Proceedings of the Korean Nuclear Society Autumn Meeting
Yongpyong, Korea, October 2002

Advanced Spacer Grid Design for the PLUS7 Fuel Assembly

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ABSTRACT

The PLUS7 ™ program is a joint KNFC and Westinghouse project to develop an advanced fuel assembly product to have extended burnup capability for a number of Korea and US reactors. This Fuel design utilized the proven advanced design features including mixing vane spacer grids to increase thermal performance, advanced high burnup materials to enable high-duty, high burnup fuel management and an optimized fuel rod diameter which improves fuel cycle cost while resulting in significant standardization of Korean fuel manufacture. PLUS7 ™ uses a patented spacer grid design with conformal fuel rod support designed to provide superior fuel rod fretting wear resistance and high seismic strength while minimizing pressure drop. PLUS7 ™ also uses small hole/slot bottom nozzle and protective grid to improve debris filtering efficiency. With aforementioned advanced design features and well-defined verification tests, PLUS7 ™ is found to have seven outstanding benefits as compared with the current 16x16 CE type fuel, which include overpower margin increase as much as 12.8 %, high burnup capability of 72 GWD/MTU, increased seismic grid mechanical strength, enhanced fuel rod fretting wear resistance, enhanced debris filtering efficiency, improved fuel productivity and more than one million dollar per cycle savings imported enriched uranium product(see Table 1 and Figure 1). For in reactor performance verification of the PLUS7 ™ fuel assembly, four(4) PLUS7 ™ Lead Test Assemblies have already been manufactured and are scheduled to be loaded in Ulchin Unit 3 in December of 2002.

I. Introduction and Design Features

The PLUS7 program is a joint KNFC and Westinghouse project to develop an advanced fuel assembly product to have extended burnup capability for a number of Korea and US reactors. Spacer grids in a nuclear fuel assembly are used to support fuel rods for maintaining proper spacing, to provide proper flow mixing and to maintain core coolable geometry. The spacer grid is formed in the shape of a lattice with intersecting lattice members defining a plurality of cells, most of which respectively support the nuclear fuel rods. The remaining cells support nuclear control rod guide tubes and instrumentation thimbles. The cells supporting the nuclear fuel rods are provided with specially designed contoured diamond-shape grid springs on two adjacent walls. The PLUS7 mid grid design is a 16x16 egg-crate grid assembly layout, which has the following unique advanced design features :

- The placement of mixing vanes and layout of the inner straps of spacer gird for anti-vibration and maximized heat transfer design considerations.
- Symmetric grid spring and dimple design for force and torque balance in a grid cell
- Contoured spring and dimple support surfaces to enhance the fretting wear resistant performance(see figure 2), and
- High seismic load bearing capability.
- Advanced alloy material for high burnup application

The grid is provided with mixing vanes, which are positioned in a symmetrical, regional pattern, with the pattern varying between adjacent regions, and configured such the hydraulic forces and bending moments across the center of the grid are balanced. The overall flow path pattern forms a "X" about the grid center(see figure3). The combination of duplicable and symmetrical features of this pattern produce a balance of hydraulic forces and bending moments reacting against the vanes, thus enhancing the grid's salient feature of anti-vibration properties.

The grid has contoured support surface dimples and specially designed diamond-shape grid springs on two adjacent walls(see figure 2). The grid spring is designed to maximize the sub-channel flow area for coolant and to minimize the pressure loss coefficient. Each grid dimple is designed to have a contoured support surface. A slightly coining edge of plain contoured dimple is to minimize potential surface scratch during fuel rod loading. Both dimple and spring have an elongated, concave surface for supporting fuel rods. The contoured surface conforms approximately to the outside surface curvature of the fuel rods, which provides sufficient contact length and area to minimize the fretting wear potential for extended nuclear fuel duty use. The grid spring characteristics are optimized to provide adequate compliance for supporting fuel rods.

A number of mechanical and thermo-hydraulic tests were performed to verify and confirm design objectives. Basic structural tests include grid spring and cell load-deflection, grid spring fatigue, fuel rod drag force, autoclave wear and static and dynamic buckling. Thermo-Hydraulic tests consist of 6x6 CHF test, high frequency vibration, pressure drop and long term viper endurance wear test.

II. 6x6 CHF Test

To evaluate the PLUS7 ™ fuel thermal performance and develop Critical Heat Flux correlation conducted CHF(Critical Heat Flux) test at the HTRF(Heat Transfer Research Facility) in Columbia University. HTRF(Heat Transfer Research Facility) is consist of Heat transfer Loop, control system ,electronic system and measurement system. This loop is operated within following limit :

- Max. Power : 9.0 MW
- Max. Inlet temp. : 650 F
- Max. Exit pressure : 2250 Psia
- Max. Inlet mass rate : 650 gpm per 100 Hp Pump

The CHF test sections are fabricated 6x6 grid sections without thimble cell for typical cell and 6x6 grid sections with thimble cell for thimble cell test. And these grid sections are assembled for PLUS 7 fuel sub-channel (see Figure 4 CHF test section). Each tests are conducted 100 test points and conducted test parameter ranges are

- Exit pressure, psia : 1,400 ~ 2490
- Inlet mass flux, Mlbm/hr-ft^2 : 0.9 ~ 3.7
- Inlet temperature, °F : 250 ~ 637
- Axial power shape : 1.475 chopped cosine
- Max. bundle average power, MW : 9.8

Test data are generated 112 points at thimble cell and 107 points at the typical cell. From these 39 data points are compared to CE 59 (see Figure 5 CHF results), this results shows minimum 3.8 % to maximum 24.0% overpower increase and average 12.8 % increase over power compare to current design.

III. Hydraulic Loop Test

To evaluate the PLUS7 ™ fuel assembly and components hydraulic loss coefficients and fuel assembly vibration characteristics FACTS(Fuel Assembly Compatibility Test System) loop tests are performed (see Figure 6 FACTS Loop) PLUS 7 fuel assembly as well as current KSNP fuel assembly. Pressure drop tests are conducted from 500 gpm until 2260 gpm with 100 gpm increase at 150 °F and 250 °F (Reynolds Number 70,000 ~ 290,000). Total PLUS 7 fuel assembly pressure drop increase about 10 % against current KSNP design, PLUS7 fuel has 9 mixing vane mid grid versus current KSNP fuel has no mixing features that enhance about 10 % thermal performance.

To investigate fuel assembly vibration characteristics assembly motions are monitored using inductive sensors using same flow loop. As shown Figure 6 PLUS7 fuel assembly vibration characteristics are very quite overall test flow range and there are not exist any indication of resonance near the plant operating flow rage 2060 gpm.

To investigate long term fretting wear characteristics PLUS7 and KSNP dual assembly hydraulic test were conducted using viper loop(see Figure 7 VIPER Loop and Housing). Test assemblies were cell size adjusted for simulate various operating conditions and VIPER long term fretting wear test was conducted 500 hr at 380 °F. From test result PLUS 7 fuel assembly shows very good fretting wear characteristics, this are caused by wide contact area of PLUS 7 contoured mid grid design.

IV. Conclusion

PLUS7 ™ fuel grid design improve following performance; The most significant improvement of the advanced fuel is the inclusion of advanced mixing vane grids into the spacer grids design. The introduction of mixing vane spacer grids has resulted in achieving overpower margin increase of as much as 12.8 percent. The increase in overpower margin by the mixing vane spacer grids has been verified by specific CHF tests. Secondly, improve fuel rod to grid-fretting wear. The advanced fuel grid has been specifically designed to eliminate this leading fuel failure causes by developing contour spring and dimple design generating area contact with fuel rod. Thirdly, the increase in mechanical strength was achieved using a laser-welded ZIRLO straight strap mid-grids for the high seismic plants such as APR 1400. Finally, the high burnup capability of the advanced fuel greater than 55 GWD/MTU batch average discharge burnup is enabled through the use of the proven ZIRLO advanced alloys for the fuel rod cladding, guide tubes, instrument tube and mid-grid structures as well as the optimization of the fuel dimensions

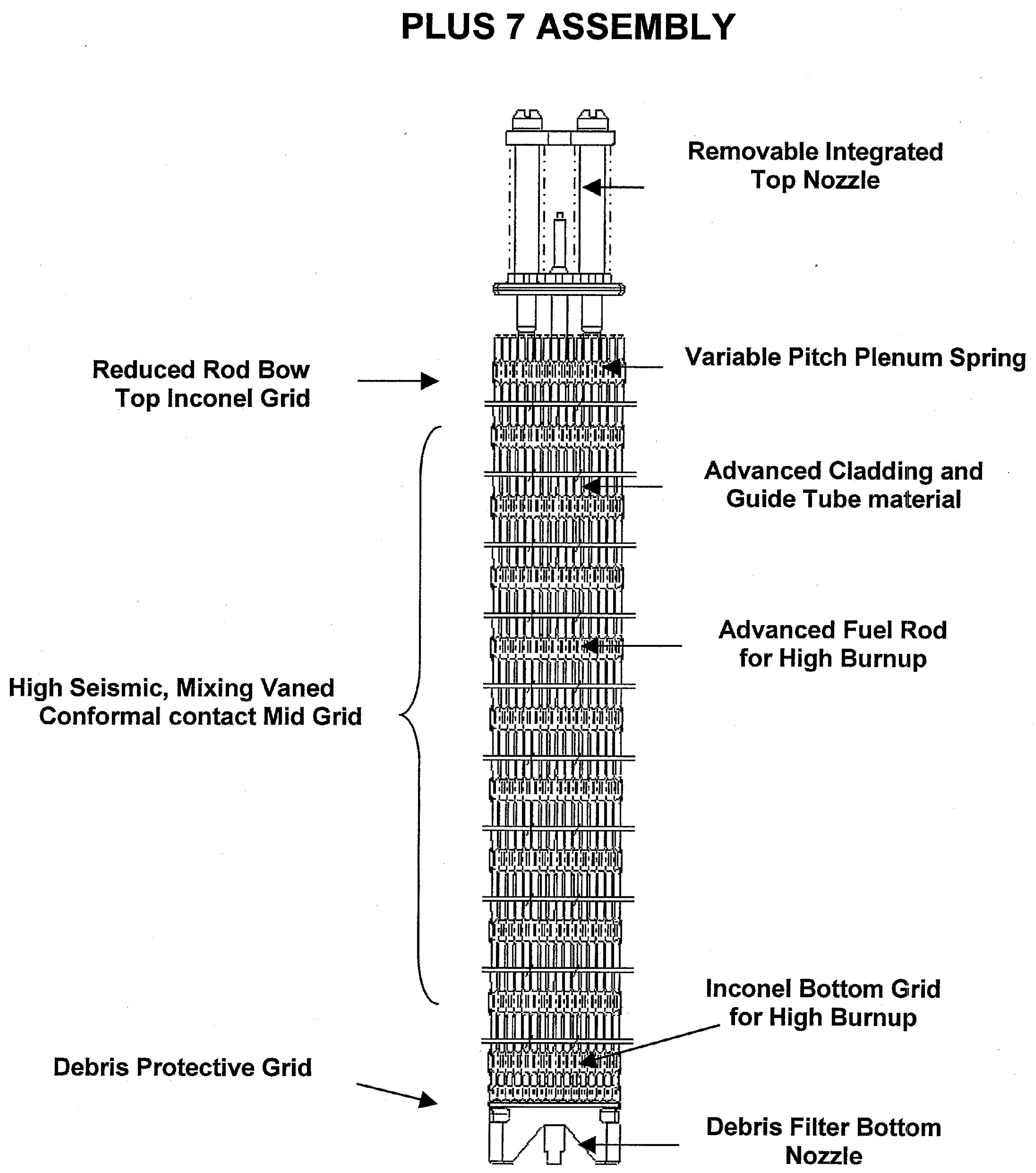
References

1. Proceedings of the KNS-KARP Joint Spring Meeting Gwangju, Korea, May 2002
2. 2002 KAIF/KNS Proceedings April 17~19 Seoul Korea
3. Final R&D Report, Development of Advanced Nuclear Fuel for KSNP's March 2002

Table 1. PLUS 7 ™ Fuel Assembly Benefit Description

Benefit	Features	Function
1. Increased thermal margin	Mixing vanes	Provide and improved coolant mixing which increases CHF performance
2. High burnup capability	Optimized fuel dimension ZIRLO ™ cladding and structures	Attains high burnup performance Proven and improved corrosion, growth and creep characteristics
3. Superior neutron economy	Optimized fuel rod size for fuel utilization Compatible with all commercially available burnable absorbers Axial blankets	Enhances fuel utilization due to increased H/U ratio and compensates for increased pressure drop due to mixing vanes Allows use of gadolinia, ZrB_2 or erbia to reduce fuel cycle cost and increase fuel management flexibility Reduce neutron leakage
4. High seismic capability	High-strength straight-strip spacers	Increases seismic-related safety margin for all Korean sites for KSNPs and APR 1400
5. Improved fuel rod frtting resistance	Large contact area conformal surface spring and dimple with optimized spring rate Inconel top & bottom grids with optimized spring rate	Provides excellent as-tested fretting wear resistance Improves high burnup performance and fretting resistance
6. Improved debris filtering capability	Debris Filter Bottom Nozzle Protective Grid/Long End Plug	Provides first line of debris filtering capability and restricts high-energy debris from reactor region Provides second and third line of debris filtering for fine debris against a solid fuel rod end plug
7. High manufacturing productivity	Standardized fuel rod size and manufacturing process Spot welded structure	Manufacturing process for fuel pellets, rods and spacer grids standized to be consistent with all KNFC-fabricated PWR fuel High strength and reliability at lower cost than previous methods

Figure 1. PLUS 7 Fuel Assembly



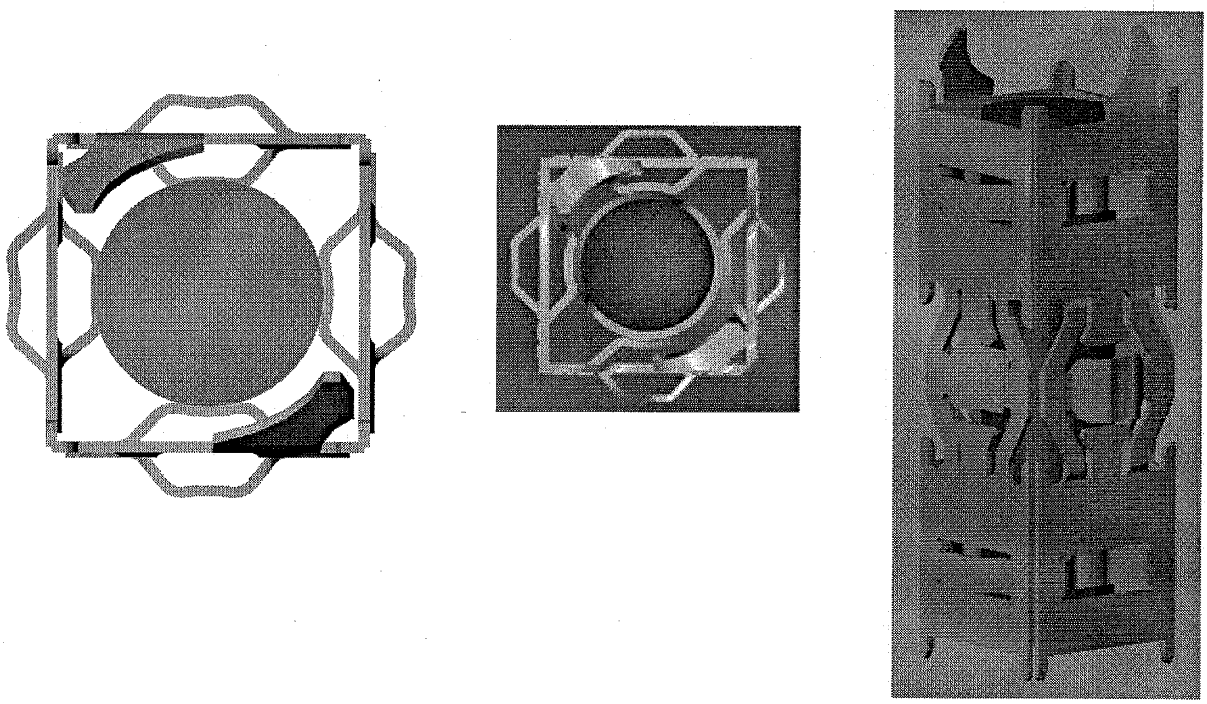


Figure 2. PLUS 7 Mid Grid Design

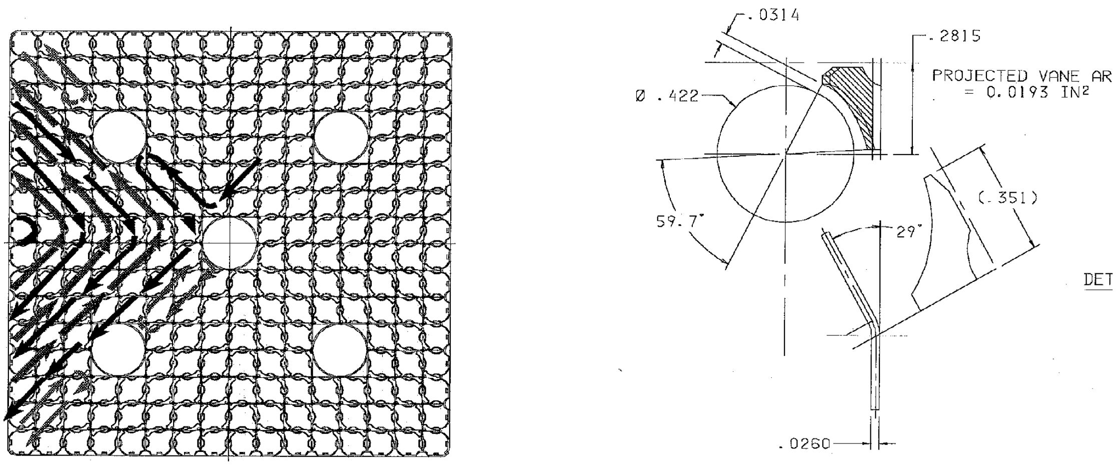


Figure 3. PLUS 7 Vane Pattern and Design

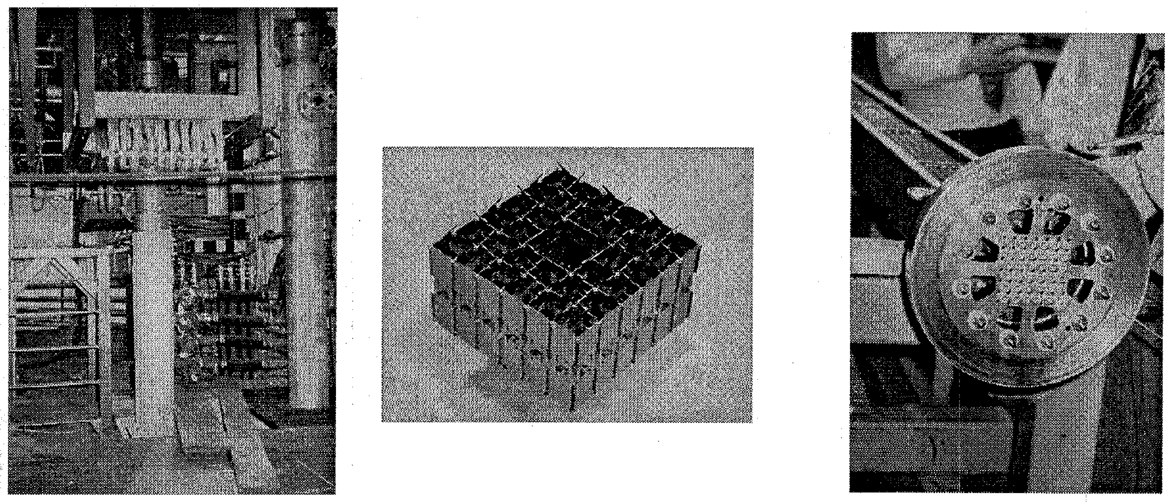


Figure 4. CHF Test Section

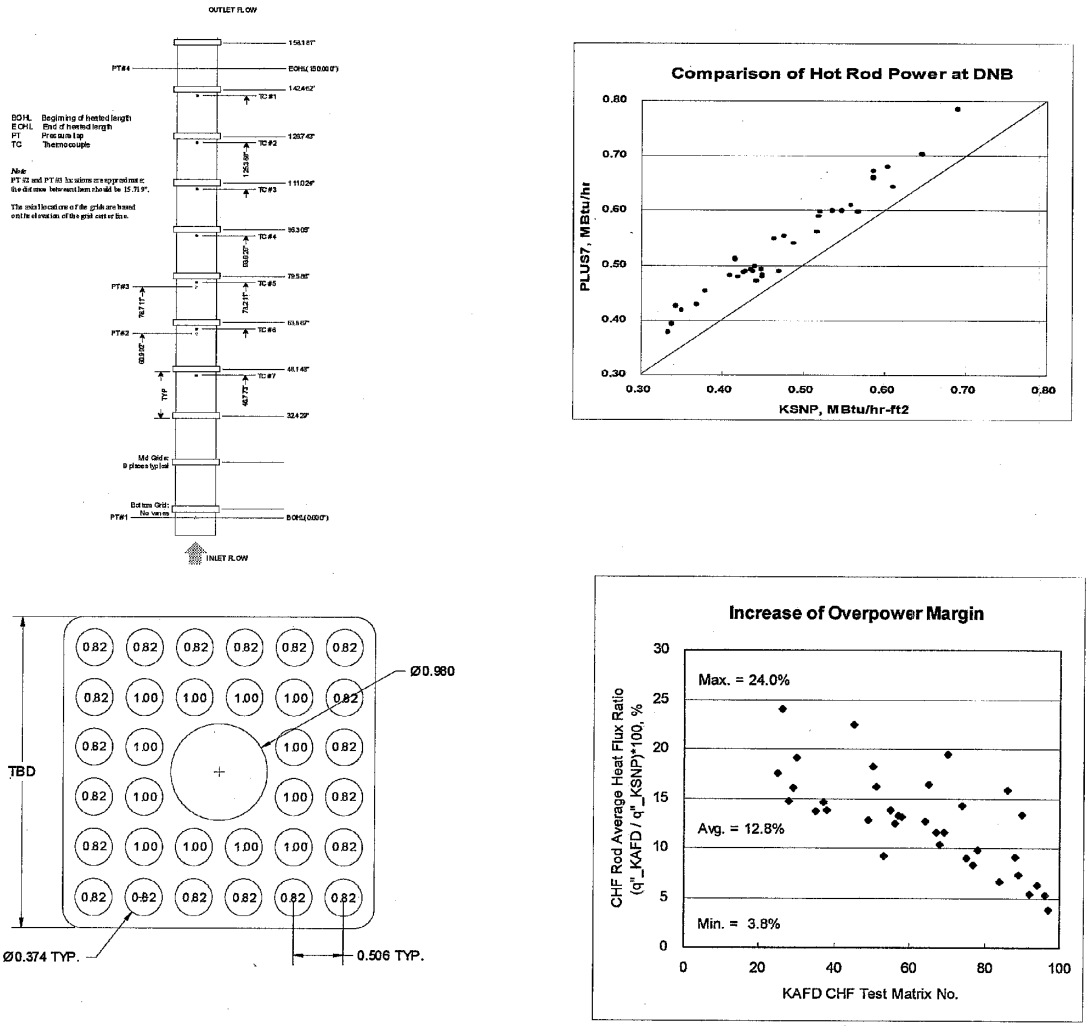
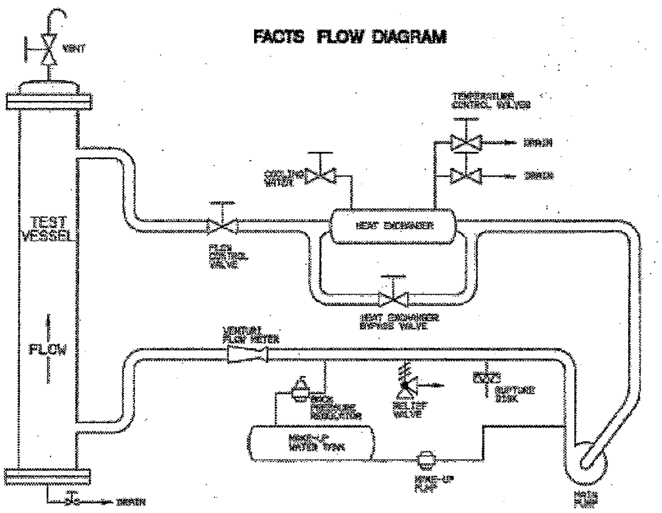


Figure 5. CHF Test Results



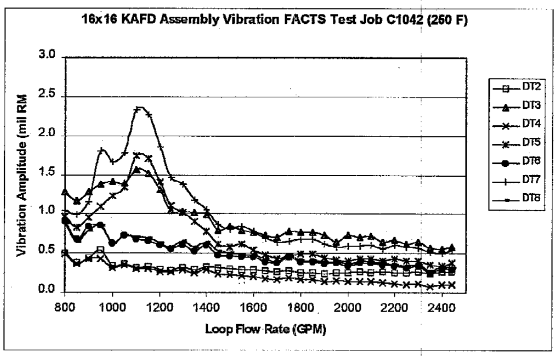


Figure 6. FACTS LOOP and Test Results

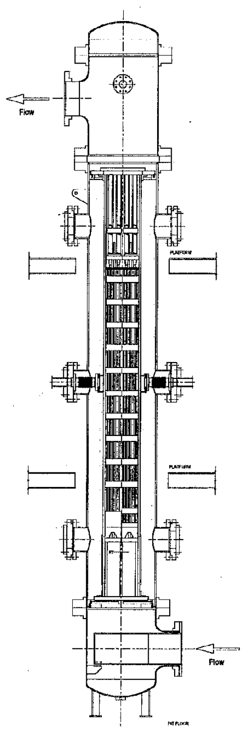


Figure 7. VIPER LOOP and HOUSING