeline.

The 40-in coldwater pipeline, along with a 71-cm diameter HDPE warm water pipeline and several other conduits, comes through the surf zone in a trench blasted out of the rock bottom to a minimum depth of 6 m below mean sea level. Construction of this trench and the onshore pump station required substantial environmental analysis because of its potential significant impact on the shoreline and the nearshore zone. The analysis clearly indicated the desirability of minimizing the number of such trenches, so as many conduits as feasible were run through the trench before it was backfilled.

The pump station (Fig. 6), located approximately 70 m from the shoreline, contains 12 pumps in two sumps. The two deep seawater pumping systems use a 10.8 m X 4.3 m X 7.5 m deep chamber containing the five HOST Park high head 66 kW (88 hp) pumps designed to provide 0.43 m^3/s through a 3.3 km long, 60-cm diameter delivery line to HOST Park projects at elevations up to 26 m above sea level.

The same sump contains three STF low-head, high volume pumps to provide 0.41 m^3/s for planned open-cycle OTEC experiments in the NELH experimental area near sea level. A 71 cm diameter surface seawater pipeline with its intake about 122 m offshore at 20 m depth supplies the adjacent 6.7 m X 4.3 m X 6.6 m deep warm water sump which contains four STF low head pumps delivering about 0.61 m^3/s warm surface water to the laboratory for OC-OTEC experiments. Cold water pump intakes are located 4.6 m and warm water 3.5 m below mean sea level reference. The pump station was poured in place and sealed on the inside with "Amerlock T-Lock" PVC liner. The surrounding area and the intake trench were backfilled, leaving a level concrete surface at approximately the original grade through the shoreline and surrounding the subterranean pump station.

Onshore Piping Systems

All of the seawater supply systems described above are interconnected to assure redundancy in case any one of them fails. Figure 7, prepared by Makai Ocean Engineering, shows the present seawater supply systems at Keahole Point. Figure 8 schematically indicates the interconnections between these systems and the distribution to the various projects.

The 3.3 km long 60 cm diameter HOST Park delivery line runs half-buried along the NELH access road to the highway. Original construction included several T-connection points for users along the route and a disposal trench at the 26 m top elevation of the pipeline. Additional interconnections are being installed for various existing projects along the NELH portion of the route.

The 18-in pipeline plans include a 45-cm delivery pipeline running back along the access road approximately 800 m to the NELH experimental compound. To allow use of seawater from that system while funding is being obtained for the delivery line, the pipeline has been connected into the 60-cm HOST Park delivery line. The 18-in system can thus provide water backwards to the NELH compound or up to about 10 m height along the HOST delivery line if required in an emergency. In late 1988, the system contains only one pump, with another on standby, which operates from a portable generator. Power directly from a new utility substation is scheduled to become available in March 1989, and plans are underway to connect all five pumps into a permanent power supply soon after.

Ocean Farms Hawaii has installed an interconnection between their two pipelines and the 60-cm HOST Park delivery line, and they are now receiving water pumped by the STF low head deep water pumps through the crossover from that system to the HOST system. A similar crossover to the NELH 12-in system header tanks has allowed for the continuous flow of water to all laboratory projects throughout the disruption of 12-in pumping caused by the recent destruction of the conduit discussed earlier.

Operational Experience

As noted above, the 12-in pipeline has operated continuously since August, 1982 (Daniel, 1986). The two Ocean Farms Hawaii pipelines have been operating since early 1988, though both have produced less than design flow due to partial collapse of the pipelines from suction pressure on the intake side of the pumps. The 18-in pipeline has operated intermittently, as described above, since its dedication in June of 1988, and the 40-in pipeline has operated continuously since its acceptance the same month.

All of the pipelines at NELH except the 18-in have had problems with submersible pump motors operating in seawater. As described in Daniel (1986), there has been a long history of various modes of failure of the 15 hp submersible motors in the 12-in system. Ocean Farms Hawaii is having similar problems in the fall of 1988, with the successive catastrophic failure of all ten of the pump motors on their two pipelines. As was the case with similar motors in the 12-in system, several different failure modes have been indicated.

The manufacturer now plans to redesign the motors for this seawater application.

In spite of our operational difficulties with submersible motors, cost and reliability considerations led the designers of the 40-in pumping system (R. M. Towill Corp., 1986) to incorporate submersible pumps and motors in that system as well. In late 1988, severe corrosion problems have developed in the large submersible pumps and motors after less than six months of operation. It appears that stray electric currents in the sump may be responsible, and a possible solution may be to change to a dry sump configuration to get the pump and motor housings out of the water.

Uses for the Seawater

Since the initiation of pumping in August 1982, NELH has provided and continues to provide cold deep seawater and warm surface seawater to a large variety of projects (Daniel, 1984, 1985; Penney and Daniel, 1988; Fast and Tanouye, 1988).

The Department of Energy has sponsored both closed- and open- cycle OTEC research projects which have provided data for OTEC plant designs. Biofouling and corrosion studies have shown that: 1) there is no appreciable biofouling in heat exchanger tubes through which deep seawater flows (Larsen-Basse and Daniel, 1983; Panchal et al., 1984), 2) the biofouling in tubes carrying tropical surface water can be easily controlled by small and environmentally-acceptable levels of electrolyticallygenerated chlorine (Berger and Berger, 1986; Sansone and Kearney, 1985), and 3) pitting corrosion is not a problem for tropical surface seawater flow through tubes made from a wide variety of aluminum alloys (Larsen-Basse, 1983; Larsne-Basse and Jain, 1986).

Open-cycle experiments have shown that the heat and mass transfer characteristics of seawater at the low temperatures and pressures of the open-cycle process are similar to those measured for fresh water (Larsen-Basse et al., 1986; Link, 1989). Krock and Zapka (1986) showed that dissolved gases are removed more easily from seawater than from freshwater, and Rabas et al. (1989) have evaluated the importance of this discovery. Mist-lift experiments (Lee and Ridgway, 1983; Ri9dgway, 1984) have demonstrated that the suspended particle distribution in natural seawater will allow continuous generation of a fine mist with droplet diameters of about 200 microns and that the coupling between that mist and a rising water vapor stream will provide the lift predicted earlier by Ridgway (1977).

Following DOE's closed-cycle experiments, ALCAN International has begun experiments with heat exchanger modules to evaluate the efficacy of various alloys and fabrication mechanisms in OTEC applications. They have recently proposed the use of roll-bonded aluminum sheet for OTEC heat exchangers, and are presently designing a closed cycle OTEC pilot plant to be built at Keahole Point (Johnson, 1989).

Many projects have used the cold deep seawater for aquaculture of plants and animals (Fast and Tanouye, 1988). Species grown successfully include: abalone, salmon, steelhead trout, Maine Lobster, Hawaiian limpets, flounder, kelp, nori (Japanese seaweed used for wrapping sushi), spirulina (a protein-rich microalga used as a food supplement), Dunaliella (a microalga valued for its high levels of beta carotene) and various other commercially valuable seaweeds. The water has three properties important to these organisms and to their growers:

1) Coldness - The low temperature not only allows the culture of cold water species such as salmon and kelp which would not normally grow in the tropics, it also provides a cost-effective temperature control mechanism for complex aquaculture systems. Since the water is always colder than required by the various organisms, temperature throughout the systems can be precisely regulated by controlling the cold water flow.

2) Nutrients - The deep water is enriched in the dissolved inorganic nutrients (nitrates, phosphates and silicates) which are limiting factors to plant growth in tropical surface waters. Plants can use this "natural fertilizer" directly, and animals benefit indirectly from the increased productivity of the plants on which they feed.

3) Purity - There are few pathogens or viable plant cells in the deep water. Sensitive larval stages of animals can thus be grown without the expensive filtration and purification needed when surface water is used. Concentrated pure algal cultures can also be grown from dilute concentrations without contamination by competing species.

The cold water is also being used to air condition the NELH laboratory building and some of the process buildings at Cyanotech Corporation, a tenant of NELH which grows microalgal products. Cyanotech also uses the cold water as a condensing medium to recover carbon dioxide from the exhaust gases from their propane fired driers. Another project irrigates temperate plants such as strawberries and alstroemeria flowers using the cold fresh water which condenses from the atmosphere onto pipes carrying the cold seawater.

Conclusions

Valuable experience has been obtained at NELH on the design, installation and operation of deep cold seawater pumping systems. The original 12-in diameter supply has increased dramatically in the past two years, providing water for new and larger experiments and commercial projects. The new systems also provide much needed redundancy to ensure reliability of the seawater supplies.

The success of ongoing research and development projecst at Keahole Point demonstrates that there may be many economically appealing uses of deep seawater pumped ashore in the tropics. Though NELH remains the only site in the world where such water is now available on a continuous basis, there should be many future opportunities at Keahole Point and elsewhere for design of alternative systems for recovery of the valuable cold water resource.

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LIST OF FIGURES (Unavailable Electronically)

TABLE

TABLE 1

Keahole Point Seawater Supply Systems, Fall 1988

System Name	Intake Depth (m)	Length fm Shore (m)	Date Installed	Pipe O.D. (cm)	Pipe O.D. (in)	Configuration	Nom. Capacity m^3/s	Nom. Capacity gal/min
COLD WATER								
12-in	583	1766	12/81	30	12	Buoyant catenary	.07	1100
OFH #1	~600	~1800	6/87	41	16	Bottom Laid	.13	2100
OFH #2	~600	~1800	11/87	41	16	Bottom Laid	.13	2100
18-in, Backup	619	1884	10/87	45	18	Pendant Weights	.16	2600
HOST/STF, 40-in	675	1916	8/87	102	40	Buoyant Catenary	.84	13400
WARM WATER								
12-in Nearshore	15	5	10/80	30	12	Bottom mounted	.10	1600

12-in Offshore	15	92.4	8/83	30	12	Bottom mounted	.10	1600
HOST/STF	21	163	5/88	71	28	Trench, riser	.61	9700