CEOG COMBUSTION ENGINEERING OWNERS GROUP

CEN-393-NP

# EVALUATION OF PRESSURIZER HEATER SLEEVE SUSCEPTIBILITY TO PRIMARY STRESS STRESS CORROSION CRACKING

A REPORT TO THE

C-E OWNERS GROUP

NOVEMBER, 1989

NUCLEAR POWER BUSINESSES

COMBUSTION ENGINEERING, INC.

WINDSOR, CONNECTICUT

## LEGAL NOTICE

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## INTRODUCTION

This report provides a review of the design, materials data, and fabrication history of C-E Owners Group pressurizers, as related to the occurrence of heater sleeve cracking in the Calvert Cliffs Unit 2 pressurizer. Comparisons are made for those factors which may influence the susceptibility to heater sleeve cracking for CEOG pressurizers.

## BACKGROUND

During routine scheduled visual inspection of the Calvert Cliffs Unit 2 pressurizer lower head, leakage of primary coolant was detected at 20 of 120 pressurizer heater penetrations. Leakage was indicated by the presence of boric acid crystals at the heater sleeve penetrations. Subsequent in-place dye penetrant and eddy current examinations identified defects in all sleeves thought to be leaking.

Sleeve samples, including one core bore sample, were removed from the pressurizer for further nondestructive and destructive testing. Results of these examinations revealed short axial cracks originating from the ID surface. No circumferentially oriented cracks were detected.

Techniques used in the course of destructive examination included light optical microscopy, scanning electron microscopy, energy dispersive spectroscopy, Auger electron spectroscopy and X-ray photoelectron spectroscopy. A dual etch technique was used to characterize microstructure of the sleeve material, and samples were subjected to a modified Huey test to determine whether the sleeve material was sensitized to oxidizing environments. Tensile tests, hardness measurements and bulk chemical analysis were also performed.

## FINDINGS AND CONCLUSION

The destructive examination of Calvert Cliffs Unit 2 heater sleeve samples by C-E resulted in the following findings:

1. Leakage at the heater sleeve penetrations resulted from intergranular stress corrosion cracking that initiated on the ID of the sleeves and propagated through-wall.

2. The cracks were axially oriented with no circumferential extent, indicating that major stresses were in the hoop direction.

3. There were no indications that the J-groove weld was defective. No indications or flaws were observed in the heat affected zone.

4. The sleeve material had high strength, a microstructure near the ID characterized by severe carbide banding and a lack of correspondence between carbide distribution and grain boundaries. Material with these characteristics is susceptible to primary water stress corrosion cracking (PWSCC).

5. Contaminants known to promote intergranular stress corrosion cracking (IGSCC) in Inconel-600 were not present on the crack surfaces, and composition of the oxide film on the crack surface was not consistent with films that develop under strongly acidic or caustic conditions.

6. A pre-installation reaming process produced a layer of smeared metal and areas of high hardness on the sleeve ID. This operation produced high residual tensile stresses which have virtually no component of stress in the longitudinal direction that would be required to initiate circumferential cracking.

Based on these findings, C-E has concluded that the cause of sleeve cracking was PWSCC, and that the stress field in the heater sleeves is such that cracking would occur in the axial direction.

PRESSURIZER AND HEATER SLEEVE DESIGNS FOR CEOG PLANTS

All C-E Owners Group pressurizers are similar in arrangement, design, and function. A cylindrical pressurizer vessel of volume sufficient for NSSS service is mounted on a cylindrical support skirt welded to the lower head. The top head contains penetrations for safety valves, instrument nozzles, a spray nozzle, and a manway access opening with a bolted closure. The bottom head contains a penetration for the surge line connection, level indication nozzles, and penetrations for the number of pressurizer heaters specific to individual plant design. Internals include a spray head assembly in the top head, a screen assembly mounted around the surge line opening in the bottom head, support plates and their supporting structure for the heaters, and the pressurizer heaters themselves. Figure 1 shows a typical CEOG pressurizer arrangement. Physical characteristics, design and operating parameters for C-E Owners Group pressurizers are presented in Table 1.

Although different pressurizers used either of two heater sizes (watt density, diameter), the heater sleeve to bottom head connections were of essentially the same design for all CEOG pressurizers. Figure 2 shows a typical heater installation assembly. Holes are machined in the Inconel-600 clad low alloy steel bottom head, parallel to the axis of the pressurizer, and a "J-weld" preparation is machined in the Inconel cladding. An Inconel-600 heater sleeve is inserted into the hole and the "J"-weld completed between the sleeve OD and the cladding, forming a partial penetration assembly in accordance with ASME Section III rules. Subsequently the heater is inserted through the sleeve and seal welded with a fillet weld between the lower end of the sleeve and the OD of the heater sheath.

The active, electrically heated portion of the pressurizer heater is positioned above the intersection with the sleeve/bottom head penetration. Two levels of Inconel-600 support plates are provided for the heaters. Alignment of the support plates is such that the heaters may move freely through the holes in the support plates during heater installation and removal. Metal temperatures in the inactive portion of the heater and in the sleeve in the bottom head are not expected to exceed primary coolant temperature in the pressurizer.

FABRICATION SEQUENCE AND PROCESSES

Material for the pressurizer heater sleeves is drawn and annealed Inconel-600 tubing to ASME Specification SB-167. When ordered, tubing ID and minimum wall thickness were specified in order to minimize the number of machining steps required in manufacture. The tubing was furnished with the ID in the final condition, generally with a grit blasted finish. Ultrasonic and dye penetrant inspections and hydrostatic test of the tubing were performed by the material supplier. The sleeves were machined on the OD to the appropriate dimension by C-E prior to installation in the pressurizer bottom head.

Machining of the pressurizer bottom head to receive the heater sleeves is performed after the final furnace heat treatment of the bottom head assembly. The sleeves are installed and a "J"-groove weld completed between the sleeve and the bottom head Inconel-600 cladding using a manual tungsten-inert gas welding procedure with Inconel-82 filler material. A problem inherent with the heater sleeve installation is the local weld shrinkage that occurs in the heater sleeve at the "J"-weld location. Because of the small clearance between the heater OD and the sleeve ID, this local weld shrinkage frequently made heater installation in the as-welded sleeve condition difficult or impossible. The initial practice employed by C-E was to gage the sleeve ID after welding and to ream the sleeve to a larger ID (within drawing tolerance) in all cases where the sleeve would not accept a check rod simulating the maximum heater OD.

For an interim period the initial practice was modified to ream the sleeves to a larger diameter for the inboard 3" to 3-1/2" prior to their installation in the pressurizer bottom head. This attempt to compensate for weld shrinkage prior to welding was not totally successful, since the pre-installation reamed sleeves, after welding into the pressurizer, sometimes required additional hand reaming before the check rod gage would pass through the sleeve. After a short period, this practice was discontinued and the initial practice of machine reaming after welding, if needed, was reinstituted.

## HEATER SLEEVE SUSCEPTIBILITY TO CRACKING

The destructive examination of a heater sleeve core bore sample from Calvert Cliffs 2 indicated that the defects producing the observed leakage were the result of IGSCC. Of the various types of IGSCC, the consensus opinion is that the failure mechanism was PWSCC. The phenomenon has affected Inconel-600 parts in numerous pressurized water reactors worldwide. The most widely affected applications include Inconel-600 steam generator tubes (including U-bends, tubesheet roll transitions and dented regions), pressurizer heaters and heater sleeves, and pressurizer instrumentation nozzles. Because of the widespread occurrence of PWSCC, numerous failure analyses and laboratory investigations have been conducted, which, when coupled with field experience, has permitted identification of the key parameters which affect PWSCC susceptibility.

As with any IGSCC mechanism three key elements must be present for PWSCC of Inconel-600 to occur:

1. An aggressive environment.
2. The material must be in a metallurgical condition that is susceptible to PWSCC.
3. Tensile stress of sufficient magnitude.

The operating environment is essentially the same for all CEOG pressurizers, consisting of 653$^{o}$F deaerated primary water. The work of numerous investigators indicates that this environment (relatively pure water) will cause PWSCC of Inconel-600 if the material is in a susceptible condition with high tensile stresses present.

Inconel-600 is used in all pressurizer heater sleeves in C-E Owners Group plants, but the actual material condition varies significantly among the various plants. The key factors in determining susceptibility to PWSCC are the final anneal temperature and cooling rate. These factors determine yield strength and microstructural characteristics, including presence and distribution of carbides. Essentially all of the materials which have failed in service or in laboratory investigations have been characterized by high strengths (Yield Strength > 55 ksi), fine grain microstructure, and intragranular as opposed to intergranular carbides. This condition results from a low temperature (1600 - 1750$^0$F) final anneal. By comparison, the Inconel-600 that has performed well in service typically has low strength (Yield Strength < 50 ksi), coarse grains, and predominantly intergranular carbides, which result from a high temperature ( >1800$^0$F) final anneal.

The failed heater sleeves at Calvert Cliffs 2 had the characteristics of susceptible material defined above, including high strength (yield strength of 63.5 ksi), relatively fine grain size, and predominantly intragranular carbides. Yield strength is affected by grain size and carbide distribution. Since the heat treatment process was basically the same for all pressurizer heater sleeve materials used in CEOG plants, specifically that the material was air cooled after final anneal, the inter-relationship is such that high strength material will also possess the undesirable microstructural characteristics. Under these circumstances, yield strength can be used as an indicator of susceptibility to PWSCC. Material that has failed has generally had yield strengths above 55 ksi while material that has performed well has yield strengths below 50 ksi. The transition from susceptible to non-susceptible material is not abrupt, thus a susceptibility criteria based on the lower yield strength (50 ksi) is reasonable for qualitative evaluation of pressurizer heater sleeve susceptibility to PWSCC.

The available data on stresses required to initiate PWSCC indicates that a total stress (operating + residual) of at least 40 ksi is required for initiation. The stress attributable to the operational pressure difference across the sleeve wall is low, approximately 9 ksi, indicating that residual stress played a major role in the Calvert Cliffs 2 failures. Another indication that this was the case is the observation that cracks were present in some sleeves above the J-weld where there were no stresses present due to a pressure differential. It follows that high residual stresses must have been present at these locations.

Welds are a frequent source of residual stresses, and the J-weld may have contributed to the residual stresses present at Calvert Cliffs 2. However, another source of residual stresses is also implied, since sleeves of the same lot of Inconel-600 installed by the same procedure (except for pre-installation reaming) have survived significantly longer in two other plants. Fabrication operations that involve metal working or removal may produce residual stresses as a result of the cold-work induced in the Inconel-600. Depending on techniques employed, sharpness of tools, etc., those stresses may be tensile or compressive. The pre-installation reaming at Calvert Cliffs 2 probably induced high tensile residual stresses based on the location of the cracks. The magnitude of these stresses has not been determined.

The pre-installation reaming process was used in the manufacture of the Calvert Cliffs Unit 2 pressurizer and two other CEOG pressurizers. It is believed that the nature of the machining process used in the pre-installation reaming operation is more likely to result in a high degree of cold working of the ID surface than are either of the post-weld "touch-up" reaming procedures. This belief is supported qualitatively by X-ray diffraction residual stress measurements on the Calvert Cliffs Unit 2 failed sleeve specimen, which showed residual tensile stresses in the pre-installation reamed region, but residual compressive stresses in the non-reamed region of the sleeve ID surface. The significant difference between these procedures is in the amount of metal removed and the likelihood of resulting cold work: the pre-installation reaming removed a relatively large amount of metal, while the post-weld reaming used a reamer of smaller diameter than the sleeve ID, removing small amounts of metal from local high spots only. Sleeves in pressurizers using the pre-installation reaming operation are likely, therefore, to have a higher degree of susceptibility to PWSCC.

## TECHNICAL ASSESSMENT OF SAFETY CONCERNS

Evaluation results to date of the primary water stress corrosion cracking of Inconel-600 pressurizer heater sleeves at Calvert Cliffs Unit 2 do not suggest that a safety concern exists for any C-E Owners Group pressurizer.

Residual stress from the reaming operation (a potential contributor to crack initiation) has virtually no component of stress in the longitudinal direction which would be required to initiate circumferential cracking. All indications and flaws observed in heater sleeves to date have been linear, axially oriented with no circumferential extent, and have been limited to the top 2-3 inches of the sleeves. No indications or flaws have been observed in the attachment J-weld.

Fracture mechanics studies performed by BG&E have shown that the potential for such cracking does not pose a significant threat to the structural integrity of the pressurizer. Sudden axial rupture due to plastic tearing would not be expected to occur. Additionally, the potential for circumferential cracking leading to catastrophic failure of a heater sleeve from a guillotine break is not considered a credible failure mode. Independent evaluation by Combustion Engineering supports this conclusion.

## SUSCEPTIBILITY OF CEOG PRESSURIZER HEATER SLEEVES TO PWSCC

Based on manufacturing data, nondestructive and destructive testing results, and plant operating experience, heater sleeves installed in CEOG pressurizers (as-built configuration) can be classified according to their degree of susceptibility to PWSCC. Such classifications apply only to Inconel-600 pressurizer heater sleeves installed using the fabrication processes discussed in this report. It is not possible to directly relate qualitative classifications of susceptibility of individual sleeves to crack growth rates or other quantitative measures. The known occurrences of heater sleeve leakage are limited to Calvert Cliffs Unit 2, which has been in operation for approximately ten years.

## RECOMMENDATIONS FOR INSPECTION

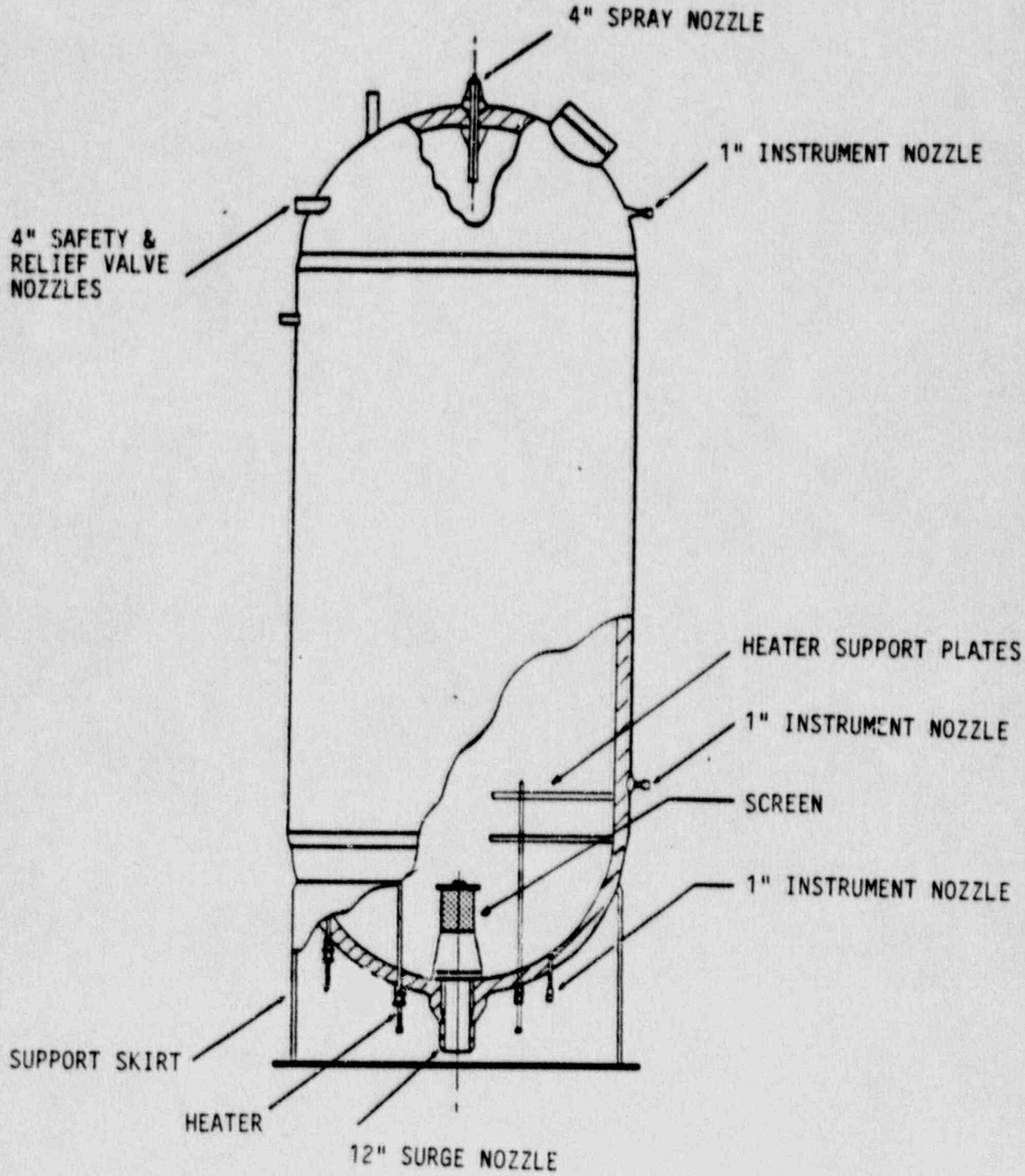
The C-E Owners Group, based on recommendations by Combustion Engineering, believes that for all susceptibility categories, some initial form of inspection of pressurizer heater sleeves is prudent. Additionally, for all susceptibility categories, requirements for subsequent inspections shall be based on evaluation of results from the initial inspection, results from further investigations of pressurizer heater sleeve failure due to PWSCC, and plant specific conditions.

TABLE 1

CEOG PRESSURIZER PHYSICAL CHARACTERISTICS AND DESIGN PARAMETERS

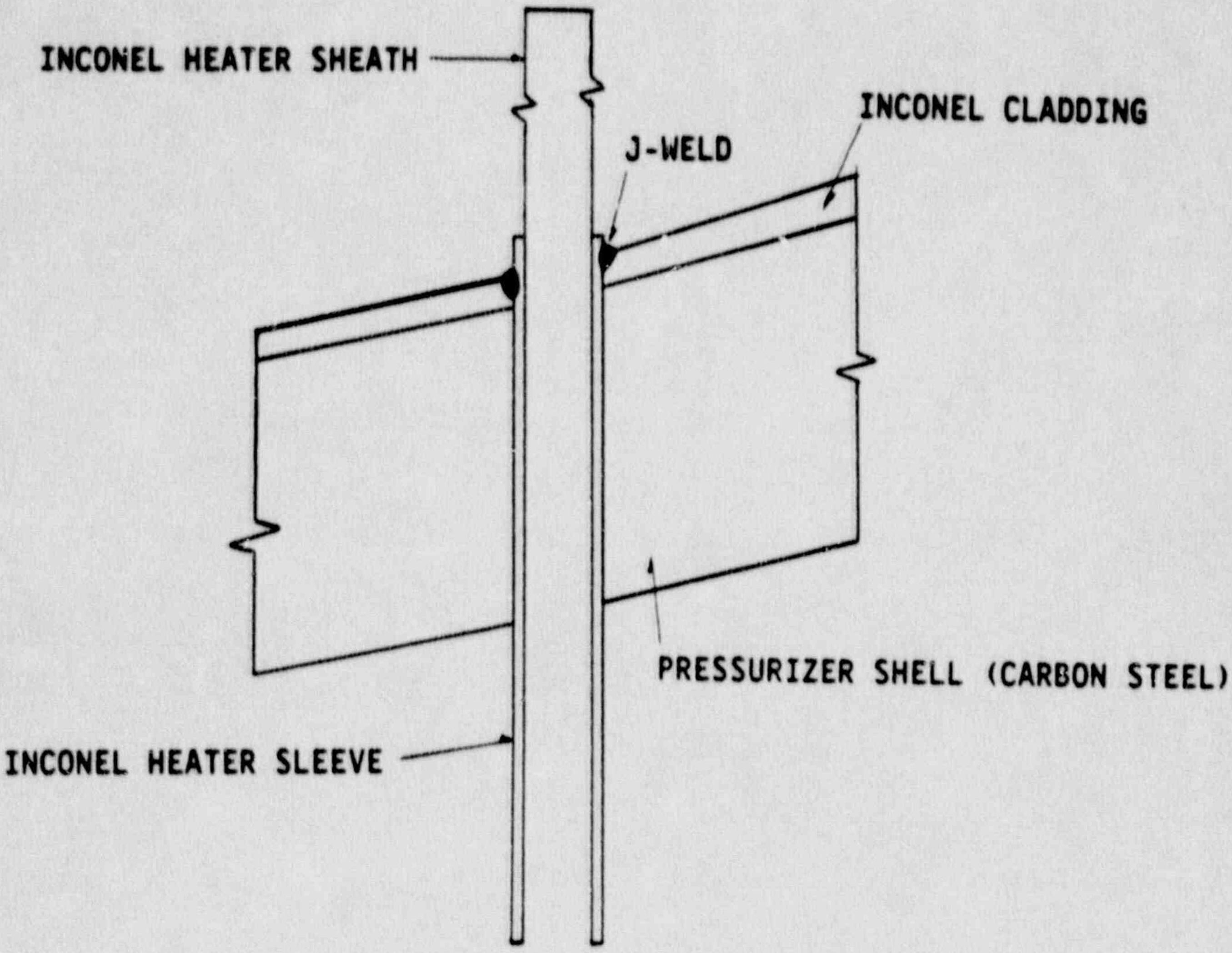
| | Palisades | Ft. Calhoun | Maine Yankee | Calvert Cliffs 1 & 2 | St. Lucie 1 | St. Lucie 2 | Millstone II | ANO-II | SONGS II & III | Waterford III | Palo Verde I, II, & III |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Design Pressure, psia | 2500 | 2500 | 2500 | 2500 | 2500 | 2500 | 2500 | 2500 | 2500 | 2500 | 2500 |
| Design Temp., F | 700 | 700 | 700 | 700 | 700 | 700 | 700 | 700 | 700 | 700 | 700 |
| Normal Operating Pressure, psia | 2060 | 2250 | 2250 | 2250 | 2250 | 2250 | 2250 | 2250 | 2250 | 2250 | 2230 |
| Normal Operating Temp., F | 640 | 653 | 653 | 653 | 653 | 653 | 653 | 653 | 653 | 653 | 653 |
| Installed Heater Capacity, Kw | 1500 | 900 | 1500 | 1500 | 1500 | 1500 | 1500 | 1200 | 1500 | 1500 | 1800 |
| Number Heaters | 120 | 72 | 120 | 120 | 120 | 30 | 120 | 96 | 30 | 30 | 36 |
| Individual Heater Capacity, Kw | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 50 | 12.5 | 12.5 | 50 | 50 | 50 |
| Heater Diameter, in. | .875 | .875 | .875 | .875 | .875 | 1.245 | .875 | .875 | 1.245 | 1.245 | 1.245 |

# TYPICAL CEOG PRESSURIZER




# FIGURE 1

# PRESSURIZER HEATER SLEEVE




# FIGURE 2