**10.3 HFIR-MFE-RB-19J THERMAL AND NEUTRONIC DESIGN—**J.L. McDuffee, C.R. Daily, N.O. Cetiner, C.M. Petrie, J.W Geringer, (Oak Ridge National Laboratory)

**OBJECTIVE**

This experiment is a collaborative effort between the US and Japan fusion programs to research tungsten as plasma facing components under divertor conditions and to evaluate blanket structural materials for DEMO Reactors.

The objective of this experiment is to irradiate tungsten and RAFM steel specimens at controlled temperatures of 300°C, 500°C, 800°C and 1200°C in the Removable Beryllium (RB) position of the High Flux Isotope Reactor (HFIR). The capsule has a gadolinium shield inside the capsule housing to reduce thermal neutron flux, and thus reduce transmutation rates in specimen materials.

This report describes the thermal and neutronic design of the RB-19J irradiation experiment.

**SUMMARY**

The HFIR RB-19J irradiation experiment contains six cylindrical holders (four temperature zones) which house ~1300 tungsten and steel specimens. The capsule and shield is design to be centered about the HFIR mid-plane, but the holders are slightly shifted toward the positive axial direction from the mid-plane. The assembly of the RB19J capsule was completed in May 2016 and installed in HFIR in June 2016. The first irradiation cycle, 466, started June 14, 2016. Starting temperatures stabilized within design range for the 500°C and the 800°C holders. The 1200°C and the 300°C were lower and higher than designed by about 50°C to 100°C respectively.

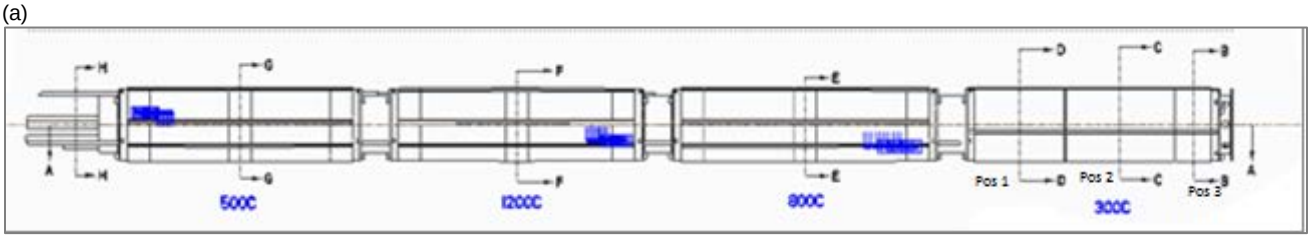
**Capsule Description**

The RB19J capsule contains six cylindrical holders located in four temperature zones 300°C, 500°C, 800°C and 1200°C as shown in Figure 1. The lower 300°C temperature zone uses a DISPAL (dispersed oxide aluminum) holder and contains only F82H steel alloy specimens, while the upper three temperature zones use a POCO graphite AXF-5Q holder and contain tungsten and tungsten alloy specimens.

The temperature regions are separated by three 20 mm Grade 5 titanium holder spacers filled with grafoil inserts. Each holder spacer also contains a flux wire dosimetry package. The three dosimetry packages 8A, 2U and 5H are located between holders 300°C & 800°C, 800°C & 1200°C and 1200°C & 500°C, respectively.

The effective total internal subcapsule length is 480 mm, with the reactor midplane crossing approximately 2 cm above the bottom of the 800°C holder. The bottom of the 300°C holder (position 3) is 217.9 mm below the midplane while the top of the 500°C holder is 261.1 mm above the midplane position.

(a)




(b)

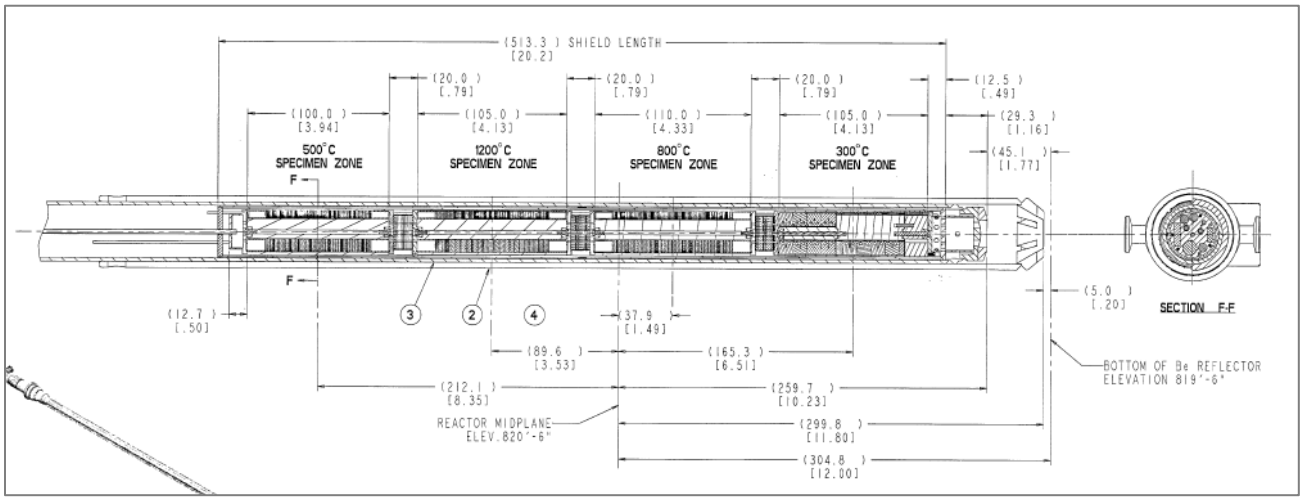



**Figure 1.** The layout of the RB19J Capsule Assembly – (a) Shows the internal holder positions and (b) shows the capsule dimensions; given in (mm) in parenthesis and in [inches] in brackets.

The holders are surrounded by a gadolinium shield (see next section) which serves to reduce the thermal neutron flux in the specimens. The sleeve-to-shield gap is designed to close due to differential thermal expansion. (The hotter aluminum sleeve has a much larger thermal expansion coefficient than does the gadolinium shield.)

Temperatures inside the capsule are controlled by a combination of gas gap size and gas composition. There are three gas gaps initially: holder to sleeve, sleeve to shield, and shield to housing tube. The top three holders (500°C, 1200°C, and 800°C) each have three design diameters: top, middle, and bottom. The 300°C region consists of three interlocking holders, and each holder has a top and bottom diameter. The naming convention is holder-region, so that “300°C holder middle-top” indicates the top diameter of the middle holder. Table 1 summarizes the initial (cold) diameters for the key design features. Outer surfaces are tapered between these design diameters.

**Table 1.** Key Design Diameters

| Feature Diameter | Design Diameter (mm) |
|---|---|
| Housing tube inside | 37.115±0.015 |
| Shield outside | 36.965±0.015 |
| Shield inside | 34.965±0.015 |
| Sleeve outside | 34.935±0.015 |
| Sleeve inside | 32.435±0.025 |
| 500°C holder top | 32.10±0.025 |
| 500°C holder middle | 32.30±0.025 |
| 500°C holder bottom | 32.10±0.025 |
| 1200°C holder top | 31.30±0.025 |
| 1200°C holder middle | 32.00±0.025 |
| 1200°C holder bottom | 31.20±0.025 |
| 800°C holder top | 32.25±0.025 |
| 800°C holder middle | 32.30±0.025 |
| 800°C holder bottom | 31.90±0.025 |
| 300°C holder top-top | 32.33±0.025 |
| 300°C holder top-bottom | 32.33±0.025 |
| 300°C holder middle-top | 32.33±0.025 |
| 300°C holder middle -bottom | 32.33±0.025 |
| 300°C holder bottom-top | 32.25±0.025 |
| 300°C holder bottom-bottom | 32.20±0.025 |
| Subcapsule end cap tabs | 32.33±0.025 |

Every temperature region has its own gas supply line to control temperature through changing gas mixtures and flow rates. Helium gas flows through all the holders from the top to the bottom and exits at the bottom of the lowest holder. To manipulate the temperature either argon or helium gas is inserted just below and outside the specimen holder for each temperature zone to modify the effective thermal conductivity of the gas gap between the specimen holder and the outer tube.

There are two Type N Thermocouple Array Tubes (TCAT) inserted in the assembly with seven thermocouple junctions per TCAT. The TCATs extend the entire length of all the stacked holders. The thermocouple junctions from the same TCAT are in the same radial location with reference to the holders but have different axial positions so that each temperature region has at least three thermocouples. Thirteen passive SiC temperature monitors (TMs) are included in the assembly, three in each of the higher temperature holders 500°C, 800°C and 1200°C and four in the 300°C holders. There are also several SiC TMs in the 300°C holders.

**Thermal Neutron Shield Design**

The gadolinium shield is highly effective at reducing the thermal neutron flux. Figure 2 shows the neutron flux per unit lethargy for the beginning of the first cycle at locations outside (containment), within (shield), and internal to (holder) the gadolinium shield.

Cycle length reduction and day-by-day control rod position indicate no significant burnout of the gadolinium shield early in the first cycle of irradiation; however, more detailed multi-cycle depletion calculations will be needed to determine effects of gadolinium burnout.

Data in Figure 2 are plotted at the mid-point energy of a 44-group energy group structure. Flux spectra in Figure 2 are for a 2 cm long tally region axially centered on the core mid-plane. Because of the effectiveness of the gadolinium shield, the relative errors for the low energy groups in the tally region inside of the shield (specimen holder region) are quite large, as seen in the Table 2 data. Some of these low energy groups have not scored a single tally after 8000 kcode cycles of 100,000 histories/cycle.

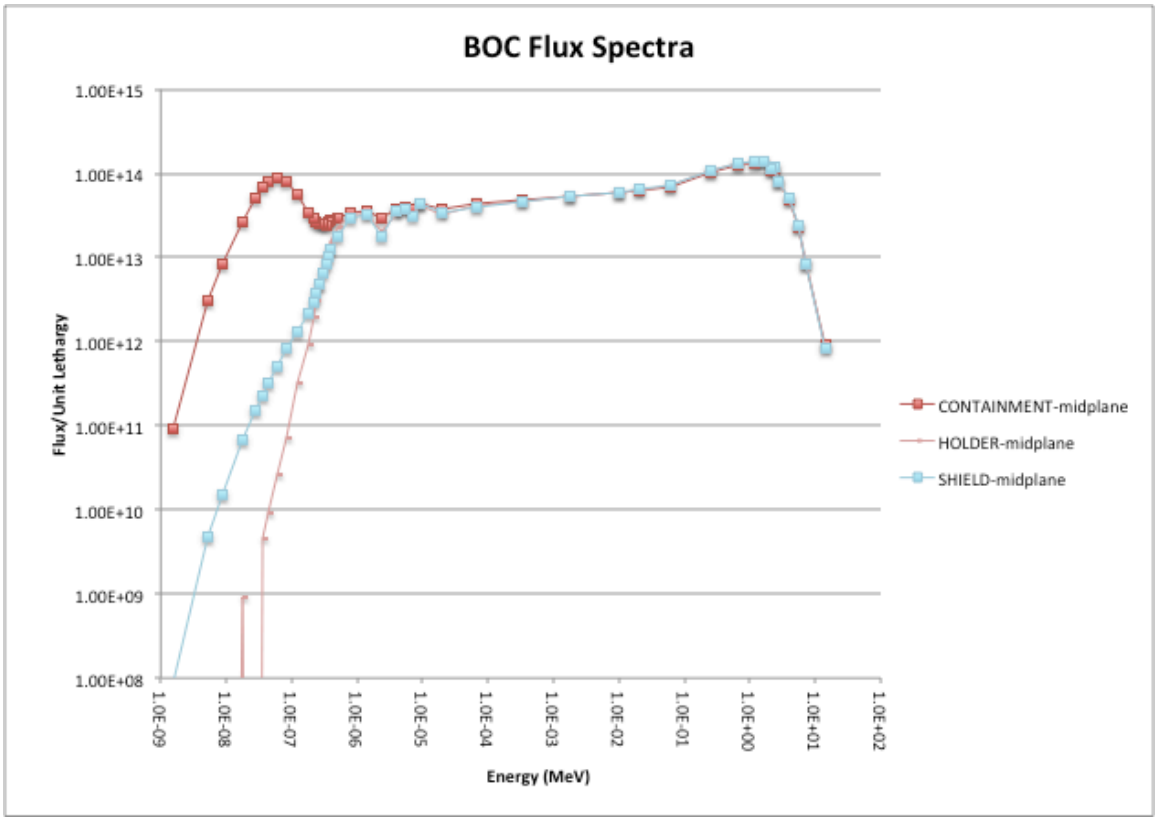



**Figure 2.** Beginning of Cycle (BOC) Flux Spectra for the MFE-RB-19J Experiment.

**Table 2.** BOC Flux Spectra Information at the Reactor Midplane for the MFE-RB-19J Experiment

| | | | Containment | | Shield | | Holder | |
|---|---|---|---|---|---|---|---|---|
| $E_{low}$ (MeV) | $E_{high}$ (MeV) | $E_{mid}$ (MeV) | Flux/ Lethargy | Relative Error | Flux/ Lethargy | Relative Error | Flux/ Lethargy | Relative Error |
| 8.19E+00 | 2.00E+01 | 1.41E+01 | 9.26E+11 | 0.0123 | 8.48E+11 | 0.0532 | 8.54E+11 | 0.0472 |
| 6.43E+00 | 8.19E+00 | 7.31E+00 | 8.41E+12 | 0.0076 | 8.58E+12 | 0.033 | 9.05E+12 | 0.0285 |
| 4.80E+00 | 6.43E+00 | 5.62E+00 | 2.27E+13 | 0.0044 | 2.35E+13 | 0.0184 | 2.36E+13 | 0.016 |
| 3.00E+00 | 4.80E+00 | 3.90E+00 | 4.85E+13 | 0.0025 | 5.03E+13 | 0.0101 | 4.88E+13 | 0.0087 |
| 2.48E+00 | 3.00E+00 | 2.74E+00 | 7.84E+13 | 0.003 | 8.20E+13 | 0.0122 | 8.17E+13 | 0.0104 |
| 2.35E+00 | 2.48E+00 | 2.41E+00 | 1.13E+14 | 0.0045 | 1.18E+14 | 0.0189 | 1.16E+14 | 0.0163 |
| 1.85E+00 | 2.35E+00 | 2.10E+00 | 1.10E+14 | 0.0023 | 1.13E+14 | 0.0093 | 1.13E+14 | 0.0079 |
| 1.40E+00 | 1.85E+00 | 1.63E+00 | 1.36E+14 | 0.0019 | 1.41E+14 | 0.0078 | 1.38E+14 | 0.0066 |
| 9.00E-01 | 1.40E+00 | 1.15E+00 | 1.32E+14 | 0.0016 | 1.38E+14 | 0.0064 | 1.34E+14 | 0.0054 |
| 4.00E-01 | 9.00E-01 | 6.50E-01 | 1.28E+14 | 0.0013 | 1.32E+14 | 0.0049 | 1.30E+14 | 0.0041 |
| 1.00E-01 | 4.00E-01 | 2.50E-01 | 1.02E+14 | 0.0012 | 1.06E+14 | 0.0043 | 1.06E+14 | 0.0036 |
| 2.50E-02 | 1.00E-01 | 6.25E-02 | 7.02E+13 | 0.0014 | 7.19E+13 | 0.0052 | 7.17E+13 | 0.0045 |
| 1.70E-02 | 2.50E-02 | 2.10E-02 | 6.27E+13 | 0.0024 | 6.51E+13 | 0.0101 | 6.33E+13 | 0.0081 |
| 3.00E-03 | 1.70E-02 | 1.00E-02 | 5.80E+13 | 0.0013 | 5.96E+13 | 0.0052 | 5.91E+13 | 0.0045 |
| 5.50E-04 | 3.00E-03 | 1.78E-03 | 5.34E+13 | 0.0014 | 5.35E+13 | 0.0054 | 5.30E+13 | 0.0047 |
| 1.00E-04 | 5.50E-04 | 3.25E-04 | 4.75E+13 | 0.0014 | 4.52E+13 | 0.0056 | 4.54E+13 | 0.005 |
| 3.00E-05 | 1.00E-04 | 6.50E-05 | 4.35E+13 | 0.0017 | 4.05E+13 | 0.0069 | 4.19E+13 | 0.006 |
| 1.00E-05 | 3.00E-05 | 2.00E-05 | 3.83E+13 | 0.0018 | 3.33E+13 | 0.0077 | 3.26E+13 | 0.0069 |
| 8.10E-06 | 1.00E-05 | 9.05E-06 | 4.28E+13 | 0.0036 | 4.32E+13 | 0.0159 | 4.11E+13 | 0.0127 |
| 6.00E-06 | 8.10E-06 | 7.05E-06 | 3.70E+13 | 0.0032 | 3.12E+13 | 0.0145 | 3.23E+13 | 0.0121 |
| 4.75E-06 | 6.00E-06 | 5.38E-06 | 3.96E+13 | 0.0036 | 3.85E+13 | 0.0159 | 3.83E+13 | 0.0126 |
| 3.00E-06 | 4.75E-06 | 3.88E-06 | 3.72E+13 | 0.0027 | 3.51E+13 | 0.012 | 3.31E+13 | 0.01 |
| 1.77E-06 | 3.00E-06 | 2.39E-06 | 2.93E+13 | 0.0027 | 1.75E+13 | 0.0121 | 2.12E+13 | 0.0116 |
| 1.00E-06 | 1.77E-06 | 1.39E-06 | 3.54E+13 | 0.0025 | 3.22E+13 | 0.0106 | 3.30E+13 | 0.0093 |
| 6.25E-07 | 1.00E-06 | 8.13E-07 | 3.45E+13 | 0.0027 | 2.89E+13 | 0.0113 | 3.27E+13 | 0.01 |
| 4.00E-07 | 6.25E-07 | 5.13E-07 | 2.94E+13 | 0.0028 | 1.81E+13 | 0.012 | 2.30E+13 | 0.0122 |
| 3.75E-07 | 4.00E-07 | 3.88E-07 | 2.75E+13 | 0.0069 | 1.23E+13 | 0.0324 | 1.50E+13 | 0.0351 |
| 3.50E-07 | 3.75E-07 | 3.63E-07 | 2.68E+13 | 0.0067 | 1.02E+13 | 0.0327 | 1.20E+13 | 0.0378 |
| 3.25E-07 | 3.50E-07 | 3.38E-07 | 2.44E+13 | 0.0065 | 8.31E+12 | 0.0329 | 1.04E+13 | 0.0397 |
| 2.75E-07 | 3.25E-07 | 3.00E-07 | 2.54E+13 | 0.0046 | 6.59E+12 | 0.0235 | 7.32E+12 | 0.0323 |
| 2.50E-07 | 2.75E-07 | 2.63E-07 | 2.56E+13 | 0.0057 | 4.78E+12 | 0.0317 | 4.31E+12 | 0.0536 |
| 2.25E-07 | 2.50E-07 | 2.38E-07 | 2.62E+13 | 0.0053 | 3.75E+12 | 0.0304 | 3.02E+12 | 0.0616 |
| 2.00E-07 | 2.25E-07 | 2.13E-07 | 2.88E+13 | 0.0048 | 2.92E+12 | 0.0291 | 2.00E+12 | 0.0677 |
| 1.50E-07 | 2.00E-07 | 1.75E-07 | 3.48E+13 | 0.0028 | 2.14E+12 | 0.0172 | 9.22E+11 | 0.0645 |
| 1.00E-07 | 1.50E-07 | 1.25E-07 | 5.62E+13 | 0.0018 | 1.34E+12 | 0.0113 | 3.19E+11 | 0.0954 |
| 7.00E-08 | 1.00E-07 | 8.50E-08 | 8.09E+13 | 0.0015 | 8.38E+11 | 0.0095 | 7.27E+10 | 0.2047 |
| 5.00E-08 | 7.00E-08 | 6.00E-08 | 8.95E+13 | 0.0014 | 5.05E+11 | 0.009 | 2.66E+10 | 0.3879 |
| 4.00E-08 | 5.00E-08 | 4.50E-08 | 8.15E+13 | 0.0017 | 3.28E+11 | 0.0113 | 9.00E+09 | 0.7088 |
| 3.00E-08 | 4.00E-08 | 3.50E-08 | 6.89E+13 | 0.0016 | 2.28E+11 | 0.0109 | 4.61E+09 | 0.6864 |
| 2.53E-08 | 3.00E-08 | 2.77E-08 | 5.17E+13 | 0.0022 | 1.55E+11 | 0.016 | 0.00E+00 | 0 |
| 1.00E-08 | 2.53E-08 | 1.77E-08 | 2.61E+13 | 0.0015 | 6.70E+10 | 0.0096 | 9.17E+08 | 0.6006 |
| 7.50E-09 | 1.00E-08 | 8.75E-09 | 8.22E+12 | 0.0039 | 1.52E+10 | 0.0307 | 0.00E+00 | 0 |
| 3.00E-09 | 7.50E-09 | 5.25E-09 | 3.14E+12 | 0.0036 | 4.89E+09 | 0.0281 | 0.00E+00 | 0 |
| 1.00E-11 | 3.00E-09 | 1.51E-09 | 9.12E+10 | 0.0078 | 8.61E+07 | 0.0667 | 0.00E+00 | 0 |

**Capsule Heat Generation Rates**

The midplane heat generation rates in the 19J experiment at a HFIR power level of 85 MW for the materials of construction are taken from Daily[1] and summarized in Table 3.

**Table 3.** Design Basis Peak Heat Generation Rates (W/g) at 85 MW Reactor Power

| Material | BOC | EOC | Design | Includes parts: |
|---|---|---|---|---|
| Steel (outside shield) | 12.66 | 14.55 | 13.60 | housing tube |
| Water | 20.58 | 21.12 | 20.85 | coolant |
| Gadolinium | 22.20 | 25.67 | 23.93 | shield, shield end caps |
| Aluminum | 11.15 | 12.59 | 11.87 | HFIR liner, holders |
| Graphite | 10.30 | 11.17 | 10.74 | holders, spacers |
| SiC | 9.54 | 10.51 | 10.03 | thermometry, springs |
| Molybdenum | 14.80 | 16.82 | 15.81 | gas lines |
| Steel (inside shield) | 9.70 | 10.64 | 10.17 | specimens, TCATS |
| Magnesium oxide | 9.09 | 9.93 | 9.51 | thermocouple insulation |
| Tungsten | 18.82 | 22.24 | 20.53 | specimens |
| Titanium | 9.88 | 10.98 | 10.43 | holder spacers, springs, end caps, bolts, screws |

Figure 3 shows the heat generation peaking factor curves for beginning of cycle (BOC), end of cycle (EOC) and Design. The EOC peaking factor curve is used for all safety-basis calculations, which maximizes the total heat generated.

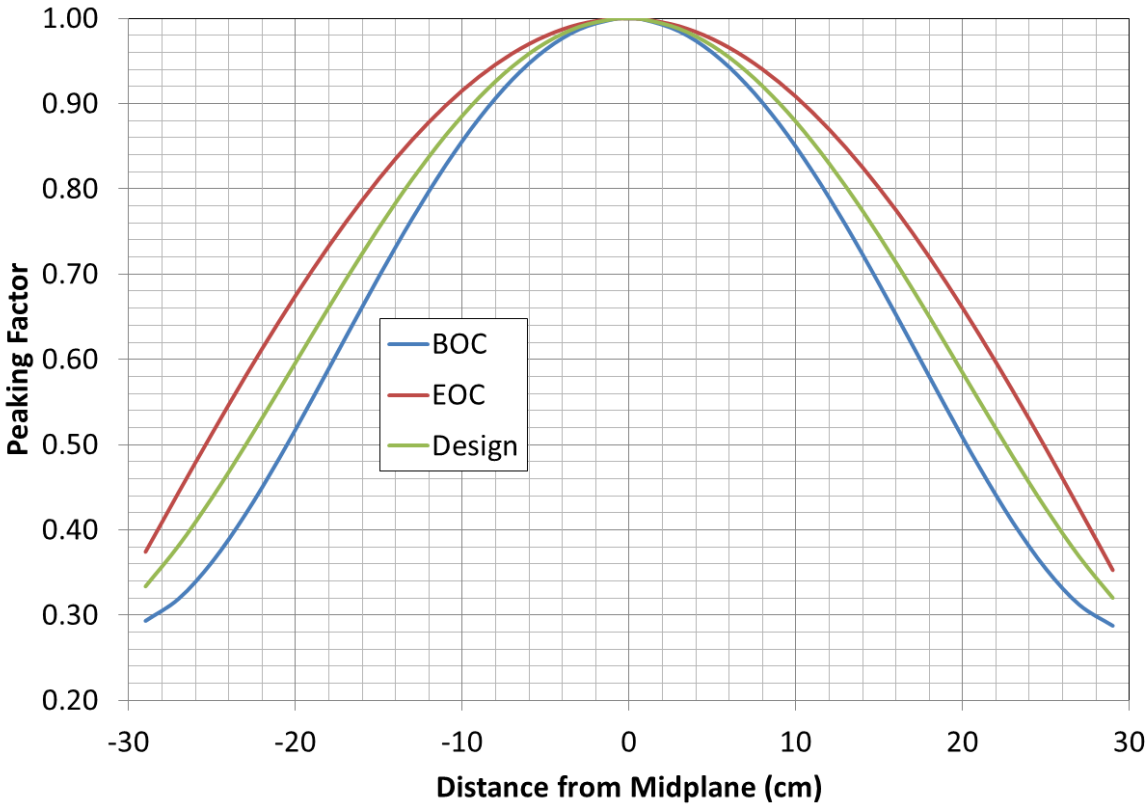



**Figure 3.** Heat Generation Peaking Factor Curve.

**Design Basis Temperatures**

Design basis temperatures are shown in Figure 4 and specimen temperatures are summarized in Table 4[2]. Contour plots for each specimen region are shown in Figure 5 through Figure 8.

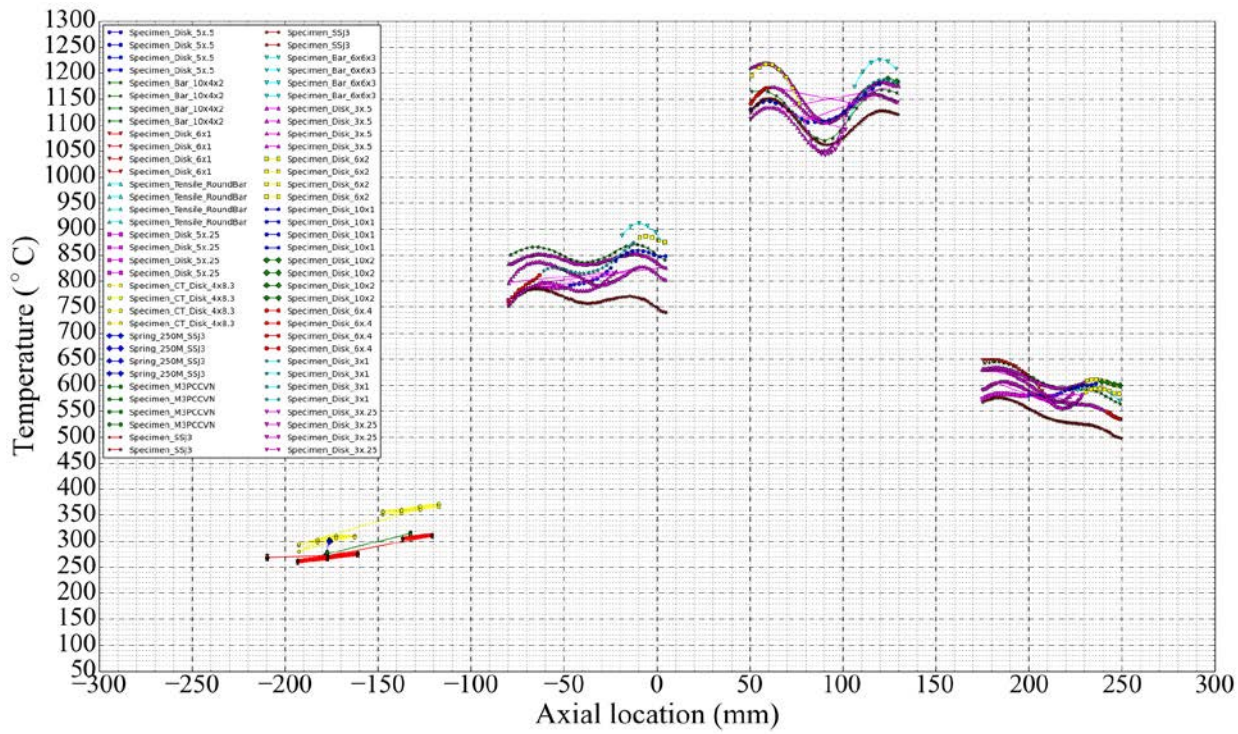



**Figure 4.** Design Basis Temperatures Under Nominal Reactor Conditions.

**Table 4.** Specimen Temperatures at Nominal Design Conditions

| Specimens | Material | $T_{avg}$ | $T_{min}$ | $T_{max}$ | $T_{.025}$* | $T_{.975}$* |
|---|---|---|---|---|---|---|
| 500C | Tungsten | 590 | 481 | 652 | 516 | 646 |
| 1200C | Tungsten | 1144 | 1019 | 1232 | 1063 | 1222 |
| 800C | Tungsten | 829 | 707 | 920 | 751 | 903 |
| 250C TOP | Steel | 345 | 293 | 380 | 303 | 375 |
| 250C MID | Steel | 289 | 253 | 317 | 260 | 314 |
| 250C BTM | Steel | 267 | 262 | 274 | 264 | 273 |

**95% of the part volume is within the $T_{.025}$ and $T_{.975}$ temperature band*

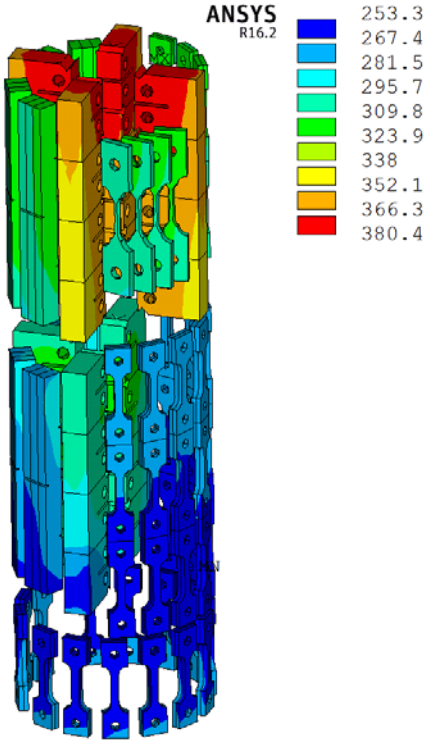



**Figure 5.** Design Basis Temperature Contour Plot for 300°C Specimens.

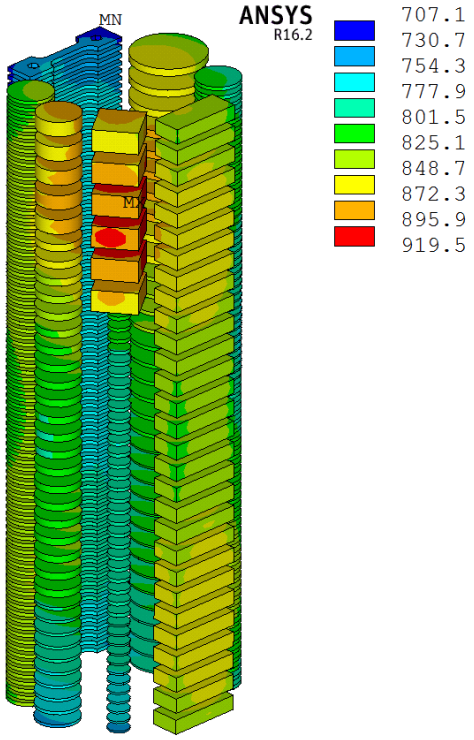



**Figure 6.** Plot for 800°C Specimens.

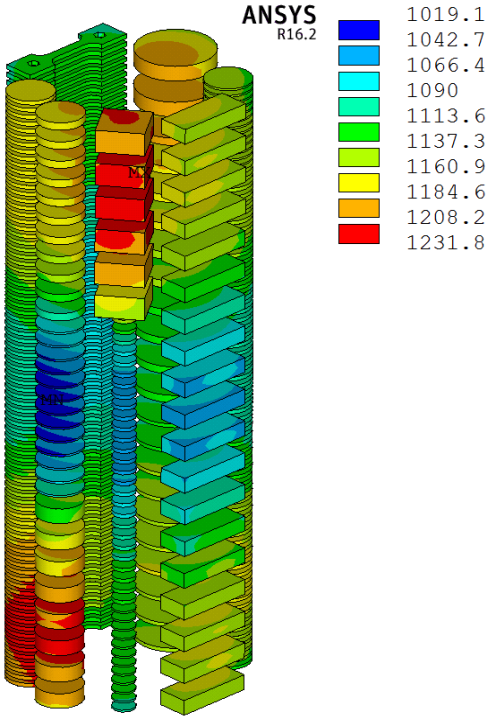



**Figure 7.** Design Basis Temperature Contour Plot for 1200°C Specimens.

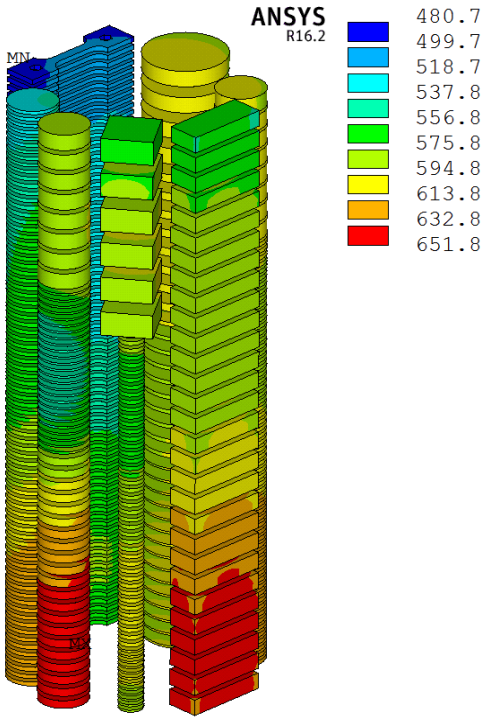



**Figure 8.** Design Basis Temperature Contour Plot for 500°C Specimens.

The capsule is designed such that the pure helium purge gas is introduced at the top of the capsule and is directed through the specimen region of each subcapsule until it exits at the bottom of the capsule. Control gas (60% argon and 40% helium) is introduced outside and below each subcapsule and inside the shield inner sleeve. Nominal gas concentrations in this region are shown in Table 5. The "purge" and "control" gases are what the operator will actually send to the capsule. The helium and argon concentrations result from mixing the pre-mixed control gas with the pure helium.

**Table 5.** Design-basis Gas Concentrations in Each Subcapsule

| Subcapsule | Purge | Control | Helium | Argon |
|---|---|---|---|---|
| 500°C | 75% | 25% | 85% | 15% |
| 1200°C | 50% | 50% | 70% | 30% |
| 800°C | 50% | 50% | 70% | 30% |
| 250°C | 75% | 25% | 85% | 15% |

Table 6 summarizes the coolant conditions for the design-basis case.

**Table 6.** Summary of Coolant Conditions for the Design-basis Condition

| Subcapsule | Minimum | Maximum | Average |
|---|---|---|---|
| Bulk coolant temperature (°C) | 49.0 | 55.9 | 52.5 |
| Capsule surface temperature (°C) | 54.6 | 81.3 | 68.0 |
| Capsule surface heat flux (kW/m²) | 191.4 | 882.9 | 593.0 |
| Heat transfer coefficient (kW/m²·°C) | 30.2 | 31.7 | 31.0 |

**Conclusion**

The MFE-RB-19J capsule has been designed to achieve nominal temperatures of 300°C, 800°C, 1200°C, and 500°C. The temperature of the capsule is controlled with a mixture of helium and control gas. The control gas is a mixture of 60% argon and 40% helium, which results in an effective thermal conductivity equivalent to neon.

**References**

[1] Daily, C., Heat Generation Rates in Gadolinium-Shielded Experiment RB19J in Position RB-5B of the HFIR Beryllium Reflector, C-HFIR-2016-010, Rev. 1, Reactor and Nuclear Systems Division, Oak Ridge National Laboratory, 2016.

[2] McDuffee, J.L., Temperature Verification, Transient Analysis, and Argon Activation for Materials Experiment MFE-RB-19J, C-HFIR-2016-007, Rev. 0, Reactor and Nuclear Systems Division, Oak Ridge National Laboratory, 2016.