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AGC-1 Experiment and Final Preliminary Design Report

Robert Bratton, Idaho National Laboratory
Tim Burchell, Oak Ridge National Laboratory

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ABSTRACT

This report details the experimental plan and design as of the preliminary design review for the Advanced Test Reactor Graphite Creep-1 graphite compressive creep capsule. The capsule will contain five graphite grades that will be irradiated in the Advanced Test Reactor at the Idaho National Laboratory to determine the irradiation induced creep constants. Seven other grades of graphite will be irradiated to determine irradiated physical properties. The capsule will have an irradiation temperature of 900°C and a peak irradiation dose of 5.8×10^{21} n/cm^2 [E > 0.1 MeV], or 4.2 displacements per atom.

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SUMMARY

This report contains the objectives, technical plan, design as of the preliminary design, and schedule for the Advanced Test Reactor (ATR) Graphite Creep-1 (AGC-1) irradiation experiment. Experiment AGC-1 will be irradiated in the ATR south flux trap to a peak irradiation dose of 5.8×10^{21} n/cm^2 [E > 0.1 MeV], or 4.2 displacements per atom (dpa), at an irradiation temperature of 900°C. Graphite specimens will be stressed in compression at two levels, namely 2 ksi (13.8 MPa) and 3 ksi (20.7 MPa).

The key data to be obtained from this experiment include:

- Irradiation creep design data and data on the effects of irradiation creep on key physical properties (e.g., strength, elastic modulus, coefficient of thermal expansion)
- The effects of neutron irradiation on the properties of a wide range of next generation nuclear plant (NGNP) relevant graphites, including dimensional changes, strength, elastic modulus, thermal conductivity, and coefficient of thermal expansion.
- Data on the single crystal irradiation behavior of graphites to be derived from highly oriented pyrolytic graphite (HOPG).

These data are critical to the design licensing of the NGNP graphite components and support ongoing work in the area of model development (e.g., irradiation effects model such as dimensional change and creep strain, structural modeling, and fracture modeling). Moreover, the data will be used to underpin the American Society of Mechanical Engineers (ASME) design code currently being prepared for graphite core components.

The report reviews the background and theory of irradiation induced creep in graphites, and details the graphite grades to be irradiated in the experiment along with the rationale for their inclusion. Details of the irradiation test conditions are reported. Detailed AGC-1 layout plans are given for each of the specimen channels in the capsule, and the specimens are tabulated by grade, location, and anticipated fluence. The process of pre and postirradiation examination (PIE) is reported, and details of the tests to be performed and the data to be acquired are given.

The second half of the report details the design to date for the AGC-1 capsule. Detailed discussions are given for the capsule requirements and how the design incorporates those requirements. The experimental plan is fully developed because all details and theory are known at the present time. This report is a snapshot of the AGC-1 design as of the preliminary design review. The final design review will occur after this report is released. Capsule insertion in the ATR is expected in November 2007. The final design will use an assumed neutronic model of the ATR core because the actual November 2007 core configuration is not know at this time. This prevents the development of a final neutronic, thermal, and mechanical analysis. The complexity of the cross-sectional geometry requires a translator to be developed to read the output of the neutronic analysis and provide a database for use by the finite element thermal analysis. The finite element model is expected to use over 150,000 elements. The database will alleviate the need to enter by hand the gamma heat generation in every element. In FY-06, ATR operations required that the schedule for design and fabrication of the AGC-1 capsule and gas control system be realigned to fit ATR's available limited resources. A resource loaded schedule was prepared and accepted by ATR operations. This scheduled split the AGC-1 gas capsule and gas control system into two separate activities. The final design for the AGC-1 capsule is expected by the end of September 2006. Fabrication of the capsule is slated to start the second quarter of FY-07. The AGC-1 gas control system design and

fabrication will start in FY-06 and will finish at the end of FY-07. This extended period of time is necessary to allow ATR personnel to install tubing and equipment in restricted ATR areas during planned outages.

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ACRONYMS

AFCI	Advanced Fuel Cycle Initiative
AG	against grain
AGC	ATR Graphite Creep
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATR	advanced test reactor
dpa	displacements per atom
GA	General Atomics
HOPG	highly oriented pyrolytic graphite
INL	Idaho National Laboratory
JAERI	Japan Atomic Energy Research Institute
MNCP	Monte Carlo N-Particle Transport Code
NGNP	Next Generation Nuclear Plant
OC	ORNL-creep
ORNL	Oak Ridge National Laboratory
PBR	Pebble Bed Reactor
PBMR	Pebble Bed Modular Reactor
PIE	postirradiation examination
SiC	silicon carbide
VHTR	very high temperature reactor
WG	with grain
XRD	X-ray diffraction

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AGC-1 Experimental Plan and Design Report

1. OBJECTIVES

The of irradiation capsule Advanced Test Reactor (ATR) Graphite Creep-1 (AGC-1) provides irradiation creep design data and data for the effects of irradiation creep on key physical properties for several candidate graphites for the Next Generation Nuclear Plant (NGNP) program. It further provides design data for the effects of neutron irradiation on the properties of a range of NGNP relevant graphites, with such data to include: dimensional changes, strength, elastic modulus, thermal conductivity, and coefficient of thermal expansion. Moreover, this experiment will provide valuable data on the single-crystal irradiation behavior of graphites to be derived from the inclusion of highly oriented pyrolytic graphite (HOPG) in this experiment.

2. INTRODUCTION

AGC-1 is one of a series of ATR irradiation creep capsules designed to provide graphite irradiation creep data for NGNP relevant graphites. The AGC-1 capsule provides design data on the effects of irradiation on NGNP relevant graphites over the neutron dose range 0.53×10^{21} n/cm^2–5.8×10^{21} n/cm^2 [E>0.1 MeV], or 0.39–4.2 displacements per atom (dpa), at an irradiation temperature of 900°C. Additional advanced graphite reactor (AGR) capsules are planned for irradiations at 600 and 1200°C to provide design data over the anticipated graphite in-reactor operating temperature.

The data to be obtained from this irradiation capsule include:

- Irradiation creep design data and data on the effects of irradiation creep on key physical properties (e.g., strength, elastic modulus, coefficient of thermal expansion) needed for design, accident analysis, and licensing for the selected NGNP reactor technology.
- The effects of neutron irradiation on the properties of a wide range of NGNP relevant graphites, including dimensional changes, strength, elastic modulus, thermal conductivity, and coefficient of thermal expansion on extruded, iso-molded, and vibrationally molded graphites fabricated from coal and petroleum pitches.
- Data on the single-crystal irradiation behavior of graphites to be derived from HOPG.

The NGNP has chosen a single graphite grade for each of the reactor concepts proposed for the NGNP. Graphite grade NBG-18 has been selected for the pebble bed reactor design while grade PCEA has been selected for the prismatic reactor design. The graphite grades to be included in the AGC-1 capsule can be categorized as follows.

A. Major Grades

These graphites are reactor vendor's candidates for the core structures of NGNP, and include four new grades (NBG-17, NBG-18, PCEA, and IG-430) as well as two historical (reference) grades (H-451 and IG-110). These grades are most likely to receive reasonably large neutron doses in their lifetime and will be subjected to significant stresses in operation. Consequently, these grades occupy the stressed and companion unstressed position in the capsule and yield irradiation creep data. These grades provide a comparison between extruded, iso-molded, and vibrationally molded graphites.

B. Minor Grades

These grades are relevant to the NGNP graphite component design by providing irradiation data on different graphite grades. The irradiation information will be used to further the understanding of all graphite irradiation behavior in computational graphite performance models used to predict graphite lifetimes for different grades.

C. Alternate Grades

These grades are chosen to evaluate the difference in irradiation performance between petroleum and coal coke and between extruded and iso-molded grades. The irradiation information will be used to further the understanding of all graphite irradiation behavior in computational graphite performance models used to predict graphite lifetimes for different grades.

D. Experimental Grades

Two experimental graphites are included in AGC-1 (BAN and A3 matrix). BAN is an experimental grade, secondary coke graphite whose manufacturing process and raw materials are such that it should offer superior irradiation stability. BAN will be studied for future use as well as an analog to recycled graphite. A3 matrix is the blend of graphites and carbonized phenolic resin used as the matrix in the NGNP fuel compact or fuel pebble. Samples of A3 are to be obtained from the Advanced Fuel Cycle Initiative (AFCI) program and will be produced at Oak Ridge National Laboratory (ORNL).

E. Single Crystal Graphite

The dimensional change behavior of graphite is particularly significant to the behavior of polycrystalline (polygranular) graphites. Therefore, samples of HOPG are included in AGC-1.

A more complete description all the graphite samples included in capsule AGC-1 is given in Sections 4 and 5 of this report.

The AGC-1 irradiation capsule contains six pneumatic pistons that apply a controlled stress to the graphite creep samples accommodated in six peripheral channels of the capsule (see Figure 1). A more detailed description of the capsule may be found in the AGC-1 capsule design report. Two stress levels will be used in AGC-1, 13.8 MPa (2 ksi) and 20.7 MPa (3 ksi). These stress levels were chosen based on: (a) historic norms from experiments performed at ORNL in the 1970s and 1980s[1] and (b) detailed discussions with reactor vendors via the American Society of Mechanical Engineers (ASME) graphite core design project team. In addition, each of the six peripheral channels in AGC-1 contains companion unstressed graphite specimens. The apparent irradiation creep strain may be determined from the difference in the dimensional changes between a stressed and unstressed sample irradiated at the same temperature and to the same neutron damage dose. In addition to the unstressed creep control samples, each peripheral channel contains a number of smaller, so-called “piggyback” samples of Very High Temperature Reactor (VHTR) relevant graphites. These piggyback specimens do not provide irradiation creep data, but do provide valuable physical properties data.

In addition, the center channel of capsule AGC-1 accommodates a large number of piggyback samples as well as silicon carbide (SiC) temperature monitors. The SiC temperature monitors provide a post irradiation check on the irradiation temperature and allows for affirmation of the real time temperature data from the capsule thermocouples. Details of the capsule loading plan are given in Section 5 of this Plan.

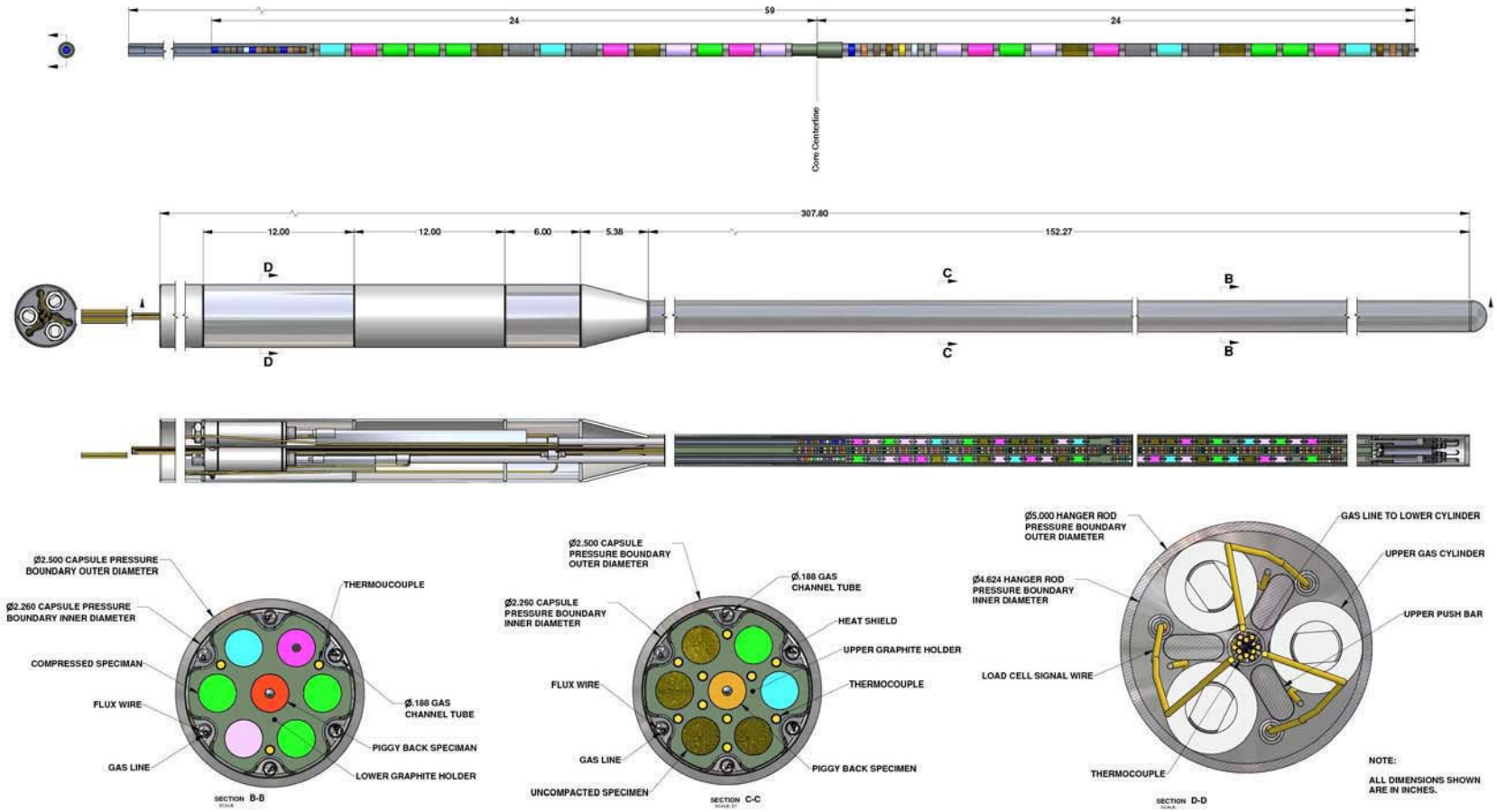


Figure 1. Capsule AGC-1 drawing showing the central and six peripheral channels and the location of the pneumatic pistons.

3. BACKGROUND AND THEORY

Graphite does not thermally creep at temperature below ~1700°C. However, graphite subjected to simultaneous neutron irradiation and temperature will creep (i.e., exhibit a nonreversible, time [neutron flux] and temperature dependant strain in response to an applied stress). The conventional definition of irradiation creep strain is the difference in dimensional changes between a stressed sample and an unstressed sample irradiated under identical conditions. Figure 2 shows this graphically.[2] The mechanism of irradiation creep is thought to be one of irradiation-induced, in-crystal, basal plane dislocation pinning/unpinning. The creep rate is proportional to the rate of atomic displacement, the applied stress, and the unirradiated elastic compliance.

Irradiation-induced creep may be represented by a linear viscoelastic creep equation:

$$\varepsilon = \frac{\sigma}{E_0} + \frac{a\sigma}{E_0}\left[1 - Exp(-b\phi)\right] + k\sigma\phi \qquad (1)$$

where

ε	=	total strain
σ	=	applied uniaxial stress
E_0	=	Initial (preirradiated) Young's Modulus
ϕ	=	fast neutron fluence

a, b, and *k* are creep constants (*a* is usually = 1).

The first term represents the elastic strain, the second term the transient or primary irradiation creep strain, and the third term the steady state or secondary irradiation creep strain. Since the experimentally determined creep strain is the result of postirradiation measurements on the unstressed control samples and the stressed samples measured unstressed, the first term in Equation 1can be neglected.

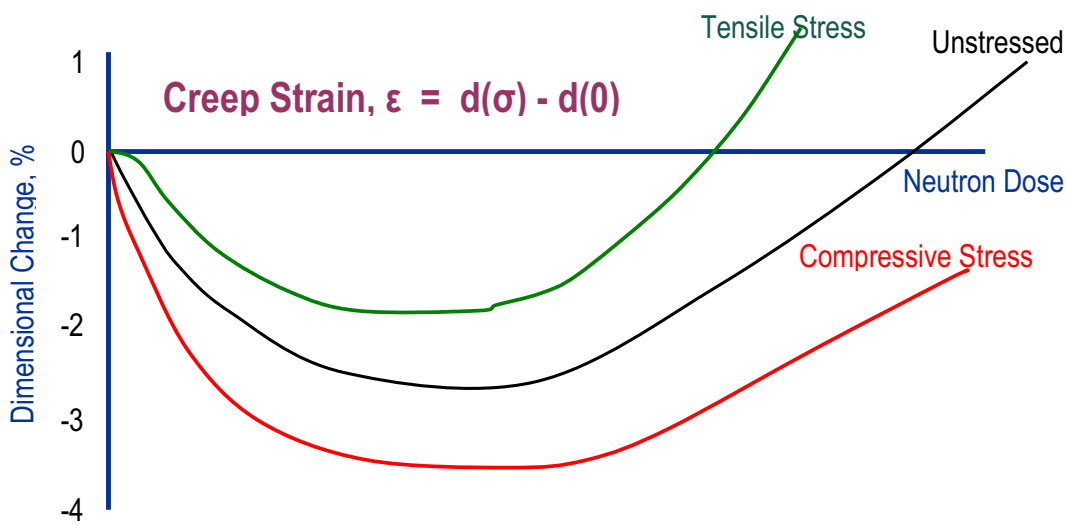


Figure 2. Irradiation-induced dimensional change in stressed and unstressed graphite.

The primary (transient) irradiation creep strain is usually small and is not significant compared to the secondary (steady state) irradiation creep strain, especially at high dose. The second term in Equation 1

suggests that the transient creep strain saturation value should be approximately one elastic strain (applied uniaxial stress divided by unirradiated Young's Modulus), assuming $a = 1$, as is typically found experimentally in low dose creep experiments.[3,4] Thus, the saturation transient creep value is approximately equal to one elastic strain (Figure 3), and the steady state creep strain is linear with dose passing through zero strain at zero dose (Figure 3). Note that dose is expressed in units of n/cm^2 [E>50 keV] in this section. The accepted conversion factor is n/cm^2 [E>50 keV] = n/cm^2 [E>0.1 MeV] × 0.932 [5]. Conversion factors from the popular dose scales to dpa are given elsewhere.[5]

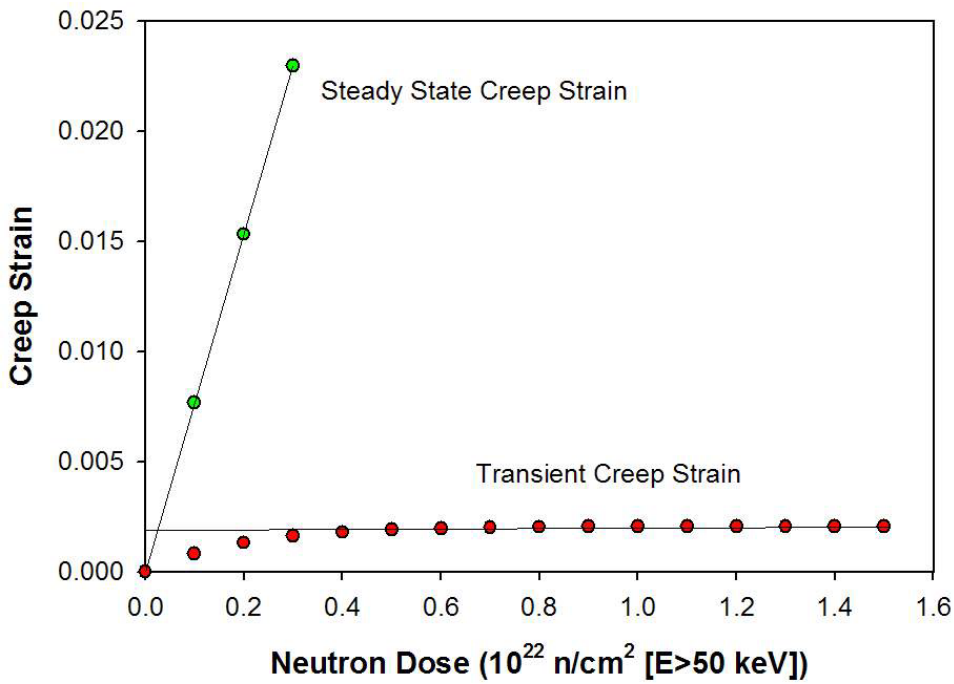


Figure 3. Schematic representations of the transient and steady state creep strains as a function of neutron dose.

The observation that the saturation value of the transient creep strain is approximately equal to the one elastic strain allows a simple linear creep model (Figure 4) of the form:

$$\varepsilon = \frac{\sigma}{E_0} + k'\phi \tag{2}$$

where

ε	=	total irradiation induced creep strain
σ	=	applied uniaxial stress
E_0	=	initial (preirradiated) Young's Modulus
ϕ	=	fast neutron fluence

k' is the steady state creep coefficient (k/σ)

In Equation 2 the transient creep strain is given as one elastic strain and the steady state creep strain as ($k\sigma\phi$) (from Equation 1).

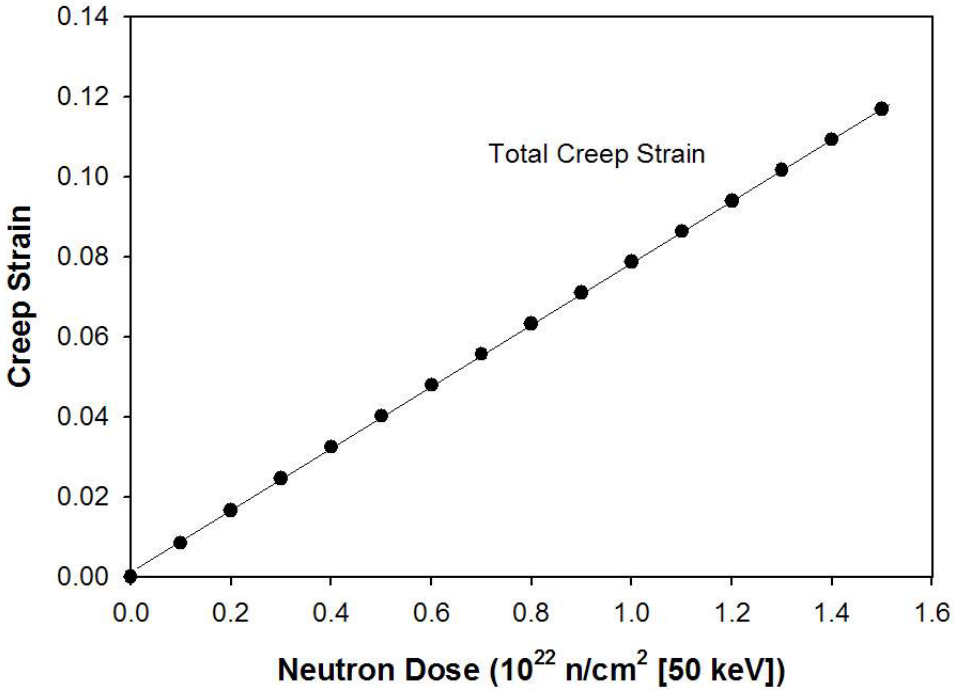


Figure 4. Schematic representation of the total (transient plus steady state) creep strain as a function of neutron dose.

Typical irradiation creep strain data for grade H-451 graphite irradiated in the Oak Ridge Research Reactor at stress levels of 20.7 and 13.8 MPa and at an irradiation temperature of 900°C is shown in Figure 5.

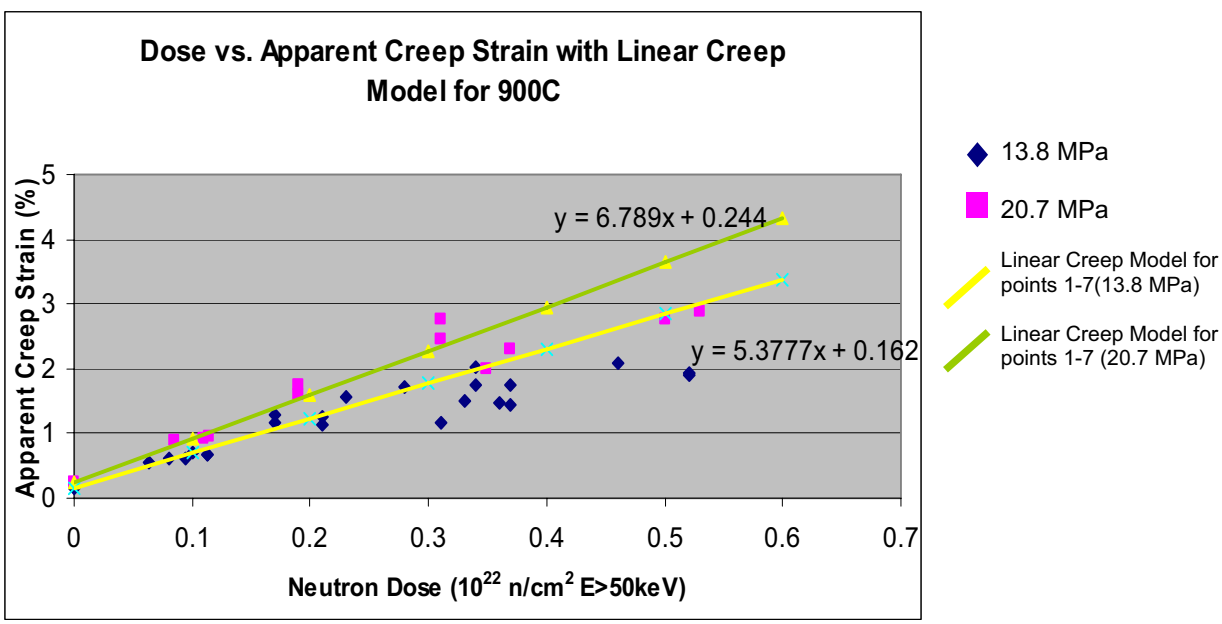


Figure 5. Grade H-451 graphite irradiation creep strain as a function of dose at an irradiation temperature of 900°C and at two compressive stress levels (13.8 and 20.7 MPa).

The apparent creep strain (measured post irradiation as discussed above) is well represented by the linear model (Equation 2) at moderate doses; but, at higher doses the fit is unsatisfactory. This observation has led to the development of a new creep model in which the apparent creep strain (determined as described above) is corrected to allow for the effect of creep strain on the dimensional change component of the graphite.[6] Indeed, the current definition of creep that is the difference in length between a stressed and an unstressed control specimen is only correct if the dimensional change component in the stressed specimen is the same as that in the control.[7] In fact, creep produces significant modifications in the dimensional change component of the stressed sample as compared to that of the control sample, and this should be accounted for in the correct evaluation of creep strain. Actually, the true (corrected) creep strains are always greater than those obtained from the current definition of creep strain.

The rate of change of dimensions with respect to neutron dose γ (n/cm^2) in appropriate units is given by the Simmons' theory for direction x in the graphite (see Reference 5):

$$g_x = \left(\frac{\alpha_x - \alpha_a}{\alpha_c - \alpha_a}\right)\left(\frac{dX_T}{d\gamma}\right) + \frac{1}{X_a}\cdot\frac{dX_a}{d\gamma} \tag{3}$$

where

α_x	=	the thermal expansion coefficient in the x-direction
α_c and α_a	=	the thermal expansion coefficients of the graphite crystal parallel and perpendicular to the hexagonal axis respectively, over the same temperature range.

The parameters $(1/X_c)(dX_c/d\gamma)$ and $(1/X_a)(dX_a/d\gamma)$ are the rates of change of graphite crystallite dimensions parallel and perpendicular to the hexagonal axis, and

$$\frac{dX_T}{d\gamma} = \frac{1}{X_c}\cdot\frac{dX_c}{d\gamma} - \frac{1}{X_a}\cdot\frac{dX_a}{d\gamma} \tag{4}$$

The imposition of a creep strain is known to change the thermal expansion coefficient of a stressed specimen, increasing it for a compressive strain and decreasing it for a tensile strain compared to an unstressed control (see Reference 4). This is illustrated in Figure 6 for H-451 graphite irradiated at 900°C. Thus, the dimensional change component of a stressed specimen at dose γ (n/cm^2) is given by:

$$g'_x = \left(\frac{\alpha'_x - \alpha_a}{\alpha_c - \alpha_a}\right)\left(\frac{dX_T}{d\gamma}\right) + \frac{1}{X_a} * \frac{dX_a}{d\gamma} \tag{5}$$

where

α'_x	=	the thermal expansion coefficient of the crept sample.

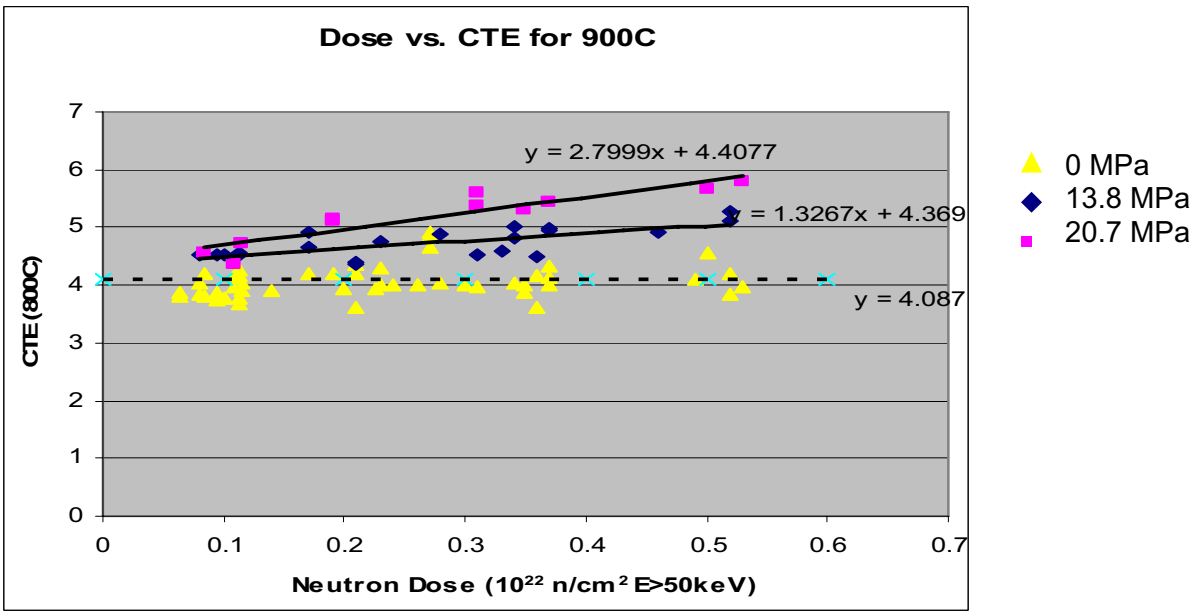


Figure 6. The variation of coefficient of thermal expansion with neutron dose for unstressed and stressed H-451 graphite samples irradiated at 900°C.

The difference between Equations 3 and 5 is the dimensional change correction that should be applied to the apparent creep strain.

$$g'_x - g_x = \left(\frac{\alpha'_x - \alpha_a}{\alpha_c - \alpha_a}\right)\left(\frac{dX_T}{d\gamma}\right) - \left(\frac{\alpha_x - \alpha_a}{\alpha_c - \alpha_a}\right)\left(\frac{dX_T}{d\gamma}\right) = \left(\frac{\alpha'_x - \alpha_x}{\alpha_c - \alpha_a}\right)\left(\frac{dX_T}{d\gamma}\right) \tag{6}$$

The true creep strain rate can now be expressed as

$$\frac{d\varepsilon}{d\gamma} = \frac{d\varepsilon'}{d\gamma} - \left(\frac{\alpha'_x - \alpha_x}{\alpha_c - \alpha_a}\right)\left(\frac{dX_T}{d\gamma}\right) \tag{7}$$

where

E = the true creep strain
ε′ = the apparent creep strain determined experimentally in the conventional manner.

Thus the true creep strain (ε_c) parallel to the applied creep stress is given by:

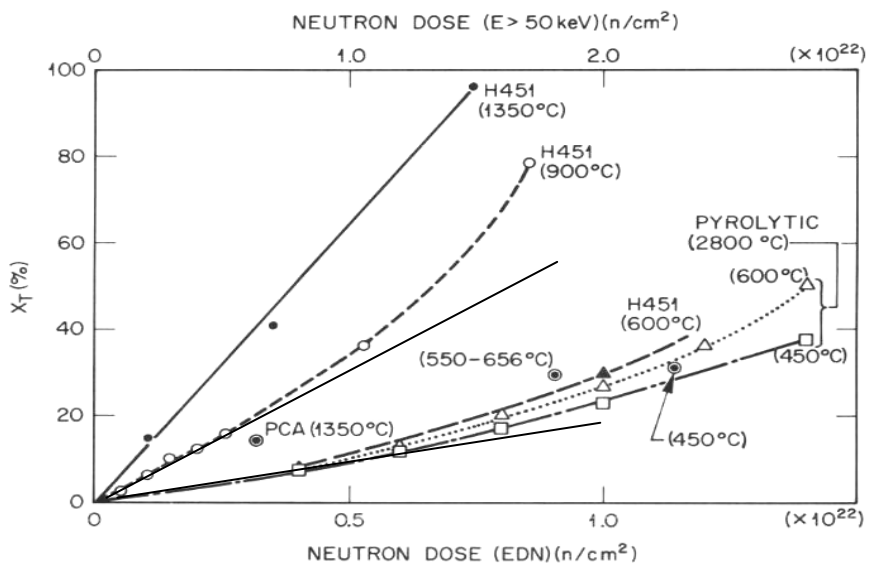
$$\varepsilon_c = \varepsilon'_c - \int_0^{\gamma}\left(\frac{\alpha'_x - \alpha_x}{\alpha_c - \alpha_a}\right)\left(\frac{dX_T}{d\gamma}\right)\cdot d\gamma \tag{8}$$

where

ε'_c = the induced apparent creep strain
$(\alpha'_x - \alpha_x)$ = the change in coefficient of thermal expansion as a function of dose

$(\alpha_c - \alpha_a)$ = the difference of the crystal thermal expansion coefficients of the graphite parallel and perpendicular to the hexagonal axis
X_T = the crystal shape change parameter given by Equation 4,
γ = the neutron dose.

Inspection of Equation 8 indicated that the true creep strain is always greater than the apparent (measured) creep strain. For compressive creep loading, the apparent creep strain is negative and $(\alpha'_x - \alpha_x)$ is positive, so the true creep strain is greater than the apparent creep strain. For tensile creep loading, the apparent creep strain is positive and $(\alpha'_x - \alpha_x)$ is negative, so the true creep strain is also greater. The parameter, X_T, is determined from the dimensional change behavior of single-crystal graphite, or its close analogue, HOPG. It can also be determined from the polycrystalline graphite behavior if there is sufficient anisotropy in the irradiation-induced dimensional changes. The parameter, X_T, is linear with dose at low doses, as shown in Figure 7. The term $(\alpha_c - \alpha_a)$ in Equation 8 is the difference between the graphite single-crystal thermal expansion coefficients (unirradiated) and has the value 27×10^{-6}°C^{-1}. The application of the correction to the apparent creep strain for H-451 graphite irradiated at 900°C is given in Figure 8. The true creep strain (i.e., the experimentally measured apparent creep strain corrected for in the manner described above) is well represented by the linear creep model (Equation 2). The fit to a linear relationship, with an intercept of one elastic strain is clearly demonstrated and correlation coefficients of 0.9 or better were attained.



Note: X_T is linear at low doses (constant $dX_T/d\gamma$) for the 600°C and 900°C data.

$dX_T/d\gamma$ (600°C) = 1.0 x 10^{-23} cm^2/neutron (E> 50keV)
$dX_T/d\gamma$ (900°C) = 3.31 x 10^{-23} cm^2/neutron (E> 50keV)

Figure 7. The variation of X_T with neutron dose for H-451 graphite at several irradiation temperatures.

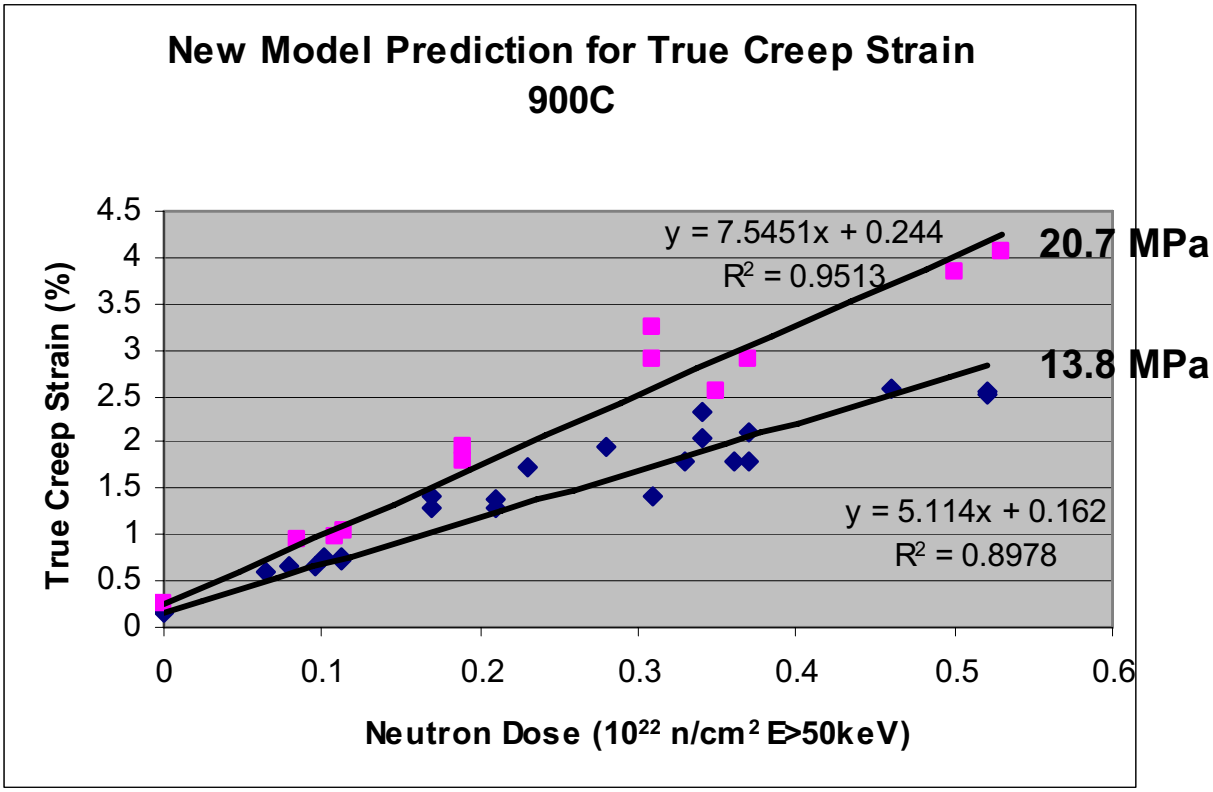


Figure 8. The variation of the true creep strain with neutron dose for H-451 graphite irradiated at 900°C and at two stress levels.

Table 1 reports the terms of the linear creep model for true creep strains for H-451 graphite determined from the prior experiments conducted in the Oak Ridge Research Reactor. For any applied compressive stress level the true creep strain in H-451 graphite is given by:

$$\varepsilon_c = \sigma/E_0 + k'\sigma\gamma \qquad (9)$$

And from Table 1 at 900 and 600°C, respectively, the compressive creep strain is given by:

$$\varepsilon_c = 10^{-1}\cdot \sigma/E_0 + 0.37\sigma\gamma \text{ (\%), and}$$

$$\varepsilon_c = 10^{-1}\cdot \sigma/E_0 + 0.20\sigma\gamma \text{ (\%)} \qquad (10).$$

Table 1. Linear creep model terms for H-451 graphite.

Irradiation Temperatures	Stress (MPa)	σ/E_0 (%)	k	k' (k/σ) 10^{-29}cm^2/n.Pa
900°	13.8	0.162	5.114	0.37
900°	20.7	0.244	7.545	0.37
600°	13.8	0.162	2.748	0.20
600°	20.7	0.244	4.164	0.20

To apply the correction to the experimentally observed (apparent) creep strain data, the effects of neutron dose on X_T and the thermal expansion coefficients (of the stressed specimens and the unstressed control specimens) must be determined. Consequently, the AGC series of experiments will contain graphite samples of sufficient size to allow the determination of the coefficients of thermal expansion and samples of HOPG to yield direct data for the effects of neutron dose on X_T.

Finally, the proper definition of creep strain (i.e., true creep strain) is "the difference in dimensions between a stressed sample and a sample with the same properties as the stressed sample irradiated unstressed."

4. MATERIALS AND TEST CONDITIONS

4.1 Graphite grades

The graphites to be included in AGC-1 are given in Table 2 along with information on their potential application in an NGNP. Creep data will be obtained for six major graphite grades (i.e., both stressed and unstressed samples of these grades are included in the capsule). The major grades are H-451 and IG-110, both of which are included as reference graphites, and four new grades: PCEA, NBG-17, NBG-18, and IG-430. These four graphites are all contenders for use in potential NGNP designs, such as the Pebble Bed Modular Reactor (PBMR), or prismatic block reactors, such as the General Atomics' design Gas Turbine Modular Helium Reactor or Framatome/AREVA's prismatic reactor design. In addition, AGC-1 contains ten minor grades of graphite. These minor grades are not located in the stressed section of the capsule. Thus, no creep data will be generated for them. However, as previously discussed, they will subsequently yield significant amounts of design data. The minor grades include candidates for lower dose locations in the prismatic reactor designs. The prismatic reactor designs include permanent reflectors and core supports components, such as grades HLM, PGX, PCIB, NBG-25, and 2020. Three additional grades of graphite are included in AGC-1 because of their interest to the NGNP program: NBG-10, PPEA, and BAN. Grade NBG-10 is an extruded grade, and its behavior is of interest in comparison with the vibrationally molded grades NBG-17 and -18. Grade PPEA provides a comparison of the performance of identical pitch-coke and petroleum-coke graphites. BAN graphite is an experimental grade that is expected to exhibit superior irradiation behavior. A3 fuel matrix (a graphite filler carbonized resin binder material) is included to yield dimensional change and physical property data for the AFCI research program. Finally, samples of HOPG are included to provide vital data on the crystal dimensional change rates and, hence, the parameter X_T. Capsule AGC-1 graphite grades, vendors, and available processing information are given in Table 3.

Table 2. Experiment AGC-1 graphite materials test matrix.

Graphite	Reactor Vendor	Proposed Use	Capsule Location	Remarks
H-451	General Atomics	Prismatic fuel element and replaceable reflector	Creep	Historical reference Only a few samples
IG-110	JAERI, INET	Prismatic fuel element, replaceable reflector, and core support pedestals Pebble bed reflector	Creep	Historical reference Only a few samples Currently being used in the HTTR and HTR-10
PCEA	AREVA	Prismatic fuel and replaceable block	Creep	AREVA wants to construct the entire graphite core out of the same graphite
NBG-18	PBMR AREVA	Pebble bed reflector structure and insulation blocks Prismatic fuel element and replaceable reflector	Creep	Candidate for PBMR replaceable reflector
NBG-17	AREVA PBMR	Prismatic fuel element and replaceable reflector Pebble bed reflector structure and insulation blocks	Creep	AREVA wants to construct the entire graphite core out of the same graphite NBG-17 is finer grain than NBG-18

Table 2 (cont.)

Graphite	Reactor Vendor	Proposed Use	Capsule Location	Remarks
IG-430	JAERI	Prismatic fuel element, replaceable reflector, and core support pedestals	Creep	JAERI wants to use this graphite in the GTHTR 300
HLM		Prismatic large permanent reflector	Piggyback	Fort St. Vrain permanent reflector. Similar to PGX
PGX	AREVA JAERI	Prismatic large permanent reflector	Piggyback	AREVA may use this material; preference is to use PCEA or NBG-17 for permanent reflector. HTTR permanent structure.
NBG-25		Core support candidate	Piggyback	Isostatic fine grain
2020		Prismatic core support pedestals and blocks	Piggyback	Fine grain isotropic NPR candidate material
PCIB		Core support candidate	Piggyback	Fine grain isotropic
BAN			Piggyback	Experimental graphite with potentially superior irradiation life
NBG-10	PBMR	Prismatic fuel element and replaceable reflector Pebble bed reflector structure and insulation blocks	Piggyback	PBMR's original choice for replaceable reflector Price/performance will be the basis between NBG-18 and NBG-10
PPEA		Needed to provide comparison with PCEA	Piggyback	Provides direct comparison of pitch coke and petroleum coke graphite performance
HOPG		Needed to determine change in crystalline structure	Piggyback	Provides insight to single crystal changes during neutron irradiation
A3 Matrix		Needed to determine fuel compact irradiated material behavior	Piggyback	Provides dimensional change and thermal conductivity data for matrix materials

Table 3. Capsule AGC-1 graphite grades, vendors, and available processing information.

Graphite Grade	Source	Country of Origin	Process Details
NBG-17	SGL Carbon	Germany/France	Pitch coke, vibrationally molded, medium grain
NBG-18	SGL Carbon	Germany/France	Pitch coke, vibrationally molded, medium grain
H-451 (Reference Grade)	SGL Carbon	USA	Petroleum coke, extruded, medium grain

Table 3 (cont.)

Graphite Grade	Source	Country of Origin	Process Details
PCEA	Graftech International	USA	Petroleum coke, extruded, medium grain
IG-110 (Reference Grade)	Toyo Tanso	Japan	Petroleum coke, isostatically molded, fine grain
IG-430	Toyo Tanso	Japan	Petroleum coke, isostatically molded, fine grain
Highly Oriented Pyrolytic Graphite	Advanced Ceramics	USA	Gas phase deposition, high temperature annealed
A3 Matrix Graphite/Carbon	ORNL	USA	Blend of natural flake and manufactured graphite powders, phenolic resin bonded, hot pressed and carbonized
HLM	SGL Carbon	USA	Petroleum coke, extruded, medium grain
PGX	GrafTech International	USA	Petroleum coke, molded, medium grain
PPEA	GrafTech International	USA	Pitch coke, extruded, medium grain
NBG-25	SGL Carbon	Germany/France	Isostatically molded, fine grained
2020	Carbone of America	USA	Isostatically molded, fine grained
PCIB	GrafTech International	USA	Petroleum coke, isostatically molded, fine grained
BAN	GrafTech International	USA	Petroleum (needle) coke, secondary/green coke process, extruded, medium grain
NBG-10	SGL Carbon	France	Pitch coke, extruded, medium grain

Tables 4 through 6 report the numbers of major (stressed/unstressed creep) samples and minor (piggyback) samples per grade in the AGC-1 capsule. Details of the locations of these specimens are given in Section 5.

Table 4. Graphite grades and the number of samples included in the central channel of irradiation capsule AGC-1.

Graphite Grade	Source	Number of Central Column Samples
Highly Oriented Pyrolytic Graphite (HOPG)	Advanced Ceramics	20
A3 Matrix Graphite/Carbon	ORNL	20
HLM	SGL Carbon	19
PGX	Graftech International	19
PPEA	Graftech International	19
NBG-25	SGL Carbon	19

Table 4 (cont.)

Graphite Grade	Source	Number of Central Column Samples
2020	Carbone of America	19
PCIB	Graftech International	19
BAN	Graftech International	19
NBG-10	SGL Carbon	19
Total		192

Table 5. The number of stressed/unstressed samples and their graphite grades included in the peripheral channels of irradiation capsule AGC-1.

Graphite Grade	Source	Number of Stressed/Unstressed Peripheral Column Samples
NBG-17	SGL Carbon	34
NBG-18	SGL Carbon	34
H-451 (Reference Grade)	SGL Carbon	20
PCEA	Graftech International	34
IG-110 (Reference Grade)	Toyo Tanso	20
IG-430	Toyo Tanso	32
Total		174

As reported in Table 5, a total of 40 reference grade specimens will be included in AGC-1 compared to 134 candidate graphite specimens. The reference samples provide a link to historic creep data, thus giving confidence that the capsule has functioned correctly and our experiment has been successful. A sufficient number of reference grade specimens are included to cover the experiment dose range.

Table 6. The number of piggyback samples, and their graphite grades, included in the peripheral channels of irradiation capsule AGC-1.

Graphite Grade	Source	Number of Peripheral Column Samples
NBG-17	SGL Carbon	20
NBG-18	SGL Carbon	20
PCEA	Graftech International	20
IG-430	Toyo Tanso	18
IG-110(Reference Grade)	Toyo Tanso	9
H-451 (Reference Grade)	SGL Carbon	9
HOPG	GE Advanced Ceramics	6
A3 MATRIX	ORNL	6
HLM	SGL Carbon	5
PGX	Graftech International	4
PPEA	Graftech International	5

Table 6 (cont.)

Graphite Grade	Source	Number of Peripheral Column Samples
NBG-25	SGL Carbon	5
2020	Carbone of America	5
PCIB	Graftech International	5
BAN	Graftech International	9
NBG-10	SGL Carbon	4
Total		150

4.2 Test Conditions

Capsule AGC-1 is the first of a planned series of graphite creep capsules to be irradiated in the ATR. Capsules AGC-1 through AGC-6 are all planned for the south flux trap, and capsules AGC-7 through AGC-9 are tentatively planned for an "A-hole" position in ATR. The A-hole irradiations are very high neutron dose and would only be relevant to a PBMR version of the NGNP. The high dose irradiations (AGC-7 through -9) will be considered at some point in the future when the NGNP concept has been selected. Capsules AGR-1 and 2 will be 900°C irradiations, AGR-3 and 4 will be 1200°C irradiations, and AGR-5 and 6 will be 600°C irradiations. The family of AGR capsules will, therefore, provide graphite irradiation effects data (especially creep data) across the anticipated in-reactor operating range for the candidate graphites discussed here.

Capsule AGC-1 will be irradiated for 170 days to an estimated peak neutron dose (fluence) of 5.8×10^{21} n/cm^2 [E>0.1MeV] or 4.2 DPA. Estimated doses have been obtained for the specimens in the capsule from prior ATR dosimetry models. The flux prediction model is a polynomial function of the form.

$$\text{Flux } \phi = A + Bx^2 + Cx^2 + Dx^2 \quad (\text{n/cm}^2.\text{s}) \text{ [E>0.1 MeV]} \tag{11}$$

where

x = the distance from the reactor core bottom in inches.

The coefficients A, B, C, and D are given in Table 7 for the center channel and six peripheral channels in the AGC-1 capsule. The flux distributions are graphically shown in Figure 9 for the six peripheral channels and the center channel. The flux center line is not coincident with the core centerline, the flux centerline being located approximately 2 in. below the core centerline. Moreover, the flux distribution is not completely symmetrical about its centerline within the ATR core.

Table 7. ATR south flux trap neutron flux model coefficients.

AGC-1 Channel	Flux Model Coefficients			
	A	B	C	D
Center	0.7371	0.2748	-0.007253	0.00002842
1-North	0.8309	0.3011	-0.007991	0.00003242
2-North East	0.7984	0.2893	-0.007618	0.00002927
3-South East	0.7244	0.2538	-0.006594	0.00002380
4-South	0.6613	0.2379	-0.006214	0.00002329
5-South West	0.7029	0.2550	-0.006588	0.00002371
6-North West	0.7966	2.8318	-0.007335	0.00002679

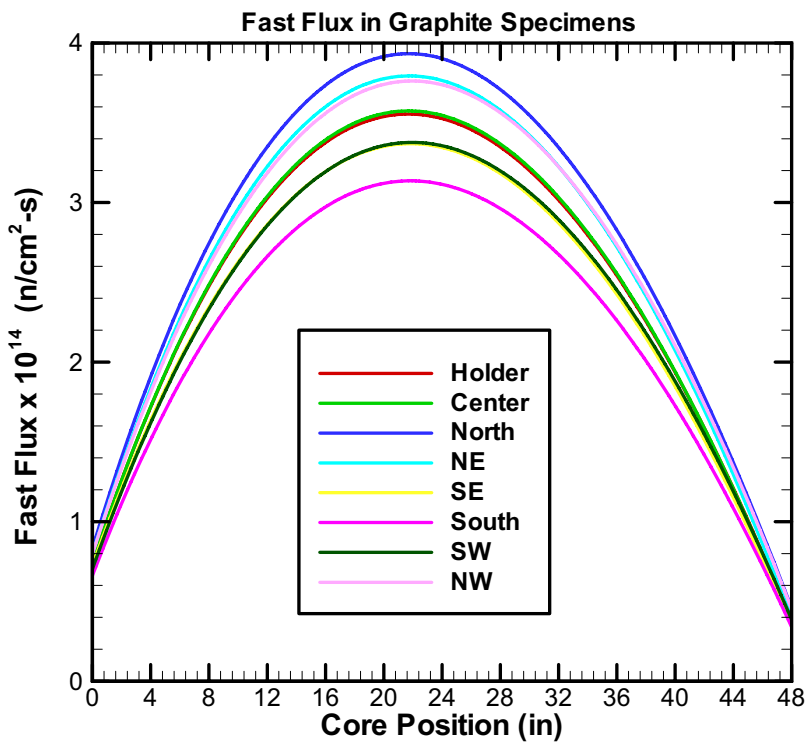


Figure 9. Neutron flux distribution in the AGC capsule channels within the ATR south flux trap.

The AGC-1 experiment will contain a series of flux wires located at intervals throughout the capsule. The postirradiation data from these wires will be used to calibrate the flux models and yield improved dose estimates for each specimen in the capsule.

The planned irradiation temperature for AGC-1 is 900°C. The capsule will be fully instrumented, containing a sufficient number of thermocouples to allow calibration of the thermal hydraulic code used to estimate the specimen temperatures. In addition, capsule AGC-1 will contain 19 SiC temperature monitors that yield postirradiation estimates of the maximum irradiation temperature attained in the capsule at each SiC monitor location.

SiC has been used as a postirradiation temperature monitor material for more than 40 years. Current usage is based on measurable electrical resistivity changes that occur when the previous maximum irradiation temperature is achieved due to annealing of dangling bonds by mobile point defects.[8] Thus, a series of isochronal anneals at discrete temperature intervals, followed by determination of the electrical resistivity using a four-point probe technique, yields an estimate of the actual maximum irradiation temperature. As discussed by Snead, et al. (See Reference 6), in experiments that have had both thermocouples and have used SiC monitors, the agreement between the in situ irradiation temperature and the postirradiation temperature determined for SiC monitors has been good, with indicated differences as small as 20°C. The SiC temperature monitors will be rods 44.5 mm in length and 2 mm in diameter with a flat ground on one side for ease of the four-point probe resistivity measurement (see Figure 10). The SiC monitors will be located in the central channel of capsule AGC-1 inside the graphite specimen clusters (see Figure 11).

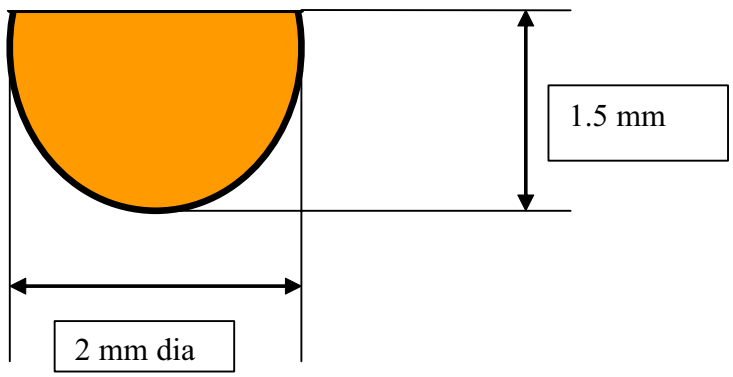


Figure 10. Cross-sectional dimensions of the SiC temperature monitors to be used in AGC-1.

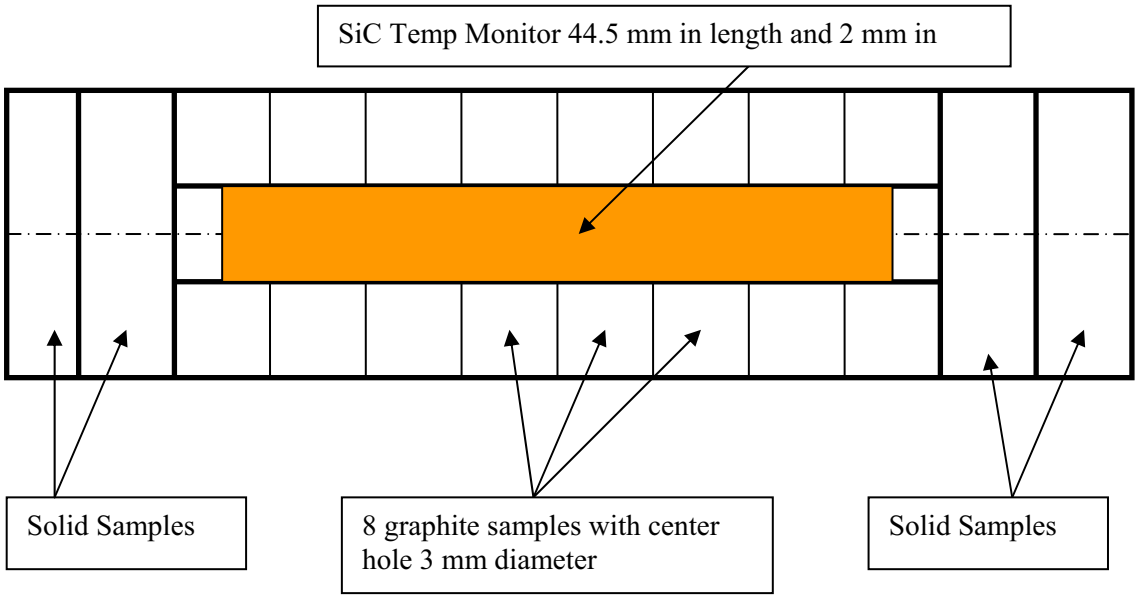


Figure 11. AGC-1 central channel graphite and SiC sample cluster.

The stressed samples in the peripheral channels will be subjected to an applied compressive stress by means of a pneumatic piston. The anticipated stress in each channel/specimen stack is given in Table 8.

Table 8. Stress levels in the stressed samples in the AGC-1 experiment.

Peripheral Channel Number	Peripheral Channel Designation	Applied Compressive Stress (ksi)	Applied Compressive Stress (MPa)
1	N	3	20.7
2	NE	2	13.8
3	SE	3	20.7
4	S	2	13.8
5	SW	3	20.7
6	NW	2	13.8

The load on each stressed graphite column will be continuously monitored by means of button-load cells located in line with each pneumatic cylinder at the top of the channel. The pressure within each pneumatic piston will be continuously controlled to maintain the design stress level.

Each peripheral channel will have a second pneumatic piston at the bottom of the capsule that is capable of loading the graphite sample stack. Periodically, the load applied by the primary piston will be relaxed, and the graphite specimen stack will be "upset" by loading from the second piston. This procedure will ensure that the graphite stack is not jammed in the channel and that the applied load is actually being transmitted to all the stressed specimens in the channel. This provision is based on prior creep capsule operating history and experience (see Reference 1).

4.3 Irradiation Specimen Geometries

Only nominal specimen dimensions are given here because the final dimensions are dependant on the capsule design thermal and mechanical analysis, which has not been completed at this time. Billet cutting plans will be developed for each of the graphites to be included in AGC-1. The cutting plans will take into account spatial variations and anisotropy considerations resulting from graphite forming (textural effects). In addition, the cutting plans will identify a specimen numbering scheme that will ensure a unique identity for each specimen traceable to the grade, billet numbers, and position within the graphite billet. The billet cutting plans will be reported in the AGC-1 preirradiation data report.

4.3.1 Center Channel Piggyback Samples

The center channel of AGC-1 is occupied by 19 clusters of graphite samples. Each cluster is made up of eight piggyback samples of nominal diameter 0.5 in. (12.7 mm) and height 0.25 in. (6.35 mm). Each of these samples has a central 3 mm diameter hole into which the SiC temperature monitor will be inserted (see Figure 10). Each eight-sample cluster has two solid graphite samples [nominal diameter 0.5 in. (12.7 mm) and height 0.25 in. (6.35 mm)] located above and below it. The center channel contains a total of 192 samples (Table 4).

4.3.2 Creep Samples

The stressed/unstressed graphite creep pairs are of identical geometry (i.e., solid cylinders of nominal length 1.0 in. [25.4 mm] and nominal diameter 0.5 in. [12.7 mm]).

4.3.3 Peripheral channel piggyback samples

The peripheral (creep) channels each contain numerous piggyback specimens. The piggybacks are not stressed. As indicated in Figure 1, the upper section of the peripheral channels contain a hollow graphite thimble within which are located 15 solid graphite specimens of nominal thickness 0.5 in. (12.7 mm). The diameter of these specimens is as yet undetermined. An additional ten piggyback specimens are located in the lower portion of each peripheral (creep) channel above and below the unstressed companion specimens. These specimens have nominal dimensions of 0.5 in. (12.7 mm) in diameter and 0.25 in. (6.35 mm) in height.

5. AGC-1 Capsule Layout

As previously discussed, the prime objective of experiment AGC-1 is to provide irradiation creep rate data. This requires matched pairs of stressed and unstressed samples to be irradiated. In previous experiments (see Reference 1), this has been achieved by having stressed and unstressed samples in adjacent channels within the capsule. However, the unique design and operational characteristics of the ATR cause a significant transverse flux gradient across the capsule, thus precluding the adjacent channel design. Therefore, the AGC series will have the matched specimens within each channel (i.e., the stressed specimens above the core centerline and the unstressed specimens below the core centerline in each channel). A further complication to this approach is the non-symmetrical flux distribution and the offset of the flux and core centerlines (see Figure 9). Consequently, the layout of the stressed and unstressed specimens is not symmetrical. In fact, there are fifteen stressed specimens above the core center plug and fourteen unstressed specimens below the core center plug, but further offset by a short stack of piggyback specimens. One of the unstressed samples (Number U11) serves as the unstressed companion to two of the stressed samples (S11 and S12) in each channel. The irradiation samples (and hence graphite grades) are distributed throughout the peripheral channels in the AGC-1 capsule. This is so the failure of any one of the channels will not jeopardize the entire data set for any single graphite grade.

Channel loading plans are given for each of the six peripheral (creep) channels and the center channel in the Appendixes A thourgh G. The peripheral channel specimens are numbered from the reactor top downward such that piggyback sample 1 (PB1) is at the top of each channel and piggyback sample 25 (PB25) is at the bottom of each channel. The 15 piggyback specimens in the top of each peripheral channel are located inside a graphite thimble that is part of the push rod assembly. The channels are numbered clockwise one through six, corresponding to the N, NE, SE, S, SW, and NW channel designations, respectively. Each channel loading plan gives:

- The specimens location within the channel
- The grade of graphite
- The specimens unique identification number (this will be laser engraved on the specimen)
- The nominal length and diameter of the specimen
- The cumulative specimen stack distance from the core bottom
- The samples centerline distance from the core bottom (used in the calculation of the estimated specimen dose)
- The calculated fast flux (from Equation 11)
- The specimens estimated neutron damage dose in n/cm^2 [E > 0.1 MeV] and dpa.

The final column in the peripheral (creep) channel loading plans indicates which stressed and unstressed specimens are paired (companion specimens). The center stack loading plan is identical in layout with the exception that the last column indicates which piggyback samples have a SiC temperature monitor inserted in their center. The loading plans are color coded for ease of interpretation. The peripheral channel piggyback samples are colored blue, stressed and unstressed creep samples are colored pink, the core center plug is colored red, and the graphite spacers are colored white. The center channel loading plan has the specimen clusters colored tan and the end pair piggyback samples colored pink.

Figures 12 through 18 provide a visual representation of each channel/specimen stack in the AGC-1 capsule. The specimens and their graphite grade are represented by bars, the heights of which are equal to the estimated total dose in dpa. The widths of the bars are representative of the specimen height, and the bars are color coded to identify the graphite grade.

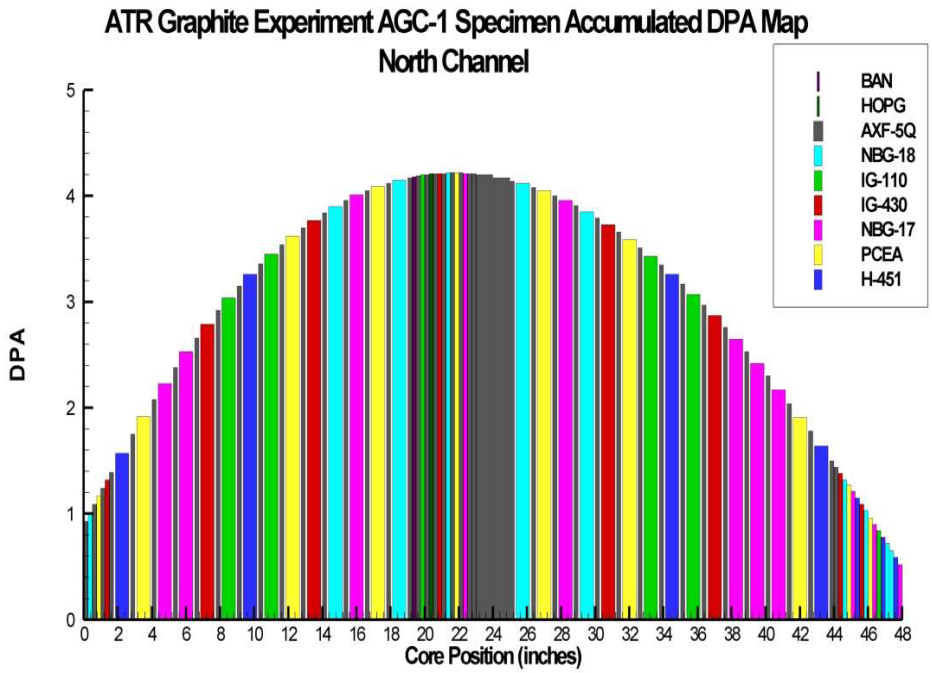


Figure 12. Neutron dose map for AGC-1 peripheral Channel 1 (North) showing the spatial location and total neutron damage dose (dpa) per specimen/graphite grade.

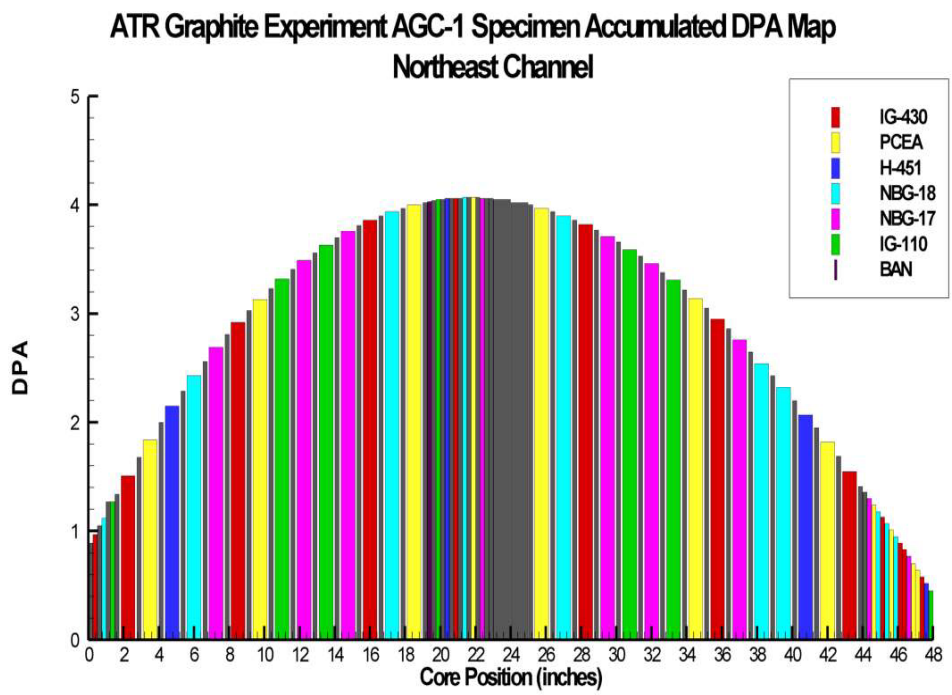


Figure 13. Neutron dose map for AGC-1 peripheral Channel 2 (North-East) showing the spatial location and total neutron damage dose (dpa) per specimen/graphite grade.

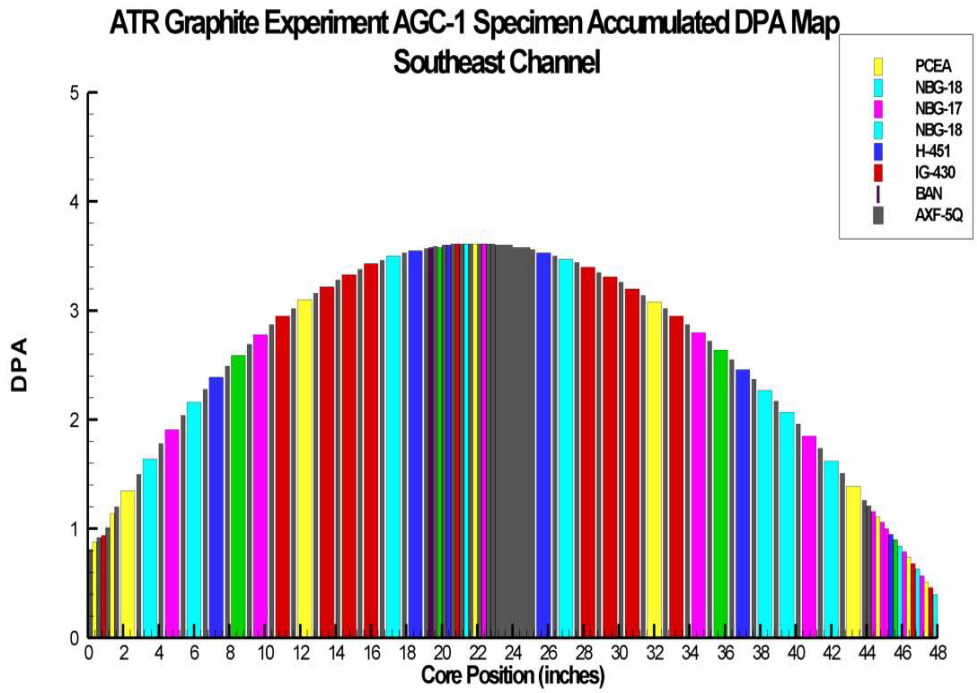


Figure 14. Neutron dose map for AGC-1 peripheral Channel 3 (South-East) showing the spatial location and total neutron damage dose (dpa) per specimen/graphite grade.

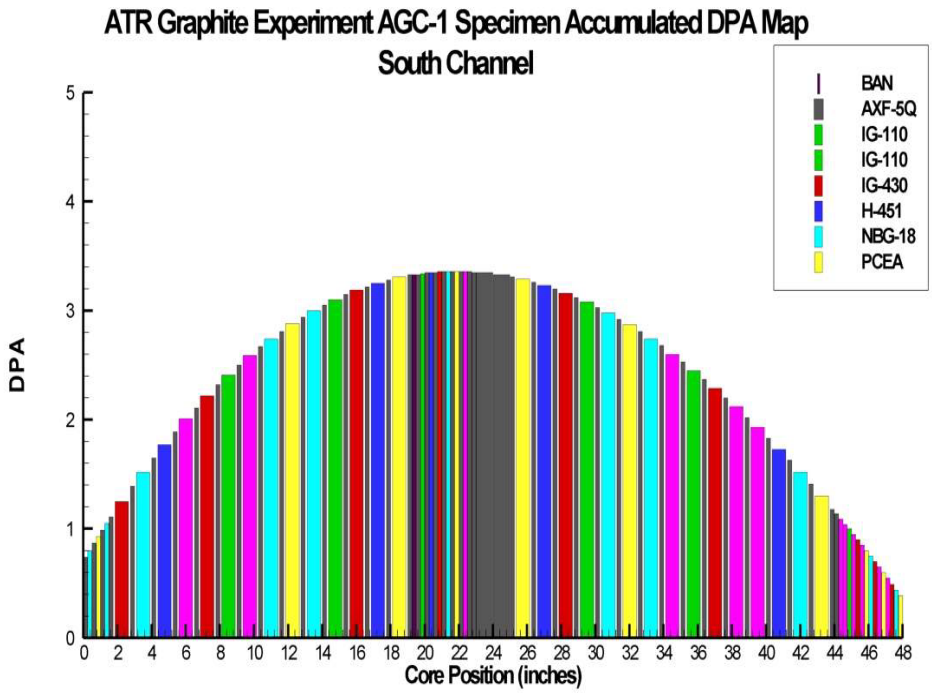


Figure 15. Neutron dose map for AGC-1 peripheral Channel 4 (South) showing the spatial location and total neutron damage dose (dpa) per specimen/graphite grade.

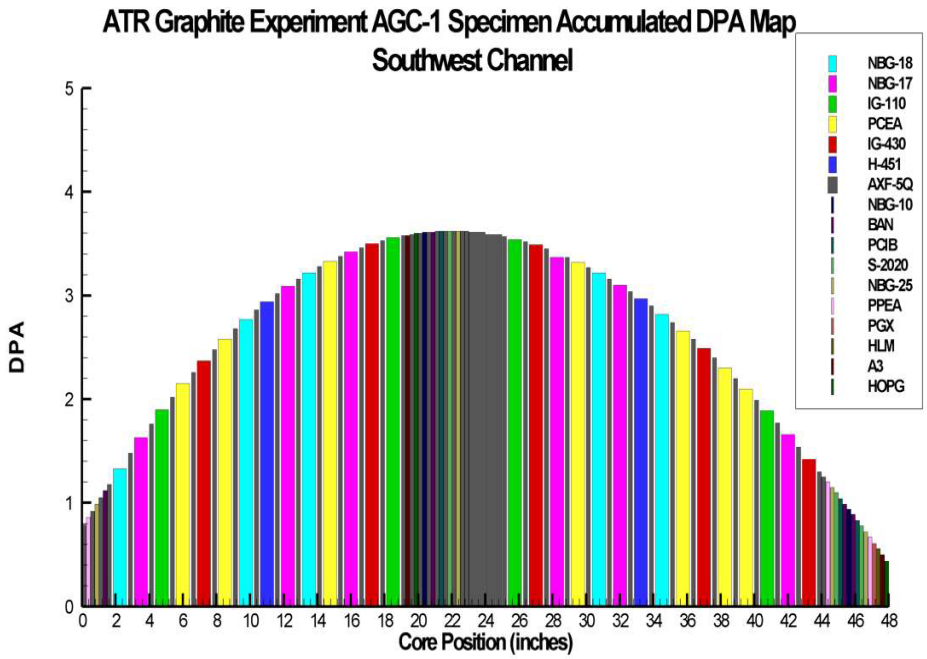


Figure 16. Neutron dose map for AGC-1 peripheral Channel 5 (South -West) showing the spatial location and total neutron damage dose (dpa) per specimen/graphite grade.

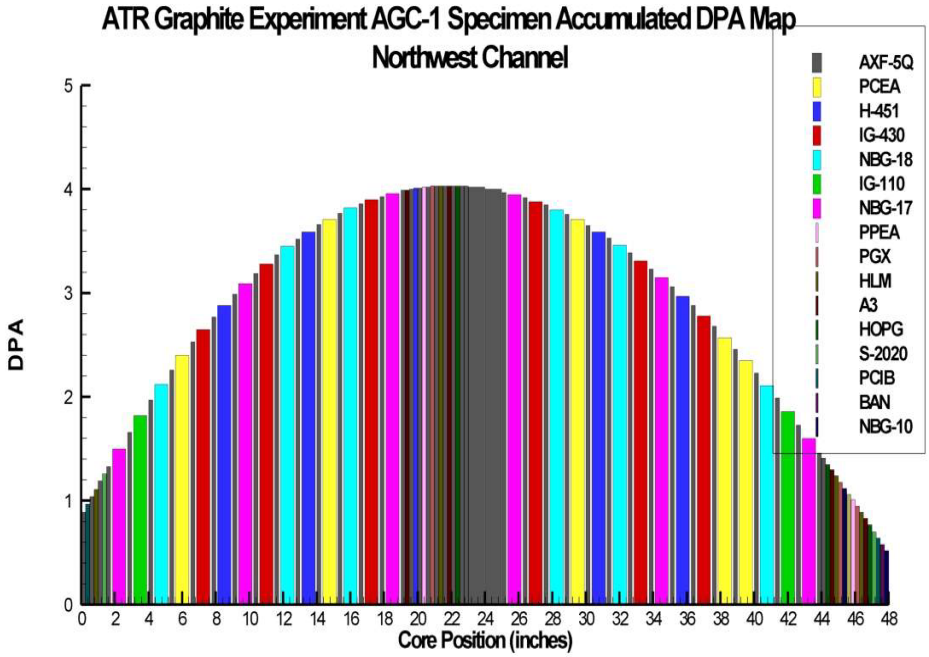


Figure 17. Neutron dose map for AGC-1 peripheral Channel 6 (North-West) showing the spatial location and total neutron damage dose (dpa) per specimen/graphite grade.

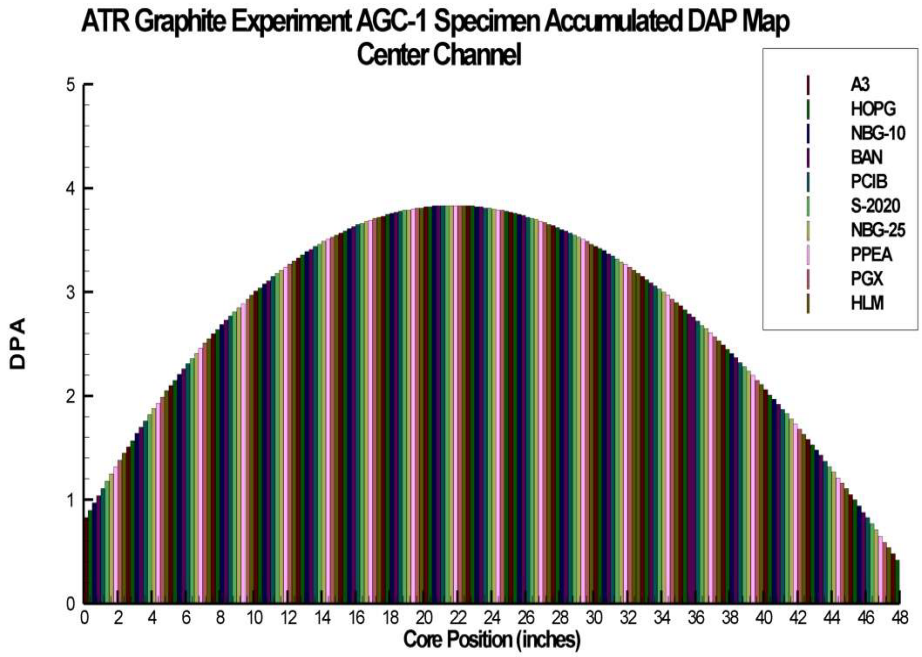


Figure 18. Neutron dose map for AGC-1 center channel showing the spatial location and total neutron damage dose (dpa) per specimen/graphite grade.

The following series of tables reports the numbers of samples (stressed, unstressed, and piggybacks) for the peripheral channels. Tables 9 through 15 pertain to the 3 ksi stress level channels (1 [N], 3 [SE], and 5 [SW]) and summarize the numbers and locations of the creep samples (Table 9) and the locations and doses (dpa) of the specimens by graphite grade (Tables 10–15). Tables 16 through 22 pertain to the 2 ksi stress level channels (2 [NE], 4 [S], and 6 [NW]) and summarize the numbers and locations of the creep samples (Table 16) and the locations and doses (dpa) of the specimens by graphite grade (Tables 17–22).

Table 9. Summary of the stressed/unstressed creep samples by graphite grade (3 ksi channels).

	3 ksi Channels						Samples Per Grade
	North (1)		South-East (3)		South-West (5)		
Graphite Grade	Stressed	Control	Stressed	Control	Stressed	Control	
NGB-17	4	3	2	2	3	3	17
NGBG-18	2	2	4	3	3	3	17
PCEA	3	3	2	2	4	3	17
IG-430	2	2	4	4	2	2	16
IG-110 (Ref)	2	2	1	1	2	2	10
H-451 (Ref)	2	2	2	2	1	1	10
Totals	15	14	15	14	15	14	87

Table 10. Location and dose of stressed and unstressed grade NBG-17 creep samples in the 3 ksi channels.

Grade NBG-17			
Stressed Samples		Control Samples	
Location	Dose (dpa)	Location	Dose (dpa)
5S14	1.66	5U13	1.63
3S13	1.85	3U12	1.91
1S13	2.17	1U12	2.23
1S12	2.42	1U11	2.53
1S11	2.65	1U11	2.53
3S8	2.80	3U8	2.78
5S6	3.10	5U6	3.09
5S3	3.41	5U3	3.42
1S3	3.96	1U3	4.01

Table 11. Location and dose of stressed and unstressed grade NBG-18 creep samples in the 3 ksi channels.

Grade NBG-18			
Stressed Samples		Control Samples	
Location	Dose (dpa)	Location	Dose (dpa)
5S15	1.42	5U14	1.33
3S14	1.62	3U13	1.64
3S12	2.07	3U11	2.16
3S11	2.27	3U11	2.16
5S8	2.82	5U8	2.77
5S5	3.22	5U5	3.22
3S2	3.47	3U2	3.50
1S4	3.85	1U4	3.90
1S1	4.12	1U1	4.15

Table 12. Location and dose of stressed and unstressed grade PCEA creep samples in the 3 ksi channels.

Grade PCEA			
Stressed Samples		Control Samples	
Location	Dose (dpa)	Location	Dose (dpa)
3S15	1.39	3U14	1.35
1S14	1.91	1U13	1.92
5S12	2.10	5U11	2.15
5S11	2.30	5U11	2.15
5S9	2.66	5U9	2.58
3S6	3.08	3U6	3.10

Table 12 (cont.)

Grade PCEA			
Stressed Samples		Control Samples	
Location	Dose (dpa)	Location	Dose (dpa)
5S4	3.32	5U4	3.33
1S6	3.59	1U6	3.62
1S2	4.05	1U2	4.09

Table 13. Location and dose of stressed and unstressed grade IG-430 creep samples in the 3 ksi channels.

Grade IG-430			
Stressed Samples		Control Samples	
Location	Dose (dpa)	Location	Dose (dpa)
5S10	2.49	5U10	2.37
1S10	2.87	1U10	2.79
3S7	2.95	3U7	2.95
3S5	3.20	3U5	3.22
3S4	3.31	3U4	3.33
3S3	3.40	3U3	3.43
5S2	3.49	5U2	3.50
1S5	3.73	1U5	3.77

Table 14. Location and dose of stressed and unstressed grade IG-110 (reference) creep samples in the 3 ksi channels.

Grade IG-110			
Stressed Samples		Control Samples	
Location	Dose (dpa)	Location	Dose (dpa)
5S13	1.89	5U12	1.90
3S9	2.64	3U9	2.59
1S9	3.07	1U9	3.04
1S7	3.43	1U7	3.45
5S1	3.54	5U1	3.56

Table 15. Location and dose of stressed and unstressed grade H-451 (reference) creep samples in the 3 ksi channels.

Grade H-451			
Stressed Samples		Control Samples	
Location	Dose (dpa)	Location	Dose (dpa)
1S15	1.64	1U14	1.57
3S10	2.46	3U10	2.39
5S7	2.97	5U7	2.94
1S8	3.26	1U8	3.26
3S1	3.53	3U1	3.55

Table 16. Summary of the stressed/unstressed creep samples by graphite grade (2 ksi channels).

	2 KSI Channels						
	South (4)		North-East (2)		North-West (6)		
Graphite Grade	Stressed	Control	Stressed	Control	Stressed	Control	Samples per grade
NGB-17	3	2	3	3	3	3	17
NGBG-18	3	3	3	2	3	3	17
PCEA	3	3	3	3	3	2	17
IG-430	2	2	3	3	3	3	16
IG-110 (Ref)	2	2	2	2	1	1	10
H-451 (Ref)	2	2	1	1	2	2	10
Totals	15	14	15	14	15	14	87

Table 17. Location and dose of stressed and unstressed grade NBG-17 creep samples in the 2 ksi channels.

Grade NBG-17			
Stressed Samples		Control Samples	
Location	Dose (dpa)	Location	Dose (dpa)
6S15	1.60	6U14	1.50
4S12	1.93	4U11	2.01
4S11	2.12	4U11	2.01
4S8	2.60	4U8	2.59
2S10	2.76	2U10	2.69
6S8	3.15	6U8	3.09
2S6	3.46	2U6	3.49
2S4	3.71	2U4	3.76
6S1	3.95	6U1	3.96

Table 18. Location and dose of stressed and unstressed grade NBG-18 creep samples in the 2 ksi channels.

Grade NBG-18			
Stressed Samples		Control Samples	
Location	Dose (dpa)	Location	Dose (dpa)
4S14	1.52	4U13	1.52
6S13	2.11	6U12	3.12
2S12	2.32	2U11	2.43
2S11	2.54	2U11	2.43
4S7	2.74	4U7	2.74
4S5	3.98	4U5	3.00
6S6	3.46	6U6	3.45
6S3	3.80	6U3	3.82
2S2	3.90	2U2	3.94

Table 19. Location and dose of stressed and unstressed grade PCEA creep samples in the 2 ksi channels.

Grade PCEA			
Stressed Samples		Control Samples	
Location	Dose (dpa)	Location	Dose (dpa)
4S15	1.30	4U14	1.25
2S14	1.82	2U13	1.84
6S12	2.35	6U11	2.40
6S11	2.57	6U11	2.40
4S6	2.87	4U6	2.88
2S8	3.14	2U8	3.13
4S1	3.29	4U1	3.31
6S4	3.71	6U4	3.71
2S1	3.97	2U1	4.00

Table 20. Location and dose of stressed and unstressed grade IG-430 creep samples in the 2 ksi channels.

Grade IG-430			
Stressed Samples		Control Samples	
Location	Dose (dpa)	Location	Dose (dpa)
2S15	1.55	2U14	1.51
4S10	2.29	4U10	2.22
6S10	2.78	6U10	2.65
2S9	2.95	2U9	2.92
4S3	3.16	4U3	3.19

Table 20 (cont.)

Grade IG-430			
Stressed Samples		Control Samples	
Location	Dose (dpa)	Location	Dose (dpa)
2S15	1.55	2U14	1.51
6S7	3.31	6U7	3.38
2S3	3.82	2U3	3.86
6S2	3.88	6U2	3.90

Table 21. Location and dose of stressed and unstressed grade IG-110 (reference) creep samples in the 2 ksi channels.

Grade IG-110			
Stressed Samples		Control Samples	
Location	Dose (dpa)	Location	Dose (dpa)
6S14	1.86	6U13	1.82
4S9	2.45	4U9	2.41
4S4	3.08	4U4	3.10
2S7	3.31	2U7	3.32
2S5	3.59	2U5	3.63

Table 22. Location and dose of stressed and unstressed grade H-451 (reference) creep samples in the 2 ksi channels.

Grade H-451			
Stressed Samples		Control Samples	
Location	Dose (dpa)	Location	Dose (dpa)
4S13	1.73	4U12	1.77
2S13	2.07	2U12	2.15
6S9	2.97	6U9	2.88
4S2	3.23	4U2	3.25
6S5	3.59	6U5	3.59

Tables 23 and 24 summarize the piggyback samples in the 3 and 2 ksi stress levels, respectively, and report the number of piggyback samples by grade in each channel. Tables 25 through Table 40 report the location and dose (dpa) of all the piggyback samples by grade in the AGC-1 peripheral channels.

Table 23. Summary of the piggyback samples by grade included in the 3 ksi peripheral channels.

Graphite Grade	3 ksi Channels			Piggyback Samples Per Grade
	North (1)	South-East (3)	South-West (5)	
NBG-17	4	6	0	10
NBG-18	6	4	0	10

Table 23 (cont.)

Graphite Grade	3 ksi Channels			Piggyback Samples Per Grade
	North (1)	South-East (3)	South-West (5)	
PCEA	4	6	0	10
IG-430	4	4	0	8
IG-110	2	2	0	4
H-451	3	2	0	5
HOPG	1	0	2	3
A3 matrix	0	0	2	2
HLM	0	0	1	1
PGX	0	0	1	1
PPEA	0	0	3	3
NBG-25	0	0	4	4
2020	0	0	3	3
PCIB	0	0	3	3
BAN	1	1	4	6
NBG-10	0	0	2	2
Total	25	25	25	75

Table 24. Summary of the piggyback samples by grade included in the 2 ksi peripheral channels.

Graphite Grade	2 KSI Channels			Piggyback Samples Per Grade
	North-East (2)	South (4)	North-West (6)	
NBG-17	3	7	0	10
NBG-18	5	5	0	10
PCEA	5	5	0	10
IG-430	6	4	0	10
IG-110	3	2	0	5
H-451	2	1	1	4
HOPG	0	0	3	3
A3 matrix	0	0	4	4
HLM	0	0	4	4
PGX	0	0	3	3
PPEA	0	0	2	2
NBG-25	0	0	1	1
2020	0	0	2	2
PCIB	0	0	2	2
BAN	1	1	1	3
NBG-10	0	0	2	2
Total	25	25	25	75

Table 25. Summary of Grade NBG-17 piggyback specimens located in the peripheral channels of AGC-1.

Grade NBG-17	
Location	Dose, dpa
1PB1	0.52
4PB4	0.55
3PB4	0.57
4PB6	0.65
2PB6	0.77
3PB8	0.79
4PB10	0.85
1PB7	0.90
4PB12	0.95
3PB12	1.00
4PB14	1.04
3PB13	1.06
4PB15	1.09
3PB15	1.16
1PB12	1.21
2PB15	1.30
4PB16	3.36
3PB16	3.61
2PB16	4.06
1PB16	4.21

Table 26. Summary of Grade NBG-18 piggyback specimens located in the peripheral channels of AGC-1.

Grade NBG-18	
Location	Dose, dpa
3PB1	0.40
4PB2	0.44
3PB5	0.63
1PB3	0.65
1PB4	0.72
4PB8	0.75
4PB25	0.80
3PB9	0.84
2PB9	0.95
1PB25	1.01
1PB9	1.03
4PB23	1.05
2PB11	1.07

Table 26 (cont.)

Grade NBG-18	
Location	Dose, dpa
2PB24	1.12
2PB13	1.18
1PB14	1.32
4PB18	3.36
3PB18	3.61
2PB18	4.07
1PB18	4.22

Table 27. Summary of Grade PCEA piggyback specimens located in the peripheral channels of AGC-1.

Grade PCEA	
Location	Dose, dpa
4PB1	0.39
3PB3	0.51
4PB5	0.60
2PB4	0.64
2PB5	0.70
3PB7	0.74
4PB9	0.80
3PB25	0.88
4PB24	0.93
1PB8	0.96
2PB10	1.01
3PB14	1.11
3PB23	1.14
1PB24	1.17
2PB14	1.24
1PB13	1.32
4PB17	3.36
3PB17	3.61
2PB17	4.07
1PB17	4.22

Table 28. Summary of Grade IG-430 piggyback specimens located in the peripheral channels of AGC-1.

Grade IG-430	
Location	Dose, dpa
3PB2	0.46
4PB3	0.49
2PB3	0.58
3PB6	0.68
4PB7	0.70
2PB7	0.83
2PB8	0.89
4PB11	0.90
2PB25	0.97
3PB24	1.01
1PB10	1.09
2PB12	1.13
1PB23	1.32
1PB15	1.38
4PB19	3.36
3PB19	3.61
2PB19	4.06
1PB19	4.21

Table 29. Summary of Grade IG-110 piggyback specimens located in the peripheral channels of AGC-1.

Grade IG-110	
Location	Dose, dpa
2PB1	0.45
1PB6	0.84
3PB10	0.90
4PB13	1.00
2PB23	1.19
4PB21	3.34
3PB21	3.59
2PB21	4.05
1PB21	4.20

Table 30. Summary of Grade H-451 piggyback specimens located in the peripheral channels of AGC-1.

Grade H-451	
Location	Dose, dpa
2PB2	0.52
1PB2	0.59
1PB5	0.78
3PB11	0.95
1PB11	1.15
4PB20	3.35
3PB20	3.60
6PB21	4.01
2PB20	4.06

Table 31. Summary of Grade HOPG piggyback specimens located in the peripheral channels of AGC-1.

Grade HOPG	
Location	Dose, dpa
5PB1	0.44
6PB5	0.77
6PB15	1.35
5PB21	3.60
6PB16	4.03
1PB20	4.21

Table 32. Summary of A3 Matrix piggyback specimens located in the peripheral channels of AGC-1.

Grade A3 Matrix	
Location	Dose, dpa
5PB2	0.50
6PB6	0.83
6PB14	1.30
5PB22	3.58
6PB22	3.99
6PB17	4.03

Table 33. Summary of Grade HLM piggyback specimens located in the peripheral channels of AGC-1.

Grade HLM	
Location	Dose, dpa
5PB3	0.56
6PB7	0.89
6PB24	1.11
6PB13	1.24
6PB18	4.03

Table 34. Summary of Grade PGX piggyback specimens located in the peripheral channels of AGC-1.

Grade PGX	
Location	Dose, dpa
5PB4	0.61
6PB8	0.95
6PB12	1.18
6PB19	4.03

Table 35. Summary of Grade PPEA piggyback specimens located in the peripheral channels of AGC-1.

Grade PPEA	
Location	Dose, dpa
5PB5	0.67
5PB25	0.86
6PB9	1.01
5PB15	1.20
6PB20	4.02

Table 36. Summary of Grade NBG-25 piggyback specimens located in the peripheral channels of AGC-1.

Grade NBG-25	
Location	Dose, dpa
5PB6	0.72
5PB24	0.99
6PB10	1.06
5PB14	1.15
5PB16	3.62

Table 37. Summary of Grade 2020 piggyback specimens located in the peripheral channels of AGC-1.

Grade 2020	
Location	Dose, dpa
6PB4	0.70
5PB7	0.78
5PB13	1.10
6PB23	1.26
5PB17	3.62

Table 38. Summary of Grade PCIB piggyback specimens located in the peripheral channels of AGC-1.

Grade PCIB	
Location	Dose, dpa
6PB3	0.64
5PB8	0.83
6PB25	0.97
5PB12	1.04
5PB18	3.62

Table 39. Summary of Grade BAN piggyback specimens located in the peripheral channels of AGC-1.

Grade BAN	
Location	Dose, dpa
6PB2	0.58
5PB9	0.89
5PB11	0.99
5PB23	1.12
4PB22	3.33
3PB22	3.58
5PB19	3.61
2PB22	4.03
1PB22	4.18

Table 40. Summary of Grade NBG-10 piggyback specimens located in the peripheral channels of AGC-1.

Grade NBG-10	
Location	Dose, dpa
6PB1	0.52
5PB10	0.94
6PB11	1.12
5PB20	3.61

Tables 41 through 50 summarize the center channel (piggyback) samples by graphite grade and report the estimated dose (dpa) per specimen.

Table 41. Summary of Grade HOPG piggyback specimens located in the central channel of AGC-1.

Grade HOPG	
Location	Dose, dpa
CPB1	0.42
CPB-191	0.90
CPB-11	1.00
CPB-21	1.53
CPB-181	1.57

Table 41 (cont.)

Grade HOPG	
Location	Dose, dpa
CPB-31	2.01
CPB-171	2.15
CPB-41	2.45
CPB-161	2.64
CPB-51	2.83
CPB-151	3.04
CPB-61	3.15
CPB-141	3.36
CPB-71	3.42
CPB-131	3.59
CPB-81	3.62
CPB-121	3.75
CPB-91	3.76
CPB-111	3.82
CPB-101	3.83

Table 42. Summary of Grade A3-Matrix piggyback specimens located in the central channel of AGC-1.

Grade A3 Matrix	
Location	Dose, dpa
CPB-2	0.48
CPB-192	0.83
CPB-12	1.05
CPB-182	1.51
CPB-22	1.58
CPB-32	2.06
CPB-172	2.10
CPB-42	2.49
CPB-162	2.60
CPB-52	2.87
CPB-152	3.01
CPB-62	3.18
CPB-142	3.33
CPB-72	3.44
CPB-132	3.57
CPB-82	3.64
CPB-122	3.73
CPB-92	3.77
CPB-112	3.82
CPB-102	3.83

Table 43. Summary of Grade HLM piggyback specimens located in the central channel of AGC-1.

Grade HLM	
Location	Dose, dpa
CPB-3	0.54
CPB-13	1.11
CPB-183	1.45
CPB-23	1.63
CPB-173	2.05
CPB-33	2.11
CPB-43	2.53
CPB-163	2.55
CPB-53	2.90
CPB-153	2.97
CPB-63	3.21
CPB-143	3.30
CPB-73	3.46
CPB-133	3.55
CPB-83	3.65
CPB-123	3.72
CPB-93	3.78
CPB-113	3.81
CPB-103	3.83

Table 44. Summary of Grade PGX piggyback specimens located in the central channel of AGC-1.

Grade PGX	
Location	Dose, dpa
CPB-4	0.59
CPB-14	1.16
CPB-184	1.38
CPB-24	1.68
CPB-174	1.99
CPB-34	2.15
CPB-164	2.51
CPB-44	2.57
CPB-54	2.93
CPB-154	2.93
CPB-64	3.24
CPB-144	3.27
CPB-74	3.49
CPB-134	3.53

Table 44 (cont.)

Grade PGX	
Location	Dose, dpa
CPB-84	3.67
CPB-124	3.71
CPB-94	3.79
CPB-114	3.81
CPB-104	3.83

Table 45. Summary of Grade PPEA piggyback specimens located in the central channel of AGC-1.

Grade PPEA	
Location	Dose, dpa
CPB-5	0.65
CPB-15	1.21
CPB-185	1.32
CPB-25	1.73
CPB-175	1.93
CPB-35	2.20
CPB-165	2.46
CPB-45	2.61
CPB-155	2.89
CPB-55	2.97
CPB-145	3.24
CPB-65	3.27
CPB-75	3.51
CPB-135	3.51
CPB-85	3.68
CPB-125	3.69
CPB-95	3.79
CPB-115	3.80
CPB-105	3.83

Table 46. Summary of Grade NBG-25 piggyback specimens located in the central channel of AGC-1.

Grade NBG-25	
Location	Dose, dpa
CPB-6	0.71
CPB-186	1.25
CPB-16	1.27
CPB-26	1.78
CPB-176	1.88

Table 46 (cont.)

Grade NBG-25	
Location	Dose, dpa
CPB-36	2.24
CPB-166	2.41
CPB-46	2.65
CPB-156	2.85
CPB-56	3.00
CPB-146	3.21
CPB-66	3.29
CPB-136	3.49
CPB-76	3.53
CPB-126	3.68
CPB-86	3.70
CPB-116	3.79
CPB-96	3.80
CPB-106	3.83

Table 47. Summary of Grade 2020 piggyback specimens located in the central channel of AGC-1.

Grade 2020	
Location	Dose, dpa
CPB-7	0.77
CPB-187	1.18
CPB-17	1.32
CPB-177	1.82
CPB-27	1.83
CPB-37	2.28
CPB-167	2.36
CPB-47	2.68
CPB-157	2.81
CPB-57	3.03
CPB-147	3.18
CPB-67	3.32
CPB-137	3.46
CPB-77	3.55
CPB-127	3.66
CPB-87	3.71
CPB-117	3.79
CPB-97	3.81
CPB-107	3.83

Table 48. Summary of Grade PCIB piggyback specimens located in the central channel of AGC-1.

Grade PCIB	
Location	Dose, dpa
CPB-8	0.83
CPB-188	1.11
CPB-18	1.37
CPB-178	1.76
CPB-28	1.87
CPB-168	2.31
CPB-38	2.32
CPB-48	2.72
CPB-158	2.77
CPB-58	3.06
CPB-148	3.15
CPB-68	3.35
CPB-138	3.44
CPB-78	3.57
CPB-128	3.65
CPB-88	3.72
CPB-118	3.78
CPB-98	3.81
CPB-108	3.83

Table 49. Summary of Grade BAN piggyback specimens located in the central channel of AGC-1.

Grade BAN	
Location	Dose, dpa
CPB-9	0.88
CPB-189	1.04
CPB-19	1.43
CPB-179	1.70
CPB-29	1.92
CPB-169	2.26
CPB-39	2.37
CPB-159	2.73
CPB-49	2.76
CPB-59	3.09
CPB-149	3.11
CPB-69	3.37
CPB-139	3.41
CPB-79	3.59

Table 49 (cont.)

Grade BAN	
Location	Dose, dpa
CPB-129	3.63
CPB-89	3.74
CPB-119	3.77
CPB-99	3.82
CPB-109	3.83

Table 50. Summary of Grade NBG-10 piggyback specimens located in the central channel of AGC-1.

Grade NBG-10	
Location	Dose, dpa
CPB-10	0.94
CPB-190	0.97
CPB-20	1.48
CPB-180	1.64
CPB-30	1.97
CPB-170	2.21
CPB-40	2.41
CPB-160	2.69
CPB-50	2.79
CPB-150	3.08
CPB-60	3.12
CPB-140	3.39
CPB-70	3.40
CPB-80	3.60
CPB-130	3.61
CPB-90	3.75
CPB-120	3.76
CPB-100	3.82
CPB-110	3.83

Table 51 summarizes the SiC temperature monitors location within the center channel of AGC-1 and reports the estimated neutron dose (dpa) per specimen.

Table 51. Location and dose of the SiC temperature monitors in the central channel of AGC-1.

SiC Temperature Monitors	
Location	Dose, dpa
Cluster 1	0.74
Cluster 2	1.30
Cluster 3	1.81
Cluster 4	2.26
Cluster 5	2.67
Cluster 6	3.02
Cluster 7	3.21
Cluster 8	3.54
Cluster 9	3.71
Cluster 10	3.81
Cluster 11	3.83
Cluster 12	3.79
Cluster 13	3.67
Cluster 14	3.48
Cluster 15	3.20
Cluster 16	3.83
Cluster 17	2.39
Cluster 18	1.85
Cluster 19	1.22

6. MATERIALS PRECHARACTERIZATION

Graphite preirradiation examination and characterization will be performed at ORNL to take advantage of existing facilities and expertise. The graphite billets purchased[9] for capsule AGC-1 will be sectioned and specimens machined in accordance with cutting plans that take into account textural variations within the graphite billets. The cutting plans will be reported in the preirradiation examination report. All graphite samples will be laser engraved with a unique number identifying the graphite grade, location within the billet, and orientation with respect to the forming direction. For the AGC-1 capsule, all graphite piggyback specimens will be cut with their length direction parallel to the forming direction (with-grain). However, HOPG will be an exception and will be machined with its length (thickness) parallel to the crystallographic <c>-axis and its diameter parallel to the <a>-axis. The stressed/unstressed creep specimens will not all be cut parallel to the forming direction. Approximately one-third of the samples per grade will be machined with their length parallel to the against-grain direction. This will yield both with-grain (WG) and against-grain (AG) creep strain data. Both specimen orientations are required to demonstrate that the creep coefficient is independent of orientation.

The codes in Table 52 will be used to designate the graphite grades included in capsule AGC-1.

Table 52. Graphite grade marking codes to be used for the AGC series of experiments.

Graphite Code Letter	Graphite Grade
A	NBG-17
B	NBG-18
C	H-451
D	PCEA
E	IG-110
F	IG-430
G	HOPG
H	A3-MATRIX
J	HLM
K	PGX
L	PPEA
M	NBG-25
N	2020
P	PCIB
R	BAN
S	NBG-10

All machined specimens shall be subjected to visual inspection to check for damage and confirm the clarity of the laser marking and full dimensional inspection. Those specimens to be encapsulated in AGC-1 will be set aside, and only nondestructive testing shall be performed on them. The remaining specimens (controls) shall be tested to determine key physical properties as detailed below. Where possible, the testing will be carried out in accordance with the appropriate American Society for Testing and Materials (ASTM) specification(s).[10] Figure 19 schematically shows the preirradiation test program.

Nondestructive measurements to be performed include:

- Dimensions
- Mass (hence bulk density)
- Elastic modulus by the dynamic (fundamental frequency) technique and sonic velocity method, yielding Young's modulus, Shear modulus, and Poisson's ratio
- Thermal flash diffusivity at room temperature and as a function of temperature (25-1200°C), and hence the thermal conductivity
- Thermal expansion (25-1200°C) and hence the coefficient of thermal expansion (creep specimens only)
- Electrical resistivity (potentially useful as an indicator of structure and crystallinity).

These measurements will be made on all the specimens to be encapsulated in AGC-1 with the exception of the elevated temperature thermal diffusivity, which will be performed on a statistically representative sample of the piggyback specimens. Additional destructive tests to be performed on the companion samples include:

- X-ray diffraction (XRD) on powdered samples of the graphites (and hence the crystallographic parameters a, c, la, lc).
- Microstructural characterization via optical microscopy, scanning electron microscopy, and Hg-porosymmetry (hence grain and pore size distributions).
- Strength tests of the specimens, the test type being dependant on the specimen geometry, will provide compressive and flexural strength data.

The determination of which tests are applied to which specimens is influenced by a number of considerations, including sample geometry, graphite texture, statistical factors, test equipment availability, test duration and complexity, and cost/budget. The data that are produced will support not only the NGNP irradiation effects program but will provide valuable data for ongoing efforts in code and model development (e.g., the ASME design code for graphite core components). Analysis of the preirradiation data must take into account factors such as statistical variations, textural effects, and volume effects (irradiation specimens are of necessity very small volume).

The preirradiation characterization and testing of graphites for the AGC-1 experiment will be reported in a preirradiation data report and in electronic format (spreadsheets). The preirradiation report will include details of the following:

- Graphite grades and billet sizes
- Cutting plans
- Specimen numbering scheme
- Test/experimental methods
- Revised AGC-1 layouts (loading plans) with specimens identity numbers
- Tabulated data by grade
- Specific preirradiation data on the AGC-1 encapsulated specimens
- Preirradiation data from AGC-1 control specimens
- Analysis and discussion of the preirradiation data.

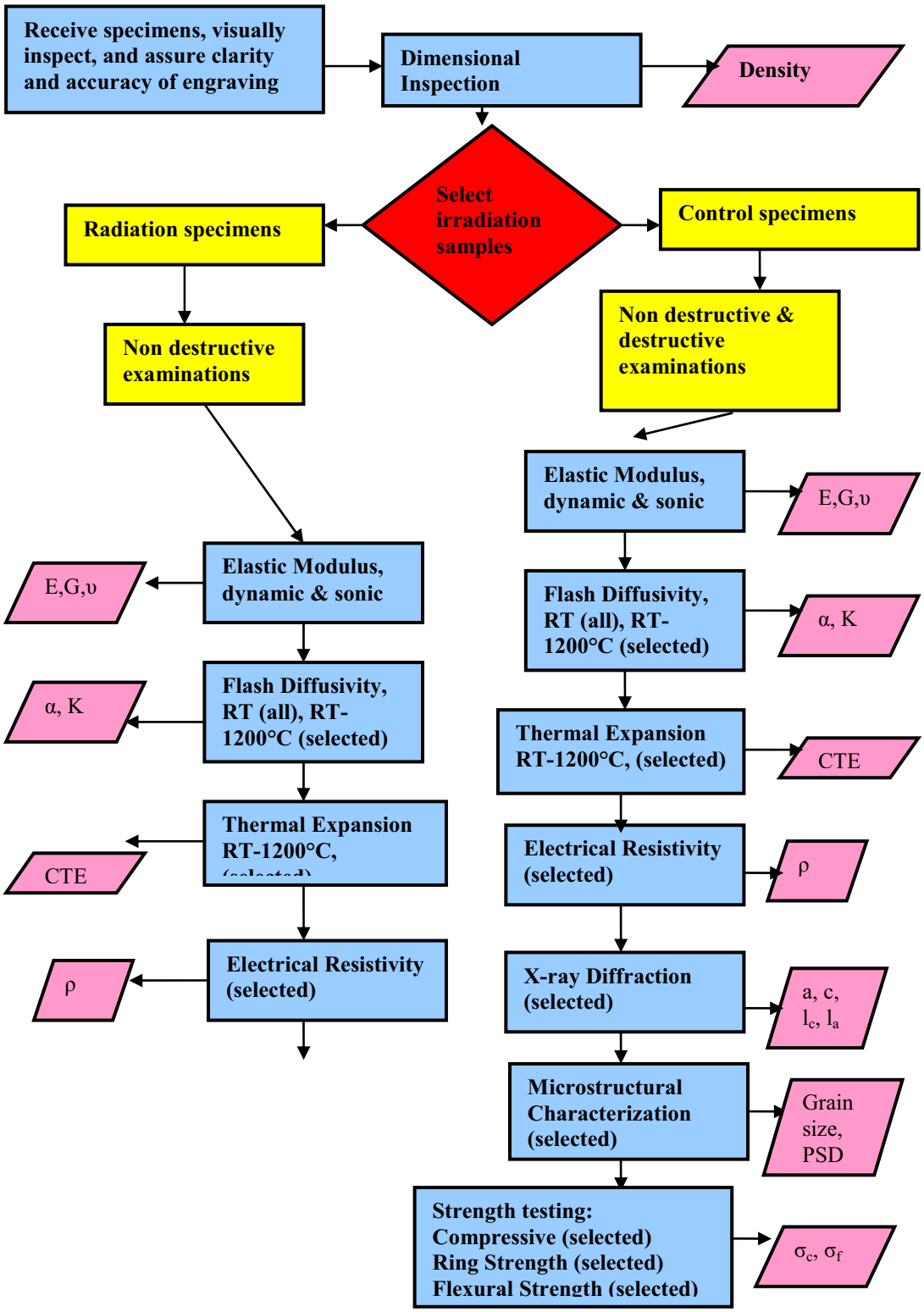


Figure 19. Preirradiation data process flow chart for irradiation creep experiment AGC-1.

7. POSTIRRADIATION EXAMINATION

Following completion of the specified irradiation period, the AGC-1 capsule contents will be subjected to PIE. The anticipated PIE process is illustrated in Figure 20.

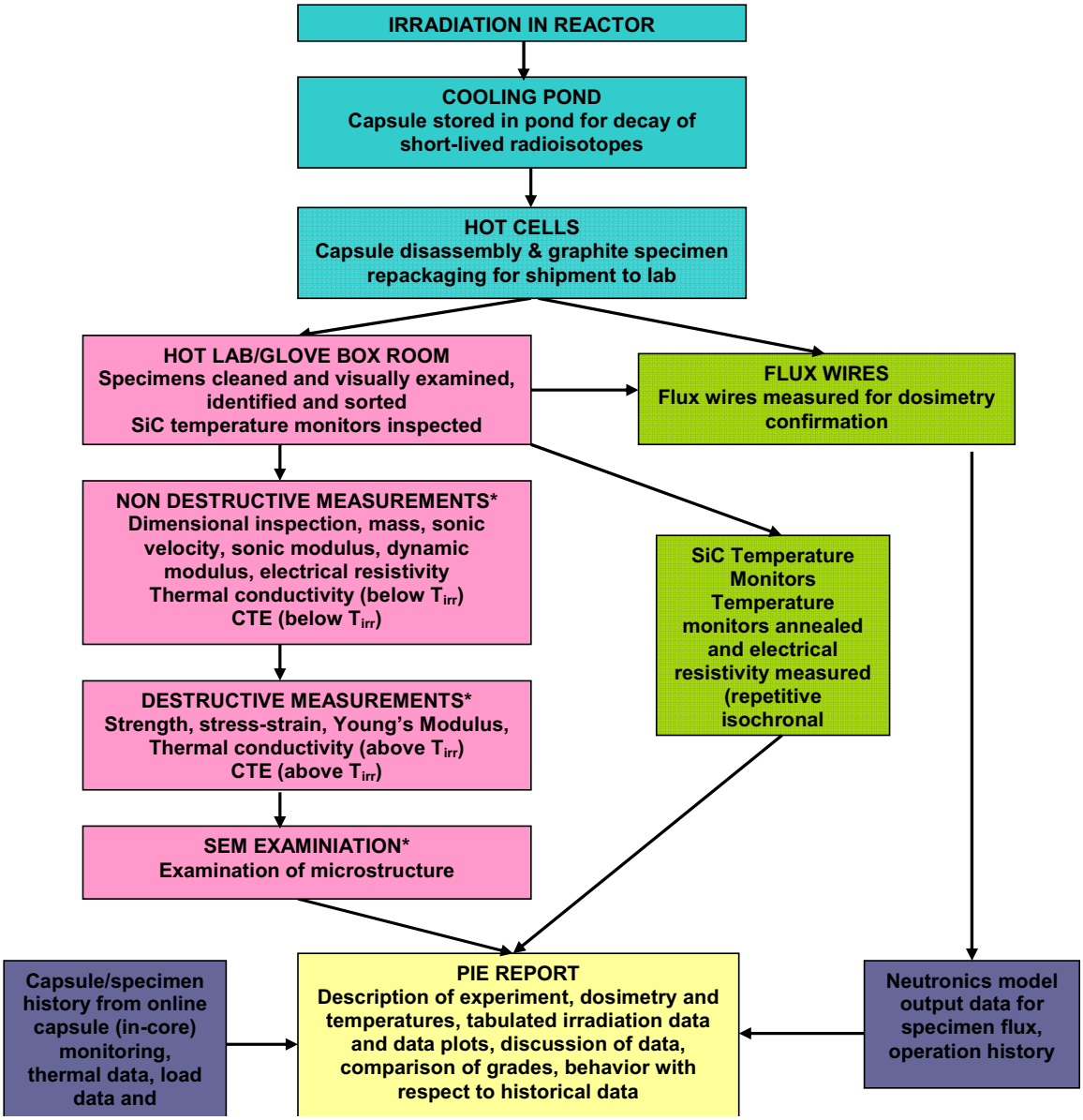


Figure 20. The postirradiation examination process for ATR experiment AGC-1.

After the requisite time in the cooling ponds at ATR, the capsule will be shipped in a commercial cask to the Hot Fuels Examination Facility at the Idaho National Laboratory (INL) for disassembly. The flux wires will be retained by INL for testing (gamma scans), and the data will be used to calibrate the flux model (see Section 4.2). The graphite specimens and SiC temperature monitors will be visually inspected and packaged for shipment to ORNL where PIE will be conducted. Prudent engineering practice dictates that the PIE should be conducted at the same laboratory as the preirradiation examination. This precludes the occurrence of bias in the data that can originate from differences in test

methods and machines, instruments, and personnel. PIE of the SiC temperature monitors in the manner described in Section 4.2 will provide additional data to calibrate the thermal model and allow accurate determinations of the irradiation temperature.

All the samples will be subjected to full dimensional analysis and will be weighed for bulk density determinations. The exact nature and order of the PIE measurements depends on irradiation sample geometry, the destructive tests being performed last. Critical PIE data for the AGC-1 experiment are those data related to the irradiation induced creep behavior and its analysis (as described in Section 2). These data include:

- Dimensional changes of the stressed and unstressed creep specimens, and hence the apparent creep strain as a function of dose
- The dimensional changes of HOPG in the with-grain (<a>) direction and against-grain (<c>) direction, and hence the parameter XT as function of dose
- The thermal expansion of the stressed and unstressed creep samples, and hence the coefficient of thermal expansion and the term $\left(\alpha_x' - \alpha_x\right)$.

These PIE data will allow the complete analysis of the irradiation induced creep data and estimation of the creep coefficient from the linear creep model (Equation 2). Data on the effects of creep strain on coefficient of thermal expansion will also be highly beneficial for the ASME design code currently being developed for graphite components. AGC-1 graphite PIE data will support model development in the areas of irradiation-induced dimensional change behavior, thermal conductivity, and fracture behavior. Additional PIE data to be obtained from the graphite creep specimens include:

- Dimensional change data
- Elastic constants (E, G, υ)
- Electrical resistivity
- Thermal conductivity, room temperature, and elevated temperature
- Strength
- Microstructural characterization.

Moreover, similar data on the effects of neutron dose will be obtained from PIE of the graphite piggyback specimens, including dimensional and density changes. The amount of PIE to be performed is budget dependant. PIE measurements are considerably more complex (and hence costly) than preirradiation measurements, because the samples must be handled and tested in gloveboxes.

The PIE data shall be reported in a PIE report that will give details of the measurements made, the experimental flux and thermal data, the revised dosimetry and temperature estimates, graphite PIE data and analysis, and revised creep models and creep coefficient.

8. GRAPHITE IRRADIATION

8.1 Graphite Qualification Program

Graphite irradiated mechanical and thermal properties are required to design a nuclear reactor core using graphite as the structural material. Unlike the nuclear fuel that is replaced on a periodic basis, the graphite structure remains in-place. The length of time the graphite remains in the core depends on the fluence accumulation, the service temperature and the grade of graphite used. The perspective graphite candidates have no irradiation history. The reactor candidates for the NGNP will use graphite as the structural material for the cores. The range of normal operating temperatures is bounded for a prismatic core between 600 and 1200°C with a maximum prototypical neutron fluence of 6 to 7 dpa with E > 0.1 MeV. The prismatic reactors historically saw graphite fuel blocks with peak doses of 5 to 6 dpa. The peak fluence requirement could go higher if the decision is made to reuse the fuel blocks. The PBR expects to see peak doses in the inner graphite reflector of approximately 34 dpa for a 35 effective full power year life. The discrepancy in the two dose levels is due to the PBR retaining its reflector for a much longer period of time.

A third of the graphite fuel blocks would be replaced every 2 years in a prismatic core. Therefore, some fuel blocks would see irradiation exposures up to 6 years. Prismatic graphite reflectors blocks would usually be replaced every 6 years. Based on this information, the AGC-1 will support the prismatic core and not directly the pebble bed core. Although the upper limit of 7 dpa in the AGC capsule series is an incremental step toward reaching the higher doses, a different series of the experiments would have to be performed to reach the higher doses to support the pebble bed core.

A program of six irradiation experiments has been proposed to acquire the irradiated mechanical and thermal properties of these candidate graphites. There are six graphite irradiation capsules planned for irradiation in ATR. There will be two capsules irradiated at 600, 900, 1200°C, respectively. For each temperature, there will be one capsule irradiated from 0.5 to 4 dpa and the second capsule irradiated from 4 to 7 dpa. Each capsule will be assembled with unirradiated specimens to acquire the full dose in a continuous irradiation. AGC-1 will be the lead off capsule for the series and will be irradiated at a temperature of 900°C with a dose of 1 to 4 dpa.

The primary objective of irradiation capsule AGC-1 is to provide irradiation creep design data, and data for the effects of irradiation creep on key physical properties, for the NGNP candidate graphites as well as for other graphites. These other graphites will be used to gather additional information on irradiated graphite behavior to supplement computational graphite performance modeling for the NGNP program. Such data include:

- Dimensional changes
- Strength
- Elastic modulus
- Thermal conductivity
- Coefficient of thermal expansion over the neutron dose range 0.53×10^{21} n/cm^2 - 3.9×10^{21} n/cm^2 [E>0.1 MeV] or 0.39–4.2 displacements per atom (dpa) at an irradiation temperature of 900°C.

Moreover, this experiment will provide valuable data on the single crystal irradiation behavior of graphites to be derived from the inclusion of HPOG in this experiment.

As stated in Section 2, the graphites grades to be included in the AGC-1 capsule can be categorized as follows.

A. Major Grades

NGNP has selected grades NBG-18 for the PBR and PCEA for the prismatic reactor design. These grades are most likely to receive reasonably large neutron doses in their lifetime and will be subjected to significant stresses in operation. Consequently, these grades occupy the stressed and companion unstressed position in the capsule and yield irradiation creep data. The other major grades are NBG-17 and IG-430. These grades will be used to broaden the graphite performance models. Two historical (reference) grades H-451 and IG-110 are included since these are grades used in the past gas reactors. Historical data is available for these grades which can be used for comparison.

B. Minor Grades

These grades are relevant to the NGNP graphite component design by providing irradiation data on different graphite grades. The irradiation information will be used to further the understanding of all graphite irradiation behavior in computational graphite performance models used to predict graphite lifetimes for different grades.

C. Alternate Grades

These grades are chosen to evaluate the difference in irradiation performance between petroleum and coal coke and between extruded and iso-molded grades. The irradiation information will be used to further the understanding of all graphite irradiation behavior in computational graphite performance models used to predict graphite lifetimes fordifferent grades.

D. Experimental Grades

Two experimental graphites are included in AGC-1 (BAN and A3 matrix). BAN is an experimental grade, secondary coke graphite whose manufacturing process and raw materials are such that it should offer superior irradiation stability. BAN will be studied for future use as well as an analog to recycled graphite. A3 matrix is the blend of graphites and carbonized phenolic resin used as the matrix in the NGNP fuel compact or fuel pebble. Samples of A3 are to be obtained from the AFCI/AGR fuel program and will be produced at ORNL.

E. Single-Crystal Graphite

The dimensional change behavior of graphite is particularly significant to the behavior of polycrystalline (polygranular) graphites. Therefore, samples of HOPG are included in AGC-1.

A more complete description of all the graphite samples included in capsule AGC-1 is given in Sections 4 and 5 of this report.

8.2 Experimental Position in the Advanced Test Reactor

The AGC-1 will be located in the south flux trap in the ATR shown in Figure 21. Only the three available flux trap positions can support the graphite irradiation because of the requirement of space above and below the core and the inherent fast flux levels in the experimental positions (see Figure 22). The east flux trap has an established program already operating in the location. The center flux trap is being planned for a future irradiation program. The other ATR positions have insufficient fast flux and

space above and below the core. The south flux trap is usually operated at higher power levels than the north flux traps. The final configuration of the ATR core is not known for the expected insertion time period beginning FY-08. In fact, there is ongoing planning for experiments in position around the south flux trap that will affect the current assumptions used to design the AGC-1 experiment. A final thermal analysis can not be completed until the ATR core configuration is known for the reactor cycles for which the experiment will be inserted. For this reason, much of the capsule design in this report is preliminary, and the final analyses will be incomplete until the final ATR core configuration is known.

Figure 21. Experimental positions in the Advanced Test Reactor core.

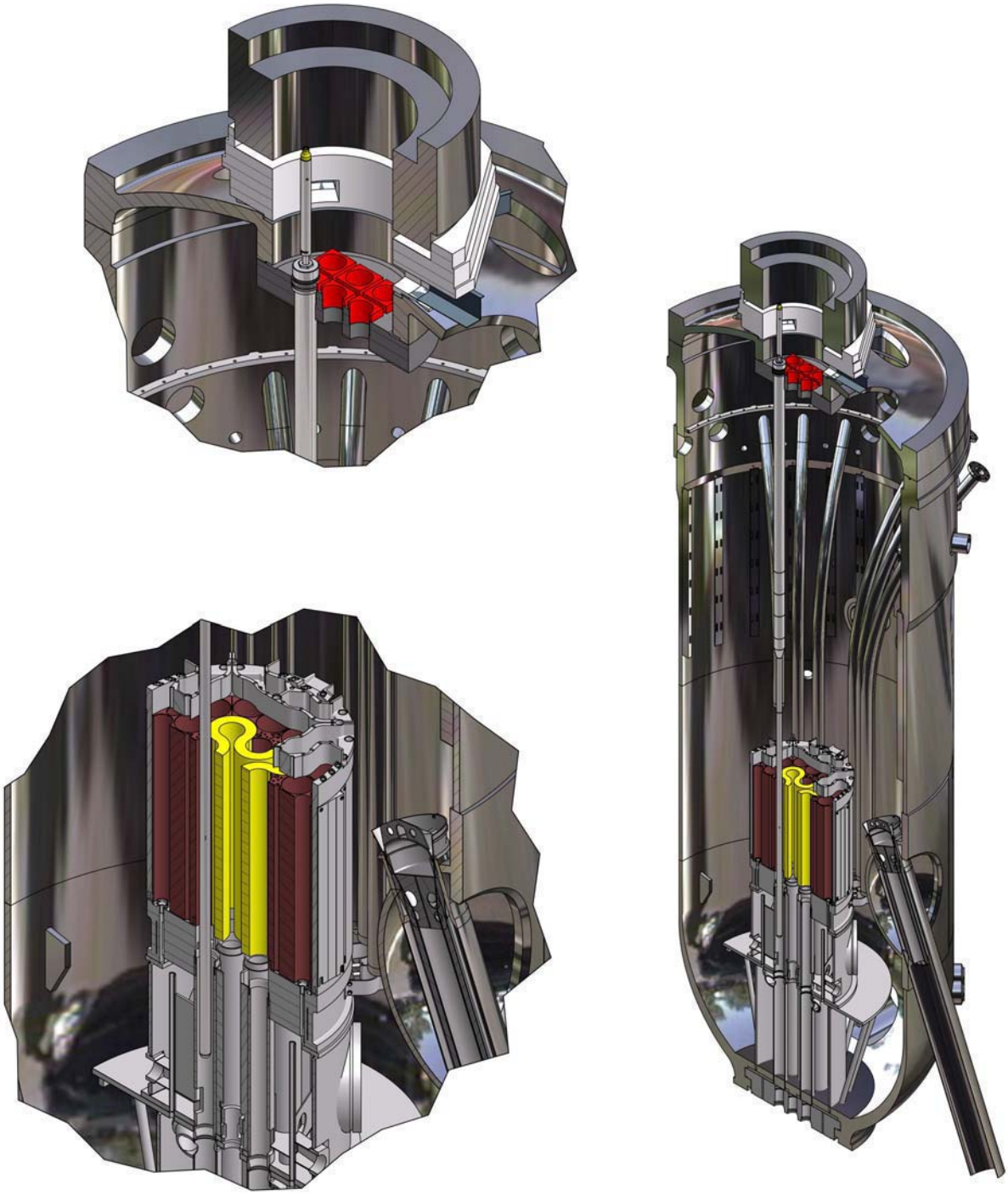


Figure 22. Cutaway of the ATR core showing the space above and below the experiment will occupy.

9. AGC-1 CREEP CAPSULE REQUIREMENTS

The AGC-1 irradiation capsule will apply two stress levels: 13.8 MPa (2 ksi) and 20.7 MPa (3 ksi). These stress levels were chosen based on previous graphite compressive capsules irradiated at the ORNL in the 1970s and 1980s (see References 3 and 11 and detailed discussions with reactor vendors via the ASME graphite core design project team). To measure the irradiation-induced creep, companion unstressed graphite specimens are required. The apparent irradiation creep strain may thus be determined from the difference in the dimensional changes between a stressed and unstressed sample pair irradiated at the same temperature and to the same neutron damage dose. There are also a large number of smaller, piggyback samples of VHTR relevant graphites. These piggyback specimens do not provide irradiation creep data, but do provide valuable physical properties data. The center channel of capsule AGC-1 additionally accommodates a large number of piggyback samples as well as SiC temperature monitors whose purpose is to provide a postirradiation check on the irradiation temperature and thus allow for affirmation of the real time temperature data from the capsule thermocouples.

During operation, the capsule will maintain a constant compressive load and specimen temperature during reactor power level changes. A constant axial temperature is achieved by adjusting the mixture of two sweep gases used to set up a quasi-stagnant gas conduction gap between objects. To a lesser extent radiation heat transfer also controls the temperature. The axial cosine flux shape reduces gamma heat generation in the ends of the experiment. To offset the decrease of temperature in the ends of the experiment, the temperature drop across the gaps between bodies must linearly increase axially toward the ends. At core centerline, the gaps are at their narrowest and then increase to their maximum separation at the top and bottom of the capsule. Twelve thermocouples are distributed along the 48-in. axial length. Any one of the 12 thermocouples signals can be used as input for the temperature control system. SiC temperature monitors will be installed in the interior of the experiment and will be interrogated during Post Irradiation Exam for the maximum temperature in the experiment.

Six flux wires (2 Fe, 2 Ni, and 2 Nb) will be used to assess the neutron fluence for $E > 0.1$ MeV along the length of the experiment. The expected irradiation duration is approximately 170 full power reactor days.

10. AGC-1 DESIGN

Prior graphite compressive creep capsule irradiations performed at ORNL and INL used pneumatically loaded graphite specimens in columns distributed in a graphite body. The most extensive series of graphite compressive creep irradiations were the OC series performed at ORNL. A lesson learned from these experiments will be incorporated into the AGC series of capsules. In the OC series, corrugated bellows were used to impart forces on the graphite specimens and were later installed in the bottom of the experiment to move the graphite specimens upwards to prevent specimens sticking in the graphite experiment body. If the specimens become jammed in the graphite body the stack of graphite specimens become unresponsive to the applied load. This type of arrangement of bellows above and below the core could only be achieved in the ATR flux traps because no other positions in the ATR core have the space above and below the core.

The use of bellows in the AGC capsule series is considered a greater risk than using off-the-shelf common pneumatic cylinders or rams. To make a bellow perform like a pneumatic ram requires that metal plates be welded on both ends of corrugated bellows stock with one of the plates taped for a pressure fitting. The welded bellows then has to be calibrated for displacement and force versus applied pressure. The bellows used in the OC capsules were 1 in. in diameter and operated at high pressures, 4.89 MPa (854 psig), to obtain the force necessary to achieve the desired compressive loads. The use of those bellows in the ATR core could pose safety issues, because the bellows are not ASME-certified pressure vessels. Commercially available pneumatic rams will be used in the AGC capsules that operate at pressures less than 1.7 MPa (250 psig) and provide the same mechanical force as the 1-in. bellows. The commercial pneumatic cylinders are larger than the bellows. Nevertheless, space exists in the experiment to house all six cylinders above the core. The size of the pneumatic rams used in the bottom of the experiment is much smaller, because they only need to lift the stack of graphite without the applied load of the upper rams. These cylinders will be located below the core (see Figure 23).

The experiment is contained in a modified loop-experiment in-pile assembly (see Figure 24). This configuration was chosen to establish a dry isolated chamber inside the reactor vessel and core. The experiment tube becomes a pressure vessel inside the ATR reactor vessel and maintains the seep gas at an internal pressure of one atmosphere while the ATR operational pressure of 26.2 atmospheres is applied to the external boundary. ATR technical specifications limit the outer temperature of the tube to prevent departure of nucleate boiling in the reactor coolant. The tube wall temperature is controlled by convecting cooling on the outside of the tube and the temperature drop across the gap between the heat shield and the inner surface of the pressure boundary. The temperature drop is controlled by the variable sweep gas composition of He and Ar.

The in-pile tube hangs from the vessel head approximately 26 feet into the vessel cavity and core and is fabricated from 304L stainless steel pipe. The first 13 feet has an outer diameter of five inches. The second 13 feet has a short transition from five inches to 2.5 inches. A section of tube with a 2.5-inch outer diameter runs the remainder of the length. The vessel formed by the in-pile tube is designed and analyzed to ASME Section III, Class 3 pressure vessel specifications.

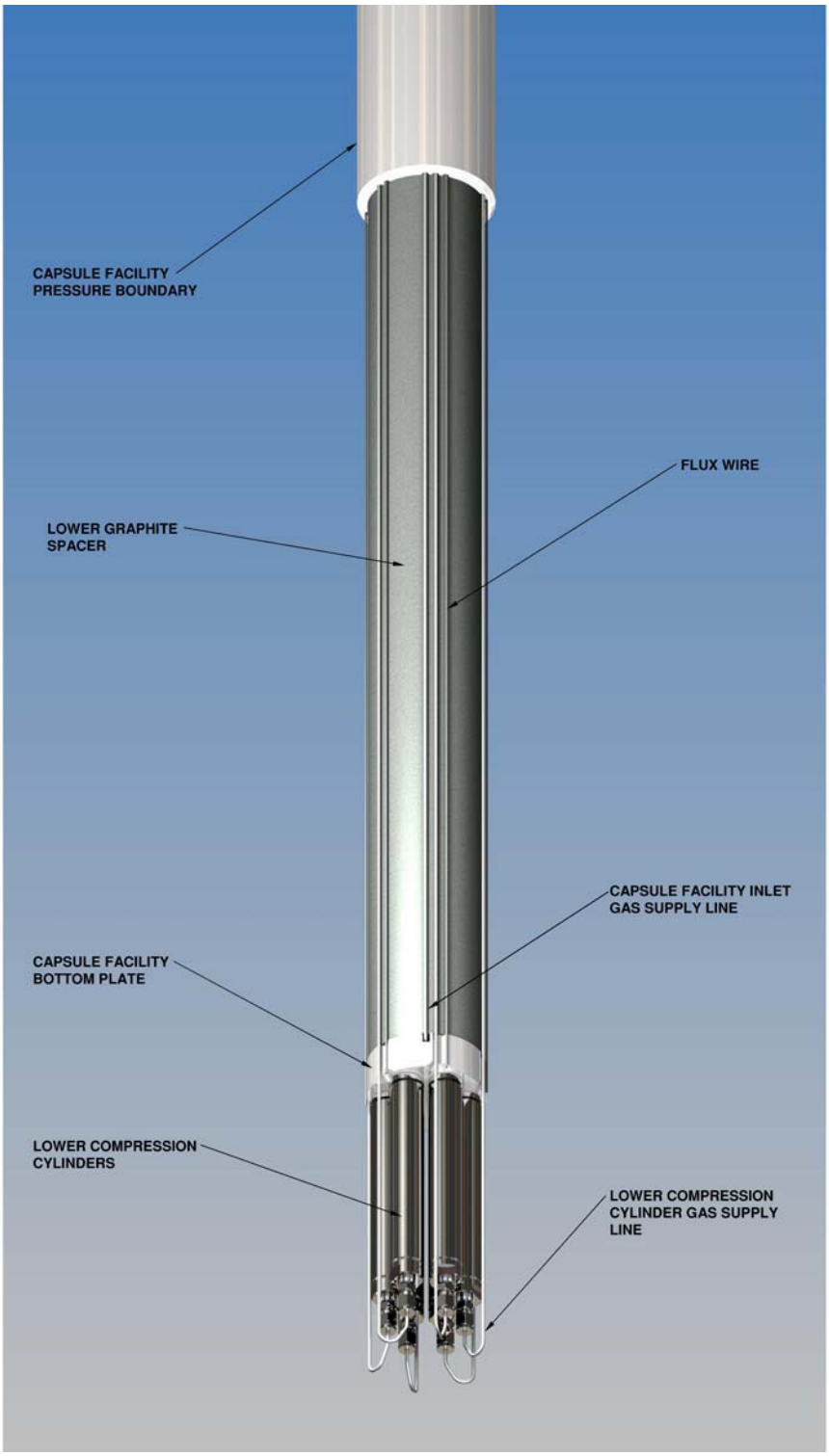


Figure 23. Arrangement of the lower pneumatic rams used to upset the graphite specimens during outages.

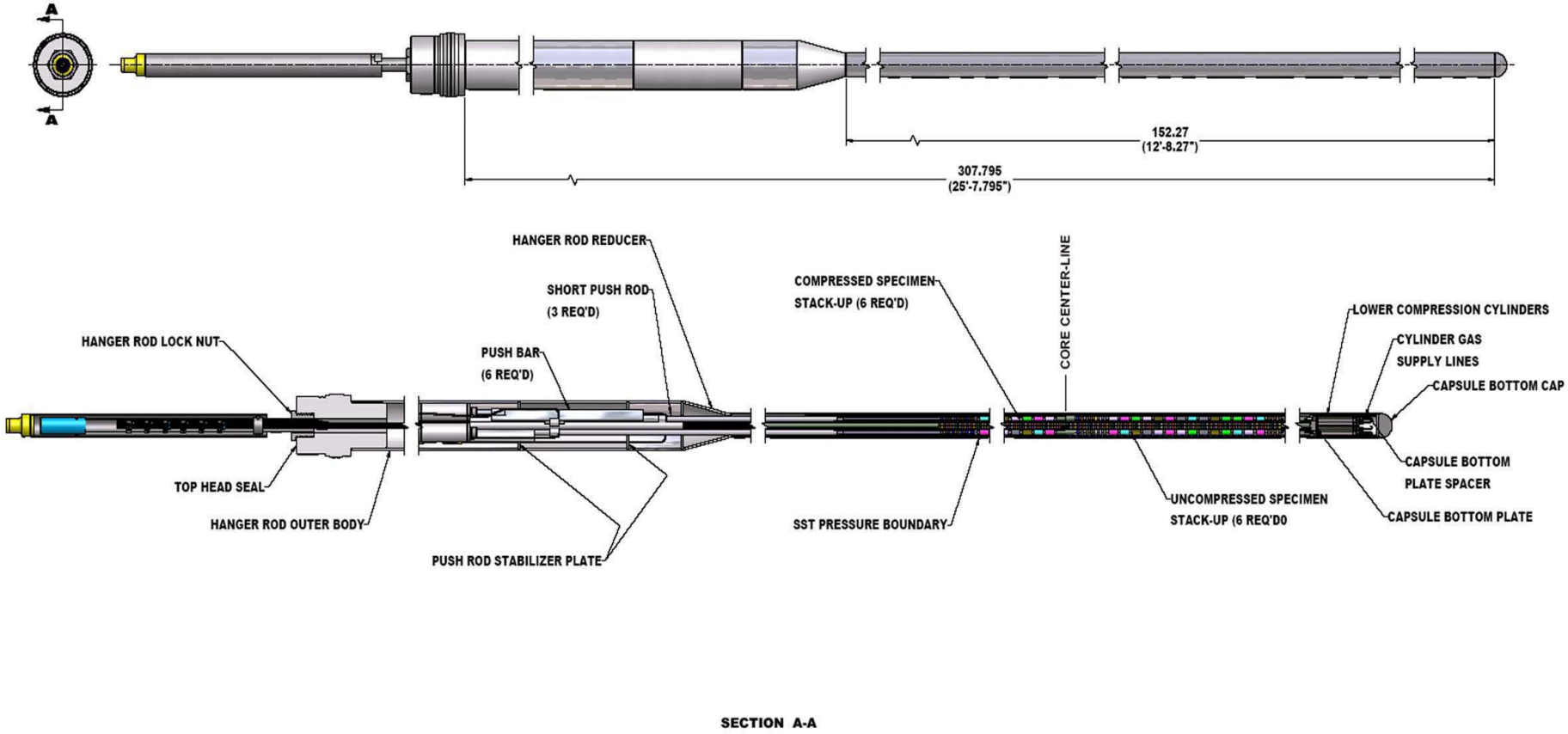
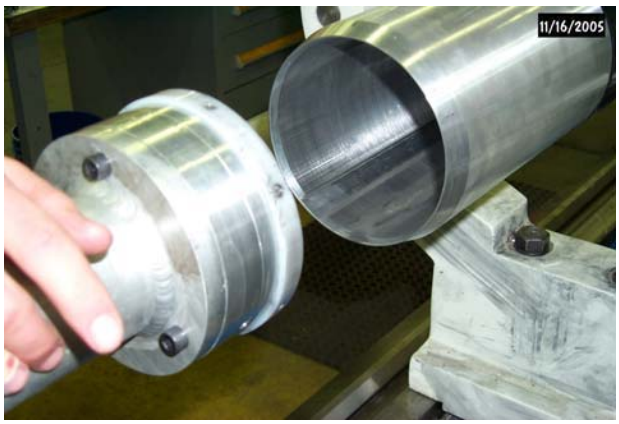


Figure 24. AGC-1 pressure boundary inside the ATR pressure vessel.

To accommodate the gas tubing and flux wires passage through the 4-foot core section, a 6-foot section of the 2.5-inch outer pressure tube spanning the 4-ft core section will have grooves machined into the inside wall by a broaching procedure developed by the ATR machine shop (see Figure 25a, b, and c). The grooves serve two purposes: (1) acting as guides to keep the flux wires and gas lines align down through the core and (2) reducing the temperature of the flux wires and gas lines. The tube wall thickness was increased to accommodate the grooves without reducing the tube thickness below the ASME required minimum wall thickness. The 6-ft. tube will be fabricated in two, 3-foot sections to accommodate machining limitations to obtain the accuracy required over the length of the tube. The gas gaps between the reactor and the outer diameter of the pressure tube and the gap between the inner diameter of the pressure boundary and the outer diameter of the graphite body play a major role in controlling the temperature.



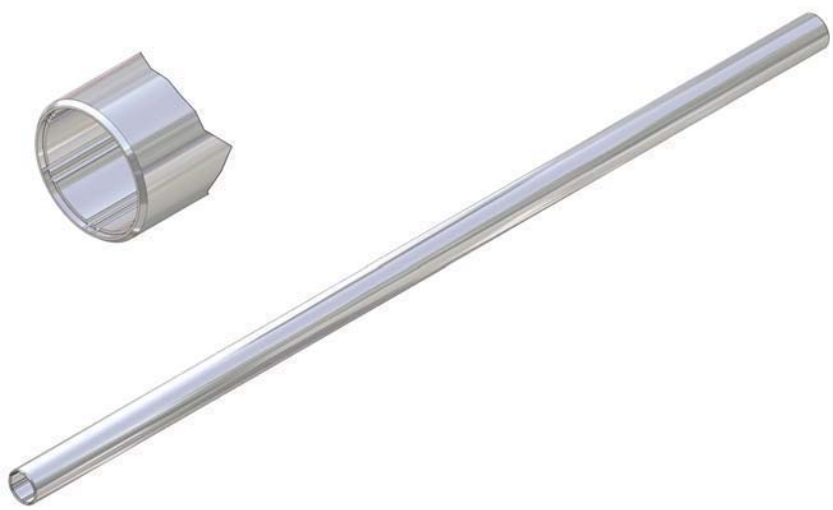


Figure 25a, b, and c. Grooved AGC-1 pressure boundary and broaching operation at the ATR machine shop

Different proposed designs were assessed for the arrangement of the specimens in the core. The arrangement chosen was six graphite specimen columns layed out in a circular pattern in the periphery of a cylindrical graphite body holder. An additional specimen column is located in the center of the graphite body (see Figure 26).

Figure 26. Cross section of the AGC-1 capsule located in the ATR core.

The graphite body provides a thermally similar material around the specimens and acts as a heat spreader distributing the generated gamma heat around all the specimens. Gamma heat is generated in the graphite specimens. Without the graphite body surrounding the specimens, the temperature gradients in the specimens would be large. Figure 27 shows the three graphite bodies that make up the graphite holder body and its support. The three bodies are machined from SGL NBG-25graphite, which has been purified to less than 3 ppm of ash content. The three bodies are constructed from smaller sections which are glued together with a special graphitic adhesive. The smaller sections were necessary to maintain the accuracy of the runout and diameter of the 0.5-inch specimen columns. Each of the glued-up bodies is heated to over 600 °C to cure and outgas. The adhesive was developed for graphite pieces in the electronics industry where outgasing at higher temperatures can not be tolerated. The smaller sections use annular dowels to align the three pieces. The dowels fit in the thermocouple holes which transverse the both holder bodies. The thermocouples do not go beyond the lower graphite support spacer. The upper and lower graphite holder bodies contain the graphite specimens. The outer diameter of the upper and lower graphite specimen holder varies with the height of the experiment. The variable outer diameter forms the variable gaps between the graphite and heat shield. The outer diameter of the two specimen holders is at their largest at the core centerline where the two graphite pieces are joined. The outer diameter reduces further away from the core centerline joint. The lower graphite spacer supports the two graphite experiment bodies by resting on the plate mounting the lower pneumatic rams. The lower support spacer also supports the heat shield.

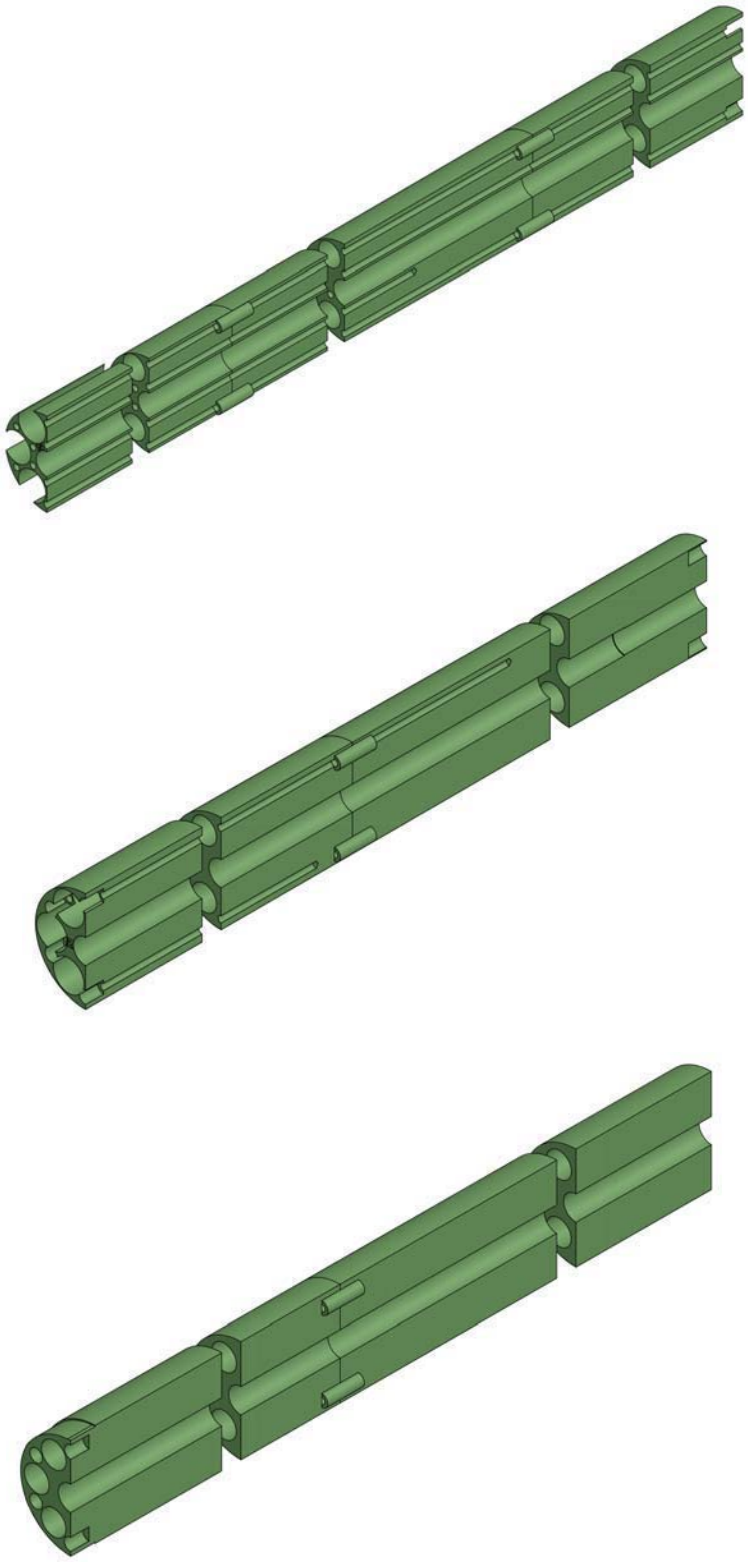


Figure 27. From top to bottom: graphite upper holder body, graphite lower holder body, and graphite lower spacer body

In the OC series of irradiations, one entire column of graphite specimens was loaded with another adjacent column left unloaded to obtain the companion stressed and unstressed samples needed to irradiation induced creep. A review of flux wires assays in a previous south flux trap experiment, SFT-1, showed the flux gradient from north to south is large. Figure 28 shows the fast flux in the northeast and southeast location in the SFT-1 experiment in the south flux trap. The vertical bars are the percent difference between the fast fluxes at the same elevation for the northeast and southeast flux wires. These data show that loading one entire column in the northeast position and irradiating an unloaded column in the southeast position would yield a 30 to 35% difference in the fluence, which is too large for the data obtained to be useful. Therefore, the AGC capsules will use the symmetry of the flux buckling to irradiate the companion stressed and unstressed samples.

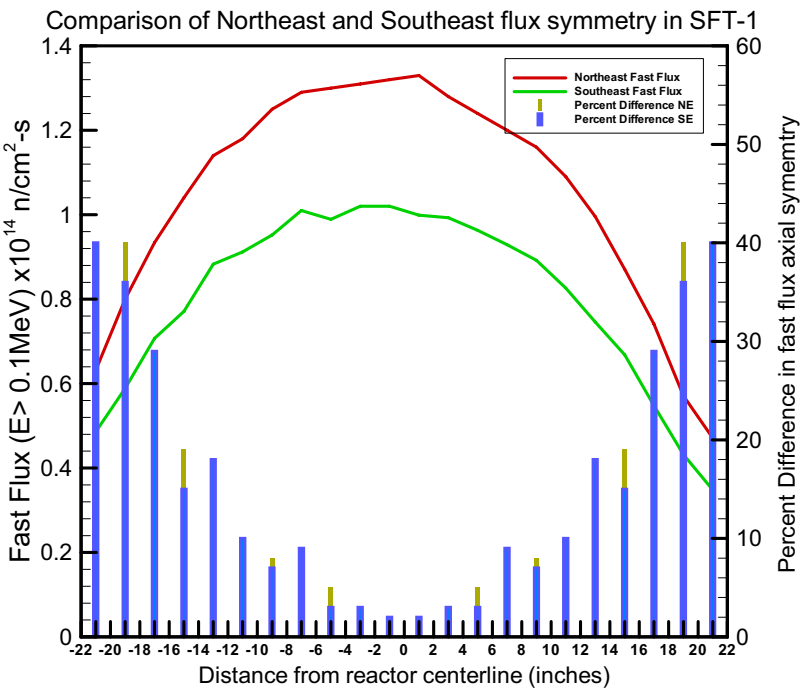


Figure 28. Symmetry of the axial flux profile in the south flux trap.

Figure 29 plots the same fast flux in the northeast and southeast location in SFT-1. The vertical bars show the percent difference in the fast flux at the same axial location above and below core centerline. This error represents symmetry in the axial cosine flux shape. The percent difference from ± 15 in. from core centerline is acceptable fast flux symmetry to irradiate companion graphite specimens. This dictates having each capsule contain stressed and unstressed specimens to achieve the smallest difference in fast fluence between corresponding stressed and unstressed specimens. This is accomplished by isolating the load on the stressed specimens from the unstressed specimens at the centerline of the reactor. This feature increases versatility of the design.

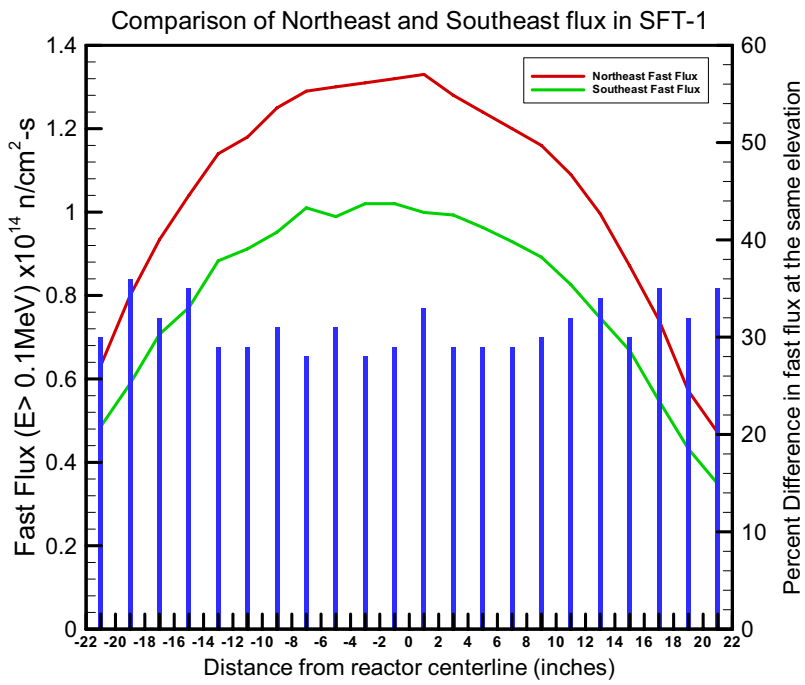


Figure 29. Comparison of the symmetry between the northeast and southeast position in the south flux trap. The vertical bars are the percent difference in the fast flux symmetry.

The heat transferred from the graphite body holder directly to the stainless steel outer pressure boundary would result in graphite temperatures less than 900°C. Adding a metallic shield between the graphite body and the outer pressure boundary will reduce the heat transferred to the outer pressure boundary by thermal radiation and increase the temperature in the graphite body (see Figure 30).

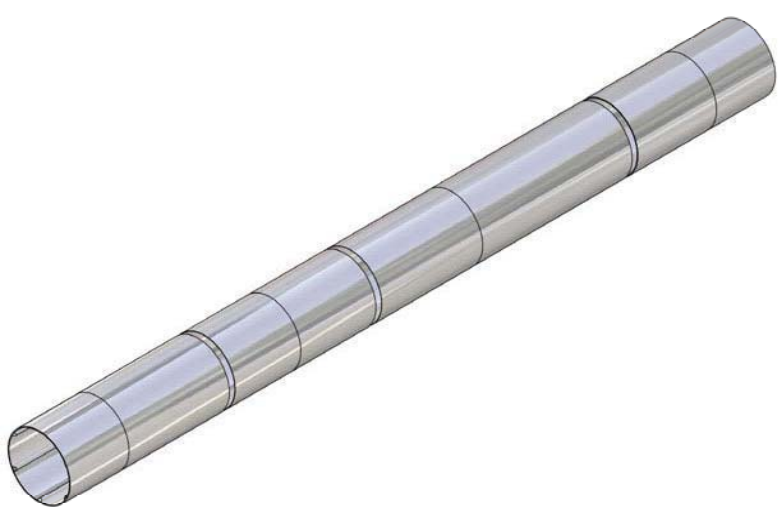
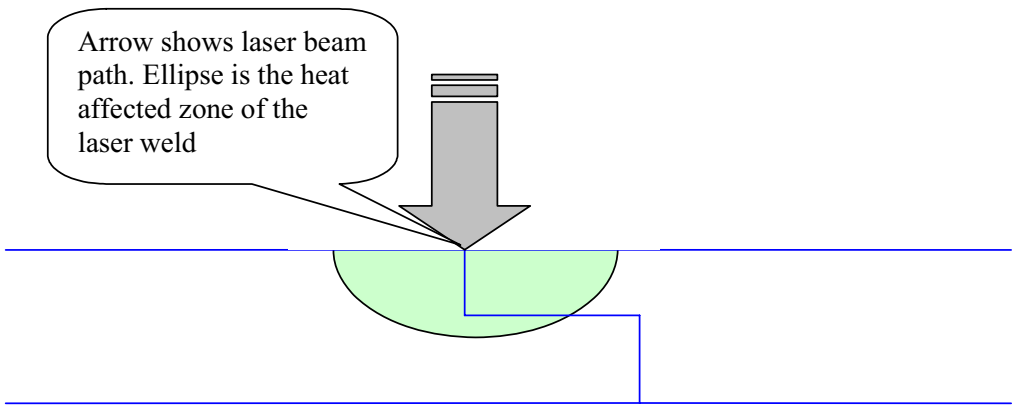


Figure 30. Haynes 230 thermal radiation shield. The spaces between pieces are drafting breaks to signified material removed to accommodate space on the page.

The metallic shield will also generate additional heat because of gamma heating. The gamma heating is proportional to the flux, thus the amount of internal heat generated drops dramatically at the ends of the experiment. The thickness of the thermal radiation shield is varied from 0.025 in. at the top and bottom to 0.005 in. at the core's midsection. In this way, additional heat is generated at the ends where it is needed to compensate for the axial flux buckling. The material chosen for the radiation heat shield is alloy Haynes 230. The maximum operational temperature is 1200°C for the metal; therefore it can be used in the 1200°C capsules. The heat shield is a tube of constant outer diameter and a varying inner diameter. The inner diameter is the largest at the core center of the tube where the tube wall thickness is 0.005 inches. The inner diameter decreases as a function of the distance from the core centerline. The tubes wall thickness increases to 0.025 inches at the top and bottom of the core. The accuracy of the tube requires the tube be machined from wrought annealed bar to minimize distortion from machining. The tube will be fabricated in smaller sections, which will be welded together by laser. The laser weld is accomplished by fabricating a lap joint between the smaller sections by means of electrode discharge machining. The lap joint is used to protect the graphite during welding. The power of the laser is adjusted to only penetrate just beyond one side of the lap joint to join the two pieces. The Figures 31a and 31b show the setup of the lap joint used for laser welding and the heat affected zone of two 0.010 inch Haynes 230 coupons laser welded.



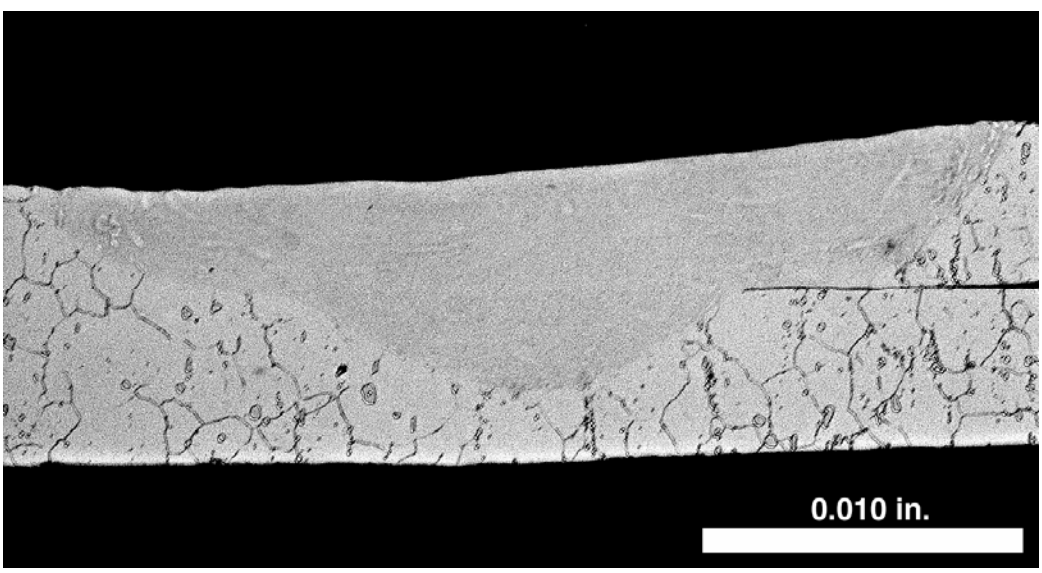


Figure 31a and b. Laser weldment of two Haynes 230 0.010 inch foil coupons

During reactor power level changes, temperature control is achieved by varying the amount of argon in the helium sweep gas. This gas mixture controls the temperature drop across the gaps between the graphite body, thermal radiation shield, and outer pressure boundary by varying the conductivity of the gas. Figure 32 is a cutaway of the upper portion of the experiment above the core. The six cylinders are staged in two groups of three with the upper set offset by 60 degrees to allow access to space in between the lower set of three. The rams are joined to the upper stainless steel push rods by an oval push rod. The oval geometry was chosen to resist bending moments by offset connection to the upper stainless steel pushrod. The offset is required to align the push rod directly above the graphite specimen column. In-line load cells are installed in the ends of the stainless steel push rods, which will read the force exerted by the push rod on the graphite specimen column. The reading from the load cell will be used to control the loading on the specimen column. The gas lines for the lower pneumatic rams and sweep gas are routed down the outer wall of the pressure boundary and then branch out to the sides to be routed in the guide tubes.

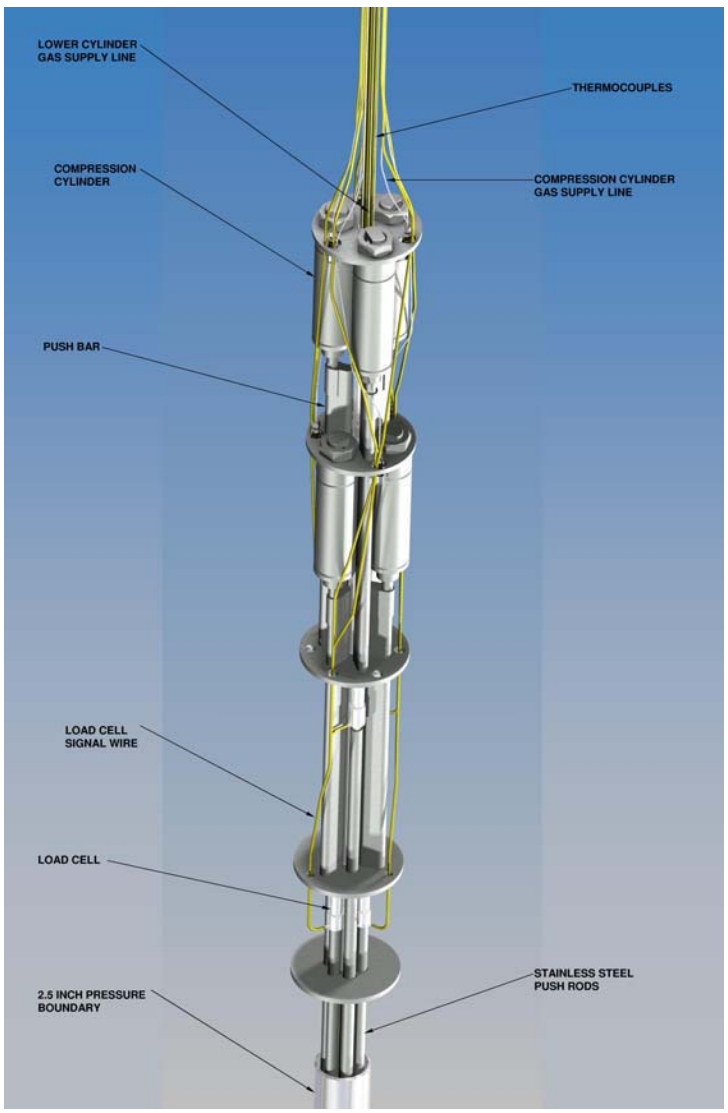


Figure 32. Cutaway of the out of core portion of the experiment showing the six pneumatic rams and pushrods. The yellow leads from the oval couplers are for the load cells in the couplers.

Figure 33 shows the stainless push rods proceeding into the graphite holder body above the core. The rods meet up with the graphite push rods that transfer the load to the specimens in the core. Graphite push rods must be used in the core because the temperature in the core is in excess of the temperature limit of stainless steel. The graphite push rods are hollow in the core region allowing small piggyback samples to reside in the upper portion of the core.

Figure 34 shows the specimen layout for the in-core portion of the experiment. The graphite push rod loads the upper portion of the stack only. At the core centerline, there is a graphite separator that bottoms out over the hole of the lower stack preventing the transfer of the load to the lower specimen column (see Figure 35). This graphite part has one end that fits in the 0.5-in. diameter hole in the upper stack, but the lower half has a diameter of 5/8 in. As the upper stack is loaded, the larger diameter end will bottom out over the 0.5 in. hole in the lower stack. When the lower push rods lift the stacks from the bottom, the upper end of the separator will slide into the 0.5-in. hole in the upper stack. This arrangement is necessary to achieve the irradiation of companion graphite specimens at the same temperature and fluence. These companion specimens provide the means to measure the irradiation-induced creep. Figure 35 shows the larger stressed and unstressed creep specimens, the smaller unloaded piggyback samples (used to determine irradiated properties), and the spacers between the samples. The spacers have axial pins that fit into the central holes in the specimens, thereby maintaining alignment within the columns in the graphite holder body.

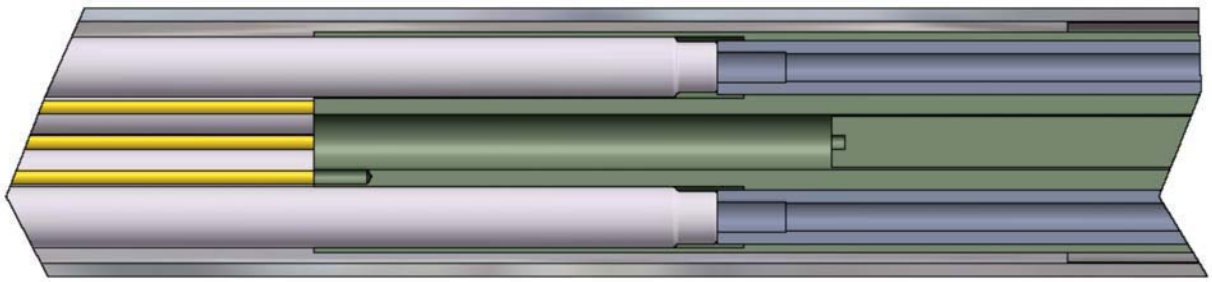


Figure 33. Cutaways showing the stainless steel pushrods entering the graphite holder body above the core and meeting the graphite push rods that will transfer the load on the specimens in the core. The center column is unloaded.

Figure 34. Layout of graphite specimens in the ATR core.

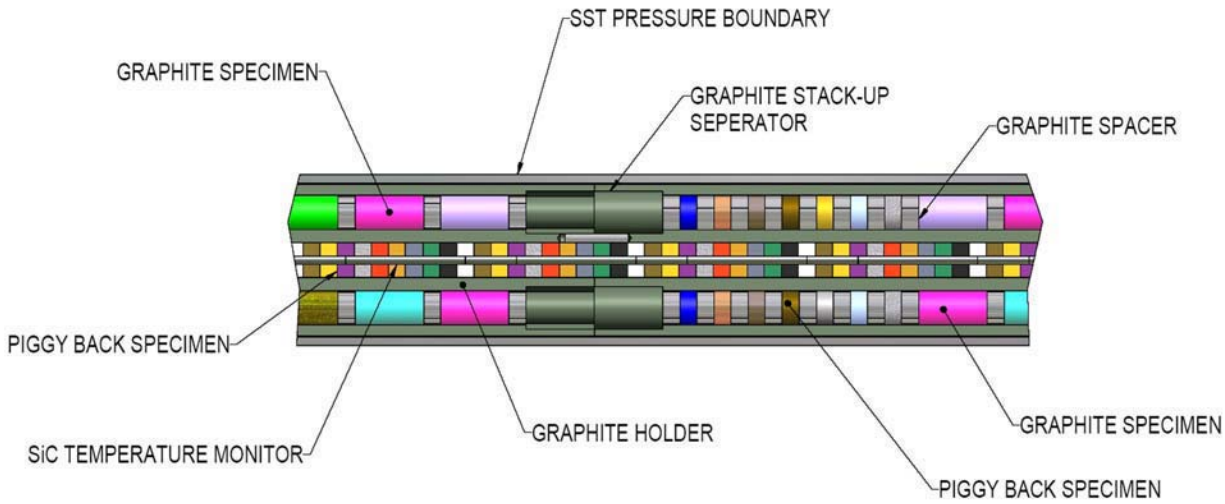


Figure 35. Sketch showing the specimen layout at core centerline. This sketch shows the separator which allows the loading of the upper portion and keeps the lower portion unloaded.

11. AGC-1 NEUTRONIC ANALYSIS

11.1 ATR Core Model

The neutronic analysis is being performed using MCNP Version 5. A Monte Carlo N-Particle Transport Code (MCNP) three dimensional model for the ATR is being used to calculate the gamma heat and dpa distribution in the south flux trap. Insertion into ATR is not expected before November 2007. The core configuration for the first quarter of FY-08 is not known at this time. Therefore, in this preliminary model, there are no fuel tests or experiment models except the AGC-1 in the MCNP model of the ATR. The assumed power levels for the different regions of the core are shown in Figure 36.

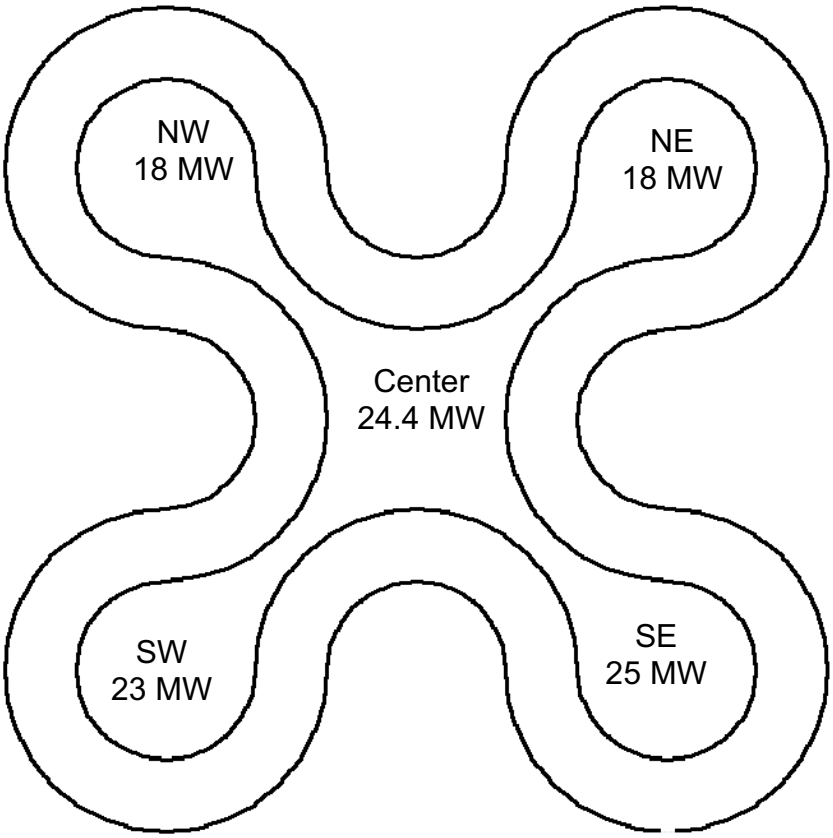


Figure 36. Standard power levels in the ATR core. All values are in MW and total to 108.4 MW. North is straight up on the page.

The AGC-1 capsule will remain in the core for ATR PALM cycles, which typically last from 5 to 14 days. The power levels during the PALM cycles are shown in Figure 37. During the PALM cycles the power level goes up from 25 to 55 MW in the south flux trap. When the ATR core configuration is know for reactor insertion, the MCNP model will be updated and rerun for the final gamma heat distribution, dpa distribution, and flux wire predictions.

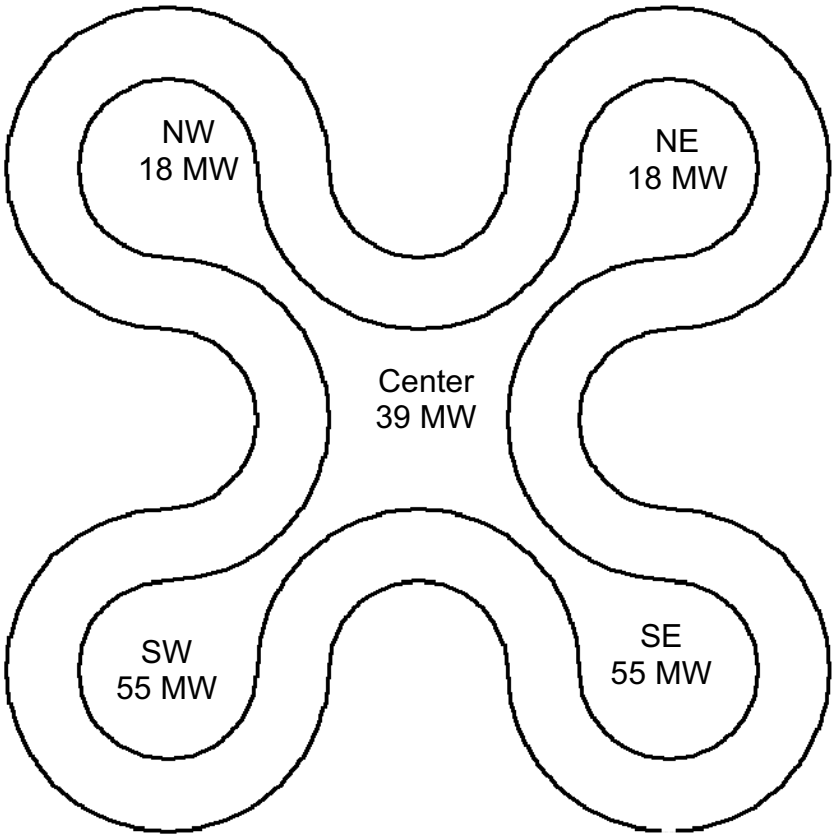


Figure 37. ATR PALM cycle power levels. All power levels are in megawatts and total to 185 MW. North is vertically straight up

11.2 AGC-1 MCNP model

There are two neutron flux gradients in the experiment. The largest gradient is from north to south, because the south flux trap has fuel on three sides without experiments. The fourth side is void of fuel. The power level in these lobes can vary from cycle to cycle and even double in the case of a PALM cycle. The north/south power gradient is even higher in the PALM cycles. The gamma heat distribution in the experiment will be asymmetrical. Figure 38 shows the individual features that have been included in the MCNP model. Figure 39 shows the cross section separated into 6 azimuthal tally regions. There are 49 tallies in the cross section. Only the thermal couples were smeared all other features were modeled explicitly. A tally is the means by which MCNP tracks random walking particles in a geometrical volume and correlates to nuclear reactions per source particle. The geometry of the model does take into account the varying diameters of the graphite and thermal radiation heat shield. Each section has a gamma heat value for the center specimen, the inner graphite body, the graphite specimen, outer graphite body, the thermal radiation shield, and the stainless steel pressure boundary. The guide tubes generate gamma heat from the wall of the guide tube, the gas tube, and the flux wire. Because the flux is not perfectly symmetrical about the axial core centerline, sampling must be performed over the entire axial length of the experiment and extending one foot above and below the core. The tallies are evaluated at every quarter of an inch in the core region and every 1 inch above and below the core for a total of 216 axial positions in the experiment. Therefore, there are 10,584 gamma heat values to be used as input in the thermal analysis.

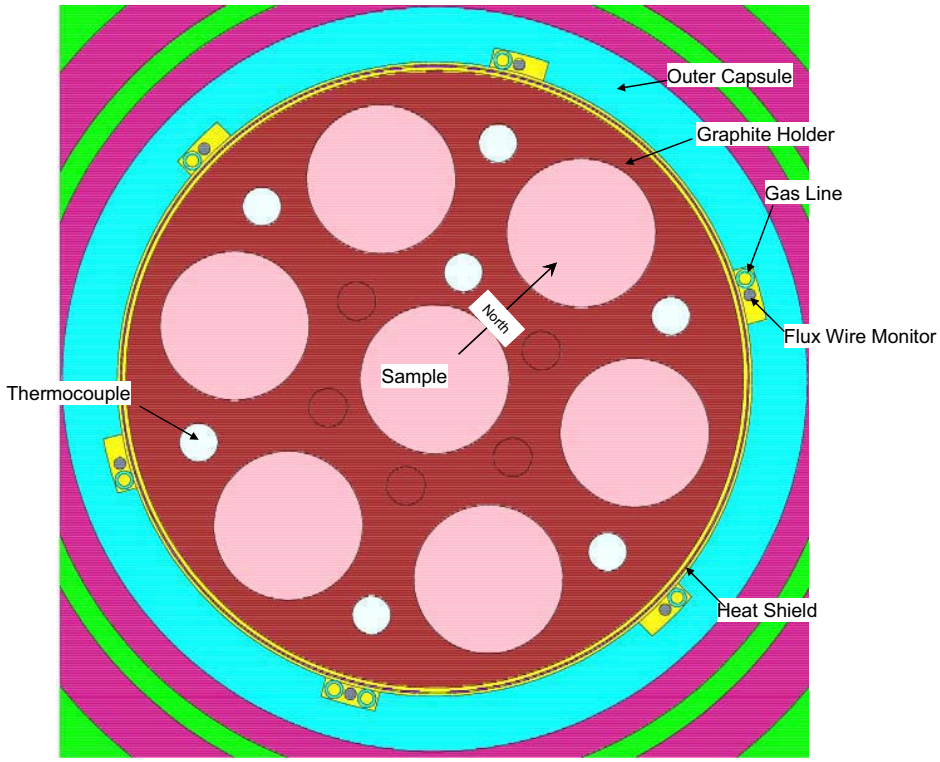


Figure 38. Tally map for the AGC-1 capsule cross section. Each color is a explicitly modeled feature.

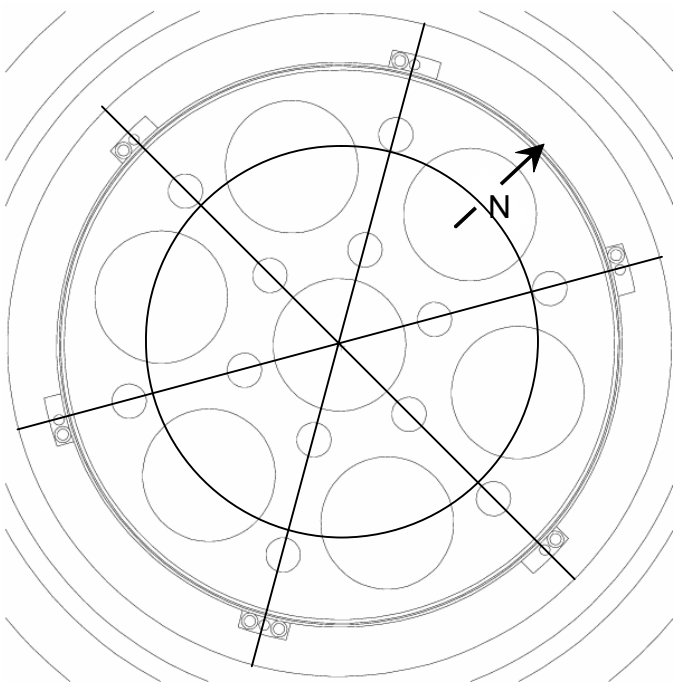


Figure 39. MCNP model separated into 6 azimuthal tally regions. Center specimen stack is not divided into azimuthal regions.

12. AGC-1 THERMAL ANALYSIS

The thermal analysis of the AGC-1 experiment was performed using ABAQUS and an INL developed data translator between MCNP and ABAQUS. The ABAQUS model contains 210,000 elements and 144,000 nodes. Figures 40 through 44 show the finite element models for the capsule pressure boundary, graphite holder, thermal heat shield, specimen stacks 1 through 6, and center specimen stack. The finite element model is complete after the individual models are assembled. The next step in the analysis is to assign gamma heat values from the MCNP analysis to the individual elements. This is done using the MCNP translator developed at the INL. The translator reads the 10, 584 gamma heat values from the MCNP output and constructs a three dimensional mesh different from the ABAQUS three dimensional mesh. A FORTRAN program was written that links with ABAQUS to lookup the gamma heat associated from the translator mesh and assigns the gamma heat value to the individual ABAQUS finite element. ABAQUS then proceeds with the calculation of the temperature distribution in the capsule. If this translator wasn't used, this process of assigning gamma heats to the individual finite elements would have to be done by hand consuming a large amount of time. The translator allows for a faster design process, since changes in the core configuration can be quickly translated to ABAQUS for thermal analysis

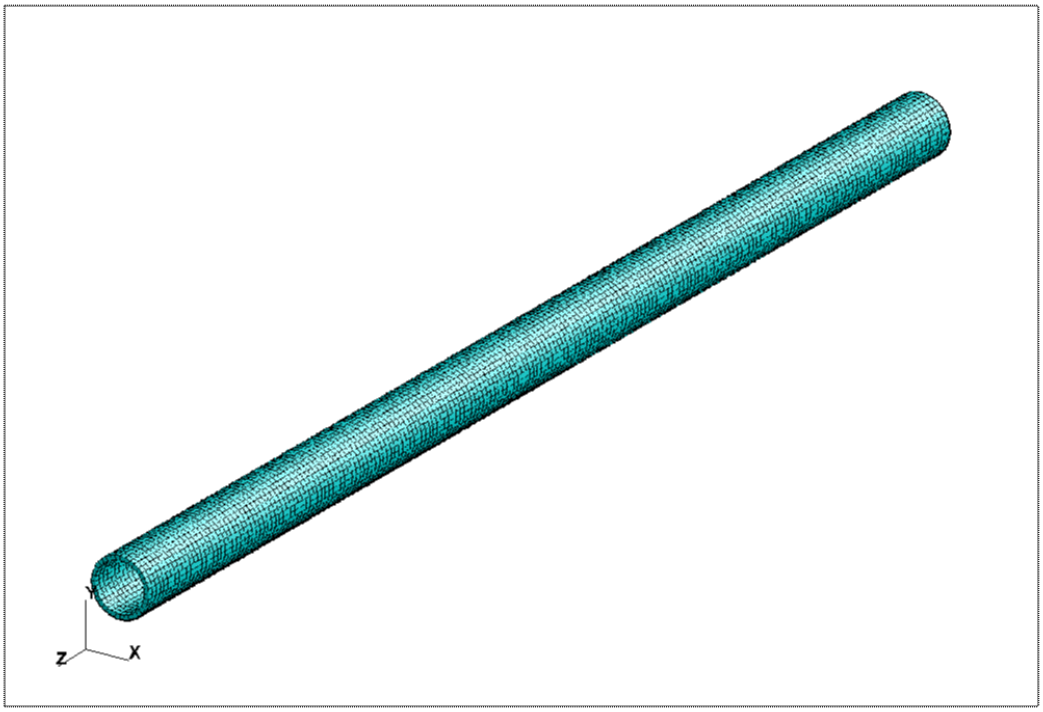


Figure 40 Finite element model for the capsule pressure boundary

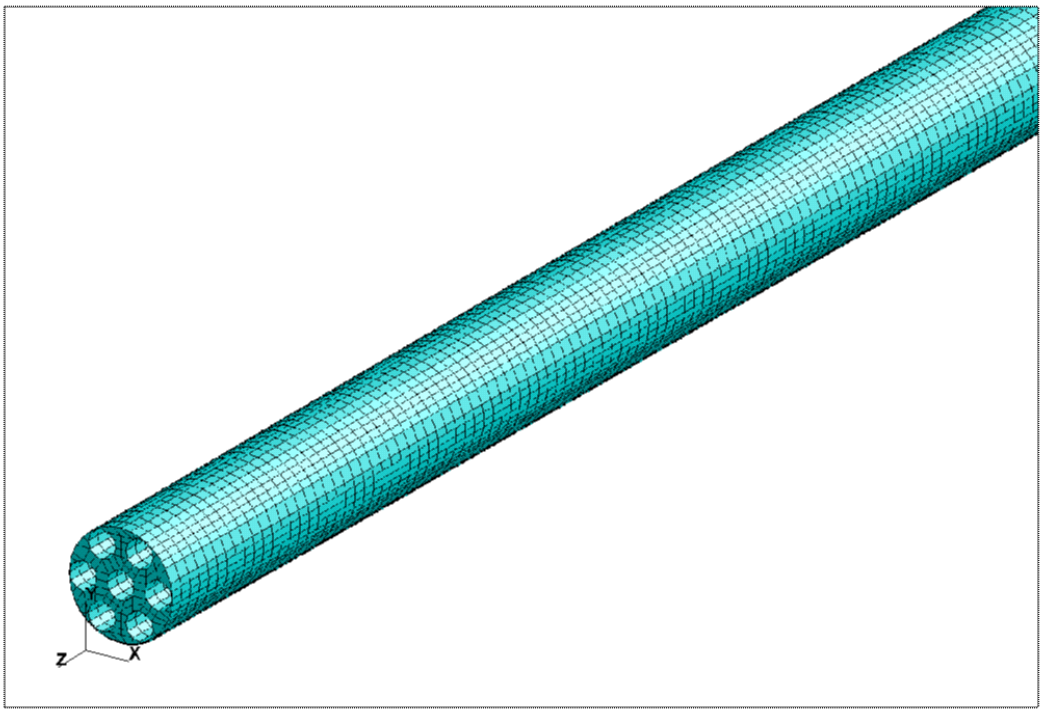


Figure 41. Finite element model for the graphite holder body

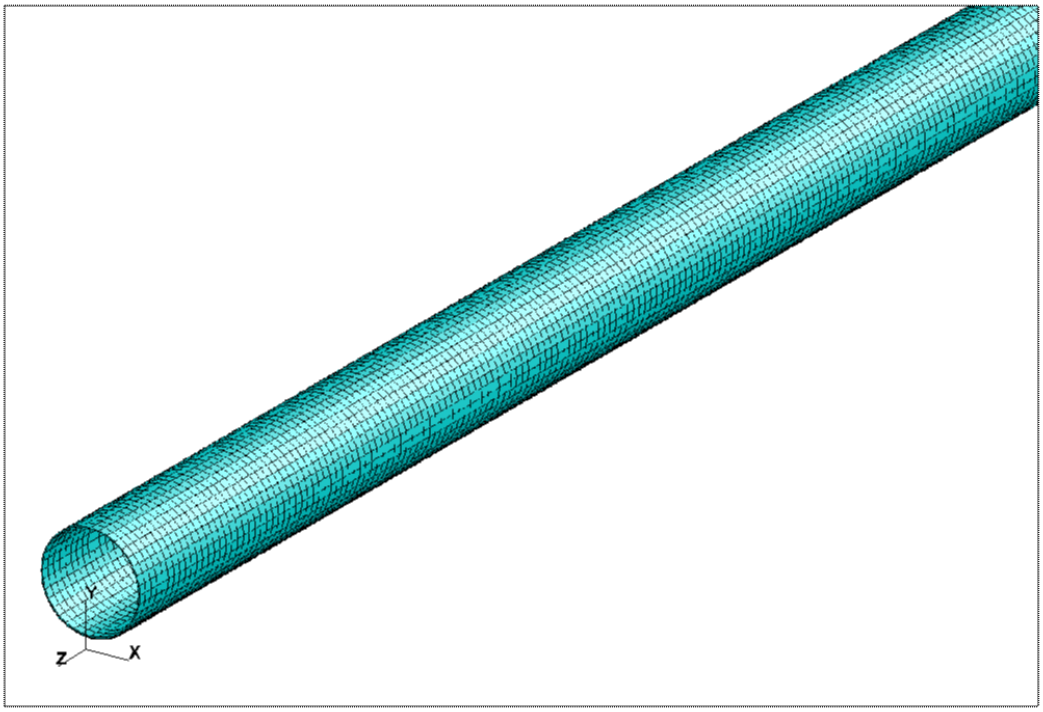


Figure 42. Finite element model for the thermal heat shield

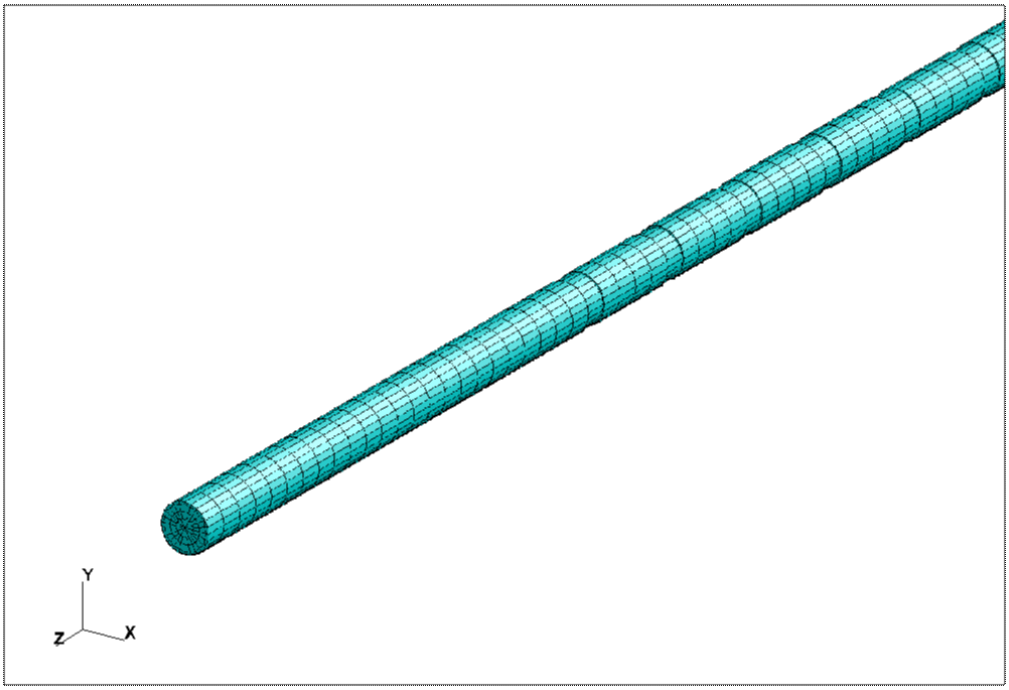


Figure 43. Finite element model for the specimen stacks 1 through 6. Note the smaller spacers between the graphite specimens.

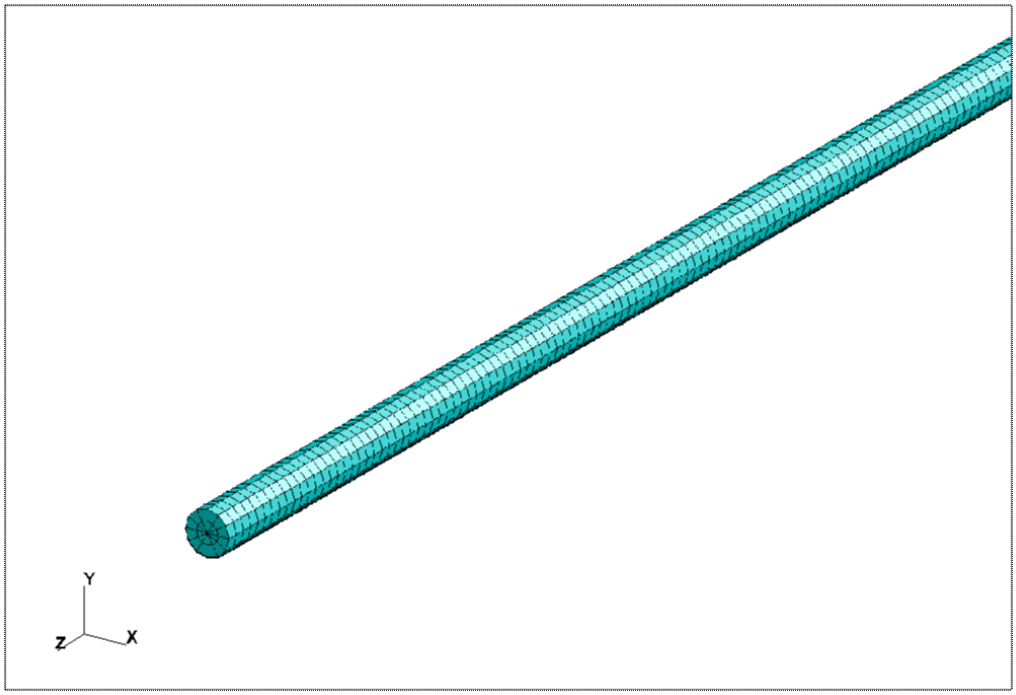


Figure 44. Finite element model for the center specimen stack

The asymmetry of the flux distribution in the AGC-1 is shown Figures 45 and 46. Similarly, the gamma heat distribution in the AGC-1 is shown in Figures 47 and 48. Flux units are neutrons/cm^2/sec and the gamma heat units are MeV/gm. North is at two o'clock. In Figures 45 through 48 note the gradient seen in the direction of north to south. In Figures 47 and 48 note the high gamma heat per gram for the heat shield. Figures 47a and b are the thermal analysis

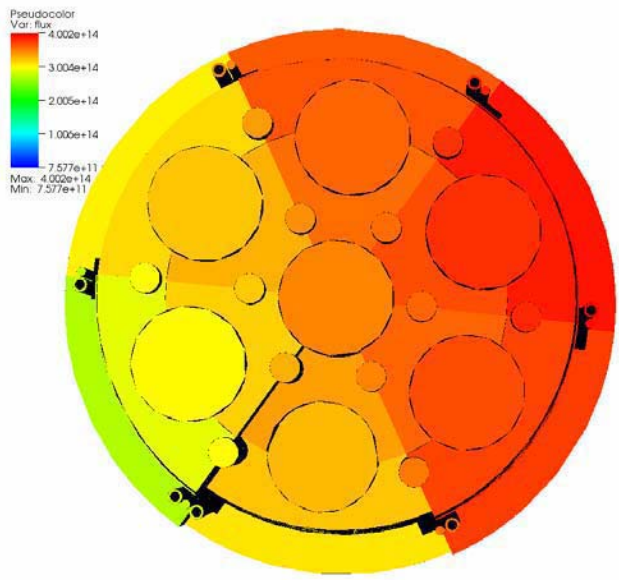


Figure 45. Fast Flux distribution in the AGC-1 in the south flux trap. Units are neutrons/cm2/sec. North is at two o'clock

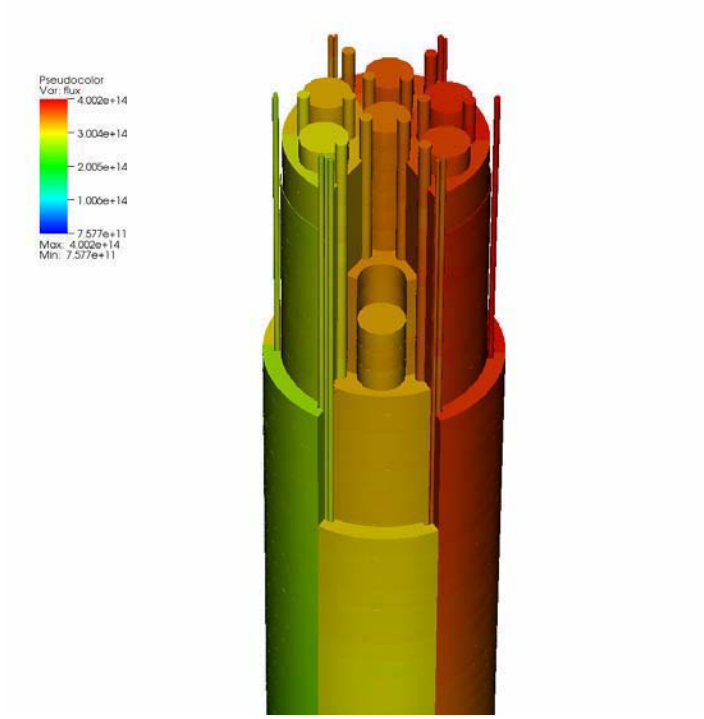


Figure 46. Fast flux distribution in the AGC-1 capsule in the south flux trap. Units are neutrons/cm2/sec

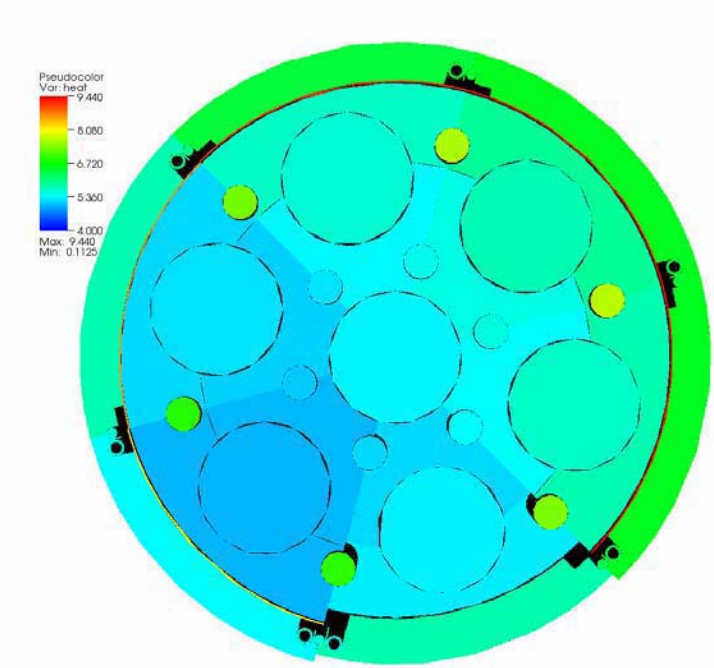


Figure 47. Gamma heat distribution in the AGC-1 capsule in the south flux trap. Units are MeV/gm. North is at two o'clock

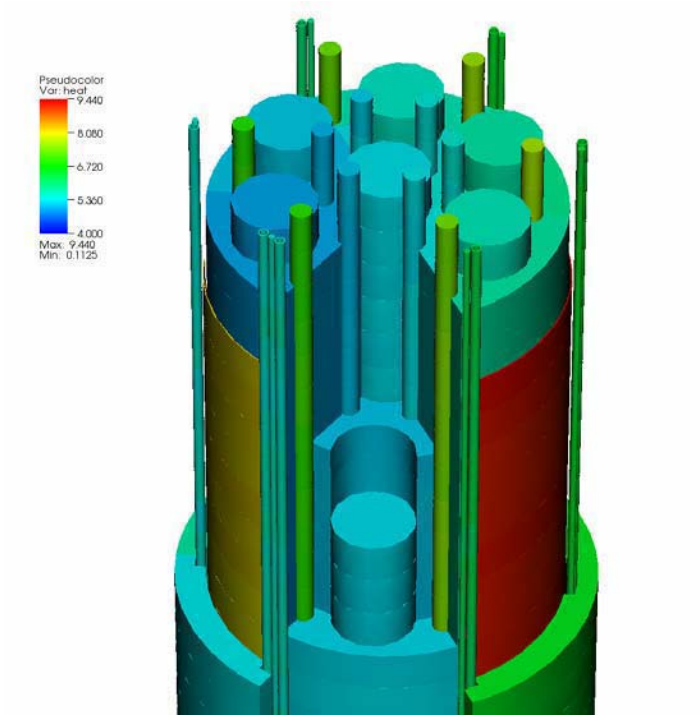
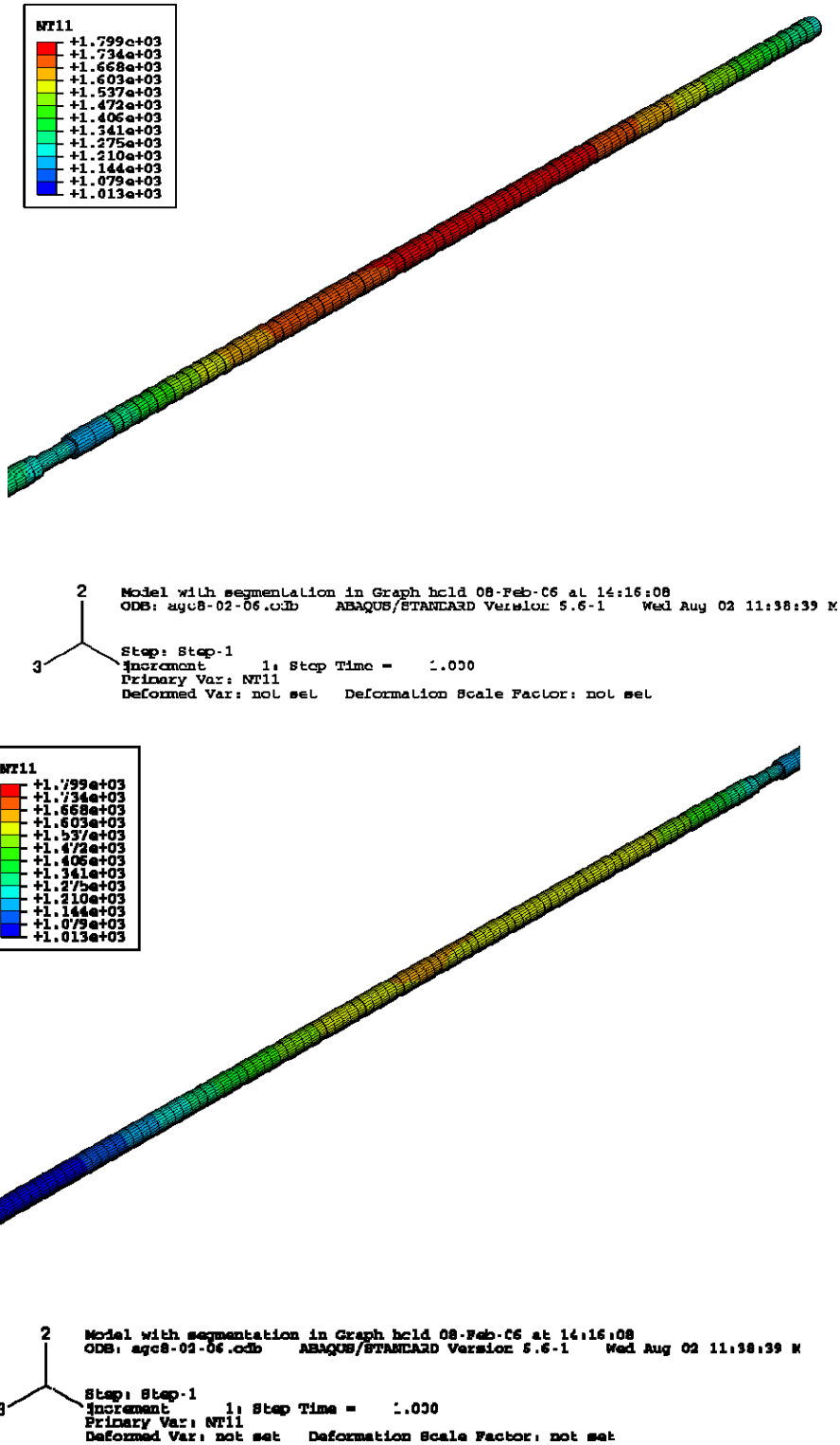


Figure 48. Gamma heat distribution in the AGC-1 capsule. Units are MeV/gm

The thermal model represents just the 4-ft. core section. The forms of heat transfer used in the model are thermal conduction in the graphite solids, thermal conduction in the gas gaps, and radiation heat transfer between the graphite surfaces. Thermal gas conduction and radiation heat transfer is used between the graphite experiment body and heat shield and similarly between the heat shield and outer pressure boundary. Convective heat transfer is used to model the heat deposited in the coolant flowing between the pressure boundary and the chopped dummy in-pile tube. Temperature dependent thermal conductivity is used for all materials. Figures 49a and b are the temperature distributions in one of the six specimen stacks. All six specimen stacks have similar temperature patterns. The temperatures are in degrees Fahrenheit. The target temperature is 900 °C which is 1652 °F. From figure 49a the bottom half of the specimen stack is at a temperature greater than 900 °C. Figure 49b shows the top half of the stack is running cooler than 900°C. The upper end of the stacks is running about 350°C colder, while the lower end of the stack is running 240°C colder.



Figures 49a and b. Temperature distribution in specimen stack. Upper figure is the top of the stack. The lower figure is the bottom of the stack. Temperatures are in degrees F.

13. AGC-1 MECHANICAL ANALYSIS

This section outlines the mechanical analysis necessary for reactor insertion and support of the safety analysis report found in Engineering Design File – 5925, "Structural Evaluation of the ATR Advanced Graphite Experiment AGC-1",May 2006 (draft). The detailed calculations will not be repeated here. The reader can review the detail calculations in the report in Appendix I. This report presents the detail calculations supporting:

- ASME design of the reactor head penetration and capsule boundary
- ANSI B31.1 analysis of gas lines in the capsule
- Capsule seismic analysis
- Thermal stress analysis
- Other component evaluations

14. STATUS OF AGC-1 DESIGN

This report details the status as of the Preliminary Design Review held May 31, 2006 in Idaho Falls, ID. The Design Review Chairman's report on the Preliminary Design Review is attached in Appendix J.

15. SCHEDULE

The planned schedule for Capsule AGC-1 is:

Task	Due Date
Complete preirradiation examination of AGC-1 graphite specimens	March 31, 2007
Complete assembly of AGC-1	June 30, 2007
Complete AGC-1 out of core shake-down testing	September 30, 2007
Reactor insertion	November, 2007
Complete irradiation	June 30, 2008
Complete hot cell disassembly	September 30, 2008
Ship graphite specimens to ORNL for PIE	October 31, 2008
Complete graphite PIE	June 30, 2009
Issue draft AGC-1 PIE report	September 30, 2009

16. REFERENCES

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9. Bratton, R., and T. Burchell, *Milestone Report: NGNP Graphite Selection Strategy*, INL/EXT-05-00269, 2005.

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11. Senn, R. L., et al., Design, Operation, and Initial Results from Capsule OC-1, the First of a Series of Graphite Creep Capsule Irradiation Experiments," ORNL/TM-5798, May 1977.

Appendix A

AGC-1 Channel 1 (North) Specimen Layout [3 ksi]

AGC-1 Channel 1 (NORTH) Layout [3 ksi]											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Companion Sample Position
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
	Insulation										
	Thimble top										
1PB1	Piggyback	NBG-17		0.25	0.50	48	47.875	0.488	7.17E+20	0.52	Top of Core
1PB2	Piggyback	H-451		0.25	0.50	47.75	47.625	0.548	8.05E+20	0.59	
1PB3	Piggyback	NBG-18		0.25	0.50	47.5	47.375	0.608	8.93E+20	0.65	
1PB4	Piggyback	NBG-18		0.25	0.50	47.25	47.125	0.667	9.79E+20	0.72	
1PB5	Piggyback	H-451		0.25	0.50	47	46.875	0.726	1.07E+21	0.78	
1PB6	Piggyback	IG-110		0.25	0.50	46.75	46.625	0.784	1.15E+21	0.84	
1PB7	Piggyback	NBG-17		0.25	0.50	46.5	46.375	0.842	1.24E+21	0.90	
1PB8	Piggyback	PCEA		0.25	0.50	46.25	46.125	0.899	1.32E+21	0.96	
1PB9	Piggyback	NBG-18		0.25	0.50	46	45.875	0.957	1.40E+21	1.03	
1PB10	Piggyback	IG-430		0.25	0.50	45.75	45.625	1.013	1.49E+21	1.09	
1PB11	Piggyback	H-451		0.25	0.50	45.5	45.375	1.069	1.57E+21	1.15	
1PB12	Piggyback	NBG-17		0.25	0.50	45.25	45.125	1.125	1.65E+21	1.21	
1PB13	Piggyback	PCEA		0.25	0.50	45	44.875	1.180	1.73E+21	1.27	
1PB14	Piggyback	NBG-18		0.25	0.50	44.75	44.625	1.235	1.81E+21	1.32	
1PB15	Piggyback	IG-430		0.25	0.50	44.5	44.375	1.290	1.89E+21	1.38	

AGC-1 Channel 1 (NORTH) Layout [3 ksi]											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Companion Sample Position
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
	Thimble Bottom			0.25		44.25	44.125	1.344	1.97E+21	1.44	
Spacer	Guide/spacer	AXF-5Q		0.25		44	43.875	1.397	2.05E+21	1.50	
1S15	stressed creep	H-451		1	0.50	43.75	43.25	1.529	2.25E+21	1.64	1U14
Spacer	Guide/spacer	AXF-5Q		0.25		42.75	42.625	1.657	2.43E+21	1.78	
1S14	stressed creep	PCEA		1	0.50	42.5	42	1.783	2.62E+21	1.91	1U13
Spacer	Guide/spacer	AXF-5Q		0.25		41.5	41.375	1.905	2.80E+21	2.04	
1S13	stressed creep	NBG-17		1	0.50	41.25	40.75	2.025	2.97E+21	2.17	1U12
Spacer	Guide/spacer	AXF-5Q		0.25		40.25	40.125	2.141	3.14E+21	2.30	
1S12	stressed creep	NBG-17		1	0.50	40	39.5	2.254	3.31E+21	2.42	1U11
Spacer	Guide/spacer	AXF-5Q		0.25		39	38.875	2.364	3.47E+21	2.53	
1S11	stressed creep	NBG-17		1	0.50	38.75	38.25	2.471	3.63E+21	2.65	1U11
Spacer	Guide/spacer	AXF-5Q		0.25		37.75	37.625	2.574	3.78E+21	2.76	
1S10	stressed creep	IG-430		1	0.50	37.5	37	2.674	3.93E+21	2.87	1U10
Spacer	Guide/spacer	AXF-5Q		0.25		36.5	36.375	2.770	4.07E+21	2.97	
1S9	stressed creep	IG-110		1	0.50	36.25	35.75	2.863	4.21E+21	3.07	1U9
Spacer	Guide/spacer	AXF-5Q		0.25		35.25	35.125	2.953	4.34E+21	3.17	
1S8	stressed creep	H-451		1	0.50	35	34.5	3.039	4.46E+21	3.26	1U8
Spacer	Guide/spacer	AXF-5Q		0.25		34	33.875	3.121	4.58E+21	3.35	

AGC-1 Channel 1 (NORTH) Layout [3 ksi]											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Companion Sample Position
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
1S7	stressed creep	IG-110		1	0.50	33.75	33.25	3.200	4.70E+21	3.43	1U7
Spacer	Guide/spacer	AXF-5Q		0.25		32.75	32.625	3.274	4.81E+21	3.51	
1S6	stressed creep	PCEA		1	0.50	32.5	32	3.346	4.91E+21	3.59	1U6
Spacer	Guide/spacer	AXF-5Q		0.25		31.5	31.375	3.413	5.01E+21	3.66	
1S5	stressed creep	IG-430		1	0.50	31.25	30.75	3.476	5.11E+21	3.73	1U5
Spacer	Guide/spacer	AXF-5Q		0.25		30.25	30.125	3.536	5.19E+21	3.79	
1S4	stressed creep	NBG-18		1	0.50	30	29.5	3.591	5.28E+21	3.85	1U4
Spacer	Guide/spacer	AXF-5Q		0.25		29	28.875	3.643	5.35E+21	3.91	
1S3	stressed creep	NBG-17		1	0.50	28.75	28.25	3.690	5.42E+21	3.96	1U3
Spacer	Guide/spacer	AXF-5Q		0.25		27.75	27.625	3.734	5.48E+21	4.00	
1S2	stressed creep	PCEA		1	0.50	27.5	27	3.773	5.54E+21	4.05	1U2
Spacer	Guide/spacer	AXF-5Q		0.25		26.5	26.375	3.808	5.59E+21	4.08	
1S1	stressed creep	NBG-18		1	0.50	26.25	25.75	3.839	5.64E+21	4.12	1U1
Spacer	Guide/spacer	AXF-5Q		0.25		25.25	25.125	3.866	5.68E+21	4.14	
Plug	Core center plug	AXF-5Q		1		25	24.5	3.888	5.71E+21	4.17	
Core Center Line											
Plug	Core center plug	AXF-5Q		1		24	23.5	3.914	5.75E+21	4.20	
GAP	GAP			0.25		23	22.875	3.925	5.77E+21	4.21	

AGC-1 Channel 1 (NORTH) Layout [3 ksi]											
				Dimensions, ins					Nominal Dose		
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Length	Dia	Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	n/cm2 [E>0.1 MeV]	dpa	Companion Sample Position
Spacer	Guide/spacer	AXF-5Q		0.25		22.75	22.625	3.928	5.77E+21	4.21	
1PB16	Piggyback	NBG-17		0.25	0.50	22.5	22.375	3.930	5.77E+21	4.21	
Spacer	Guide/spacer	AXF-5Q		0.25		22.25	22.125	3.932	5.78E+21	4.22	
1PB17	Piggyback	PCEA		0.25	0.50	22	21.875	3.933	5.78E+21	4.22	FLUX CL
Spacer	Guide/spacer	AXF-5Q		0.25		21.75	21.625	3.933	5.78E+21	4.22	
1PB18	Piggyback	NBG-18		0.25	0.50	21.5	21.375	3.932	5.78E+21	4.22	
Spacer	Guide/spacer	AXF-5Q		0.25		21.25	21.125	3.931	5.77E+21	4.21	
1PB19	Piggyback	IG-430		0.25	0.50	21	20.875	3.929	5.77E+21	4.21	
Spacer	Guide/spacer	AXF-5Q		0.25		20.75	20.625	3.926	5.77E+21	4.21	
1PB20	Piggyback	HOPG		0.25	0.50	20.5	20.375	3.923	5.76E+21	4.21	
Spacer	Guide/spacer	AXF-5Q		0.25		20.25	20.125	3.918	5.76E+21	4.20	
1PB21	Piggyback	IG-110		0.25	0.50	20	19.875	3.913	5.75E+21	4.20	
Spacer	Guide/spacer	AXF-5Q		0.25		19.75	19.625	3.907	5.74E+21	4.19	
1PB22	Piggyback	BAN		0.25	0.50	19.5	19.375	3.901	5.73E+21	4.18	
Spacer	Guide/spacer	AXF-5Q		0.25		19.25	19.125	3.893	5.72E+21	4.17	
1U1	unstressed control	NBG-18		1	0.50	19	18.5	3.872	5.69E+21	4.15	1S1
Spacer	Guide/spacer	AXF-5Q		0.25		18	17.875	3.845	5.65E+21	4.12	
1U2	unstressed control	PCEA		1	0.50	17.75	17.25	3.813	5.60E+21	4.09	1S2

AGC-1 Channel 1 (NORTH) Layout [3 ksi]											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Companion Sample Position
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
Spacer	Guide/spacer	AXF-5Q		0.25		16.75	16.625	3.777	5.55E+21	4.05	
1U3	unstressed control	NBG-17		1	0.50	16.5	16	3.735	5.49E+21	4.01	1S3
Spacer	Guide/spacer	AXF-5Q		0.25		15.5	15.375	3.689	5.42E+21	3.96	
1U4	unstressed control	NBG-18		1	0.50	15.25	14.75	3.638	5.34E+21	3.90	1S4
Spacer	Guide/spacer	AXF-5Q		0.25		14.25	14.125	3.581	5.26E+21	3.84	
1U5	unstressed control	IG-430		1	0.50	14	13.5	3.519	5.17E+21	3.77	1S5
Spacer	Guide/spacer	AXF-5Q		0.25		13	12.875	3.452	5.07E+21	3.70	
1U6	unstressed control	PCEA		1	0.50	12.75	12.25	3.380	4.96E+21	3.62	1S6
Spacer	Guide/spacer	AXF-5Q		0.25		11.75	11.625	3.302	4.85E+21	3.54	
1U7	unstressed control	IG-110		1	0.50	11.5	11	3.219	4.73E+21	3.45	1S7
Spacer	Guide/spacer	AXF-5Q		0.25		10.5	10.375	3.131	4.60E+21	3.36	
1U8	unstressed control	H-451		1	0.50	10.25	9.75	3.037	4.46E+21	3.26	1S8
Spacer	Guide/spacer	AXF-5Q		0.25		9.25	9.125	2.938	4.31E+21	3.15	
1U9	unstressed control	IG-110		1	0.50	9	8.5	2.833	4.16E+21	3.04	1S9
Spacer	Guide/spacer	AXF-5Q		0.25		8	7.875	2.722	4.00E+21	2.92	
1U10	unstressed control	IG-430		1	0.50	7.75	7.25	2.606	3.83E+21	2.79	1S10
Spacer	Guide/spacer	AXF-5Q		0.25		6.75	6.625	2.484	3.65E+21	2.66	
1U11	unstressed control	NBG-17		1	0.50	6.5	6	2.357	3.46E+21	2.53	1S11/12

AGC-1 Channel 1 (NORTH) Layout [3 ksi]											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Companion Sample Position
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
Spacer	Guide/spacer	AXF-5Q		0.25		5.5	5.375	2.223	3.27E+21	2.38	
1U12	unstressed control	NBG-17		1	0.50	5.25	4.75	2.084	3.06E+21	2.23	1S13
Spacer	Guide/spacer	AXF-5Q		0.25		4.25	4.125	1.939	2.85E+21	2.08	
1U13	unstressed control	PCEA		1	0.50	4	3.5	1.788	2.63E+21	1.92	1S14
Spacer	Guide/spacer	AXF-5Q		0.25		3	2.875	1.631	2.40E+21	1.75	
1U14	unstressed control	H-451		1	0.50	2.75	2.25	1.468	2.16E+21	1.57	1S15
Spacer	Guide/spacer	AXF-5Q		0.25		1.75	1.625	1.299	1.91E+21	1.39	
1PB23	Piggyback	IG-430		0.25	0.50	1.5	1.375	1.230	1.81E+21	1.32	
Spacer	Guide/spacer	AXF-5Q		0.25	0.50	1.25	1.125	1.159	1.70E+21	1.24	
1PB24	Piggyback	PCEA		0.25	0.50	1	0.875	1.088	1.60E+21	1.17	
Spacer	Guide/spacer	AXF-5Q		0.25	0.50	0.75	0.625	1.016	1.49E+21	1.09	
1PB25	Piggyback	NBG-18		0.25	0.50	0.5	0.375	0.943	1.38E+21	1.01	
Spacer	Guide/spacer	AXF-5Q		0.25	0.50	0.25	0.125	0.868	1.28E+21	0.93	End of core

Appendix B

AGC-1 Channel 2 (North-East) Specimen Layout [2 ksi]

AGC-1 Channel 2 (NORTH EAST) Layout [2 ksi]											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Companion Sample Position
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
	Insulation										
	Thimble top										
2PB1	Piggyback	IG-110		0.25	0.50	48	47.875	0.423	6.21E+20	0.45	Top of Core
2PB2	Piggyback	H-451		0.25	0.50	47.75	47.625	0.482	7.08E+20	0.52	
2PB3	Piggyback	IG-430		0.25	0.50	47.5	47.375	0.541	7.94E+20	0.58	
2PB4	Piggyback	PCEA		0.25	0.50	47.25	47.125	0.599	8.80E+20	0.64	
2PB5	Piggyback	PCEA		0.25	0.50	47	46.875	0.657	9.65E+20	0.70	
2PB6	Piggyback	NBG-17		0.25	0.50	46.75	46.625	0.715	1.05E+21	0.77	
2PB7	Piggyback	IG-430		0.25	0.50	46.5	46.375	0.772	1.13E+21	0.83	
2PB8	Piggyback	IG-430		0.25	0.50	46.25	46.125	0.829	1.22E+21	0.89	
2PB9	Piggyback	NBG-18		0.25	0.50	46	45.875	0.885	1.30E+21	0.95	
2PB10	Piggyback	PCEA		0.25	0.50	45.75	45.625	0.941	1.38E+21	1.01	
2PB11	Piggyback	NBG-18		0.25	0.50	45.5	45.375	0.996	1.46E+21	1.07	
2PB12	Piggyback	IG-430		0.25	0.50	45.25	45.125	1.051	1.54E+21	1.13	
2PB13	Piggyback	NBG-18		0.25	0.50	45	44.875	1.105	1.62E+21	1.18	
2PB14	Piggyback	PCEA		0.25	0.50	44.75	44.625	1.159	1.70E+21	1.24	
2PB15	Piggyback	NBG-17		0.25	0.50	44.5	44.375	1.212	1.78E+21	1.30	
	Thimble Bottom			0.25		44.25	44.125	1.266	1.86E+21	1.36	

AGC-1 Channel 2 (NORTH EAST) Layout [2 ksi]											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Companion Sample Position
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
Spacer	Guide/spacer	AXF-5Q		0.25		44	43.875	1.318	1.94E+21	1.41	
2S15	stressed creep	IG-430		1	0.50	43.75	43.25	1.447	2.13E+21	1.55	2U14
Spacer	Guide/spacer	AXF-5Q		0.25		42.75	42.625	1.574	2.31E+21	1.69	
2S14	stressed creep	PCEA		1	0.50	42.5	42	1.697	2.49E+21	1.82	2U13
Spacer	Guide/spacer	AXF-5Q		0.25		41.5	41.375	1.817	2.67E+21	1.95	
2S13	stressed creep	H-451		1	0.50	41.25	40.75	1.934	2.84E+21	2.07	2U12
Spacer	Guide/spacer	AXF-5Q		0.25		40.25	40.125	2.048	3.01E+21	2.20	
2S12	stressed creep	NBG-18		1	0.50	40	39.5	2.159	3.17E+21	2.32	2U11
Spacer	Guide/spacer	AXF-5Q		0.25		39	38.875	2.267	3.33E+21	2.43	
2S11	stressed creep	NBG-18		1	0.50	38.75	38.25	2.371	3.48E+21	2.54	2U11
Spacer	Guide/spacer	AXF-5Q		0.25		37.75	37.625	2.472	3.63E+21	2.65	
2S10	stressed creep	NBG-17		1	0.50	37.5	37	2.570	3.77E+21	2.76	2U10
Spacer	Guide/spacer	AXF-5Q		0.25		36.5	36.375	2.664	3.91E+21	2.86	
2S9	stressed creep	IG-430		1	0.50	36.25	35.75	2.755	4.05E+21	2.95	2U9
Spacer	Guide/spacer	AXF-5Q		0.25		35.25	35.125	2.842	4.17E+21	3.05	
2S8	stressed creep	PCEA		1	0.50	35	34.5	2.926	4.30E+21	3.14	2U8
Spacer	Guide/spacer	AXF-5Q		0.25		34	33.875	3.006	4.42E+21	3.22	
2S7	stressed creep	IG-110		1	0.50	33.75	33.25	3.082	4.53E+21	3.31	2U7

AGC-1 Channel 2 (NORTH EAST) Layout [2 ksi]											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Companion Sample Position
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
Spacer	Guide/spacer	AXF-5Q		0.25		32.75	32.625	3.155	4.63E+21	3.38	
2S6	stressed creep	NBG-17		1	0.50	32.5	32	3.225	4.74E+21	3.46	2U6
Spacer	Guide/spacer	AXF-5Q		0.25		31.5	31.375	3.290	4.83E+21	3.53	
2S5	stressed creep	IG-110		1	0.50	31.25	30.75	3.352	4.92E+21	3.59	2U5
Spacer	Guide/spacer	AXF-5Q		0.25		30.25	30.125	3.409	5.01E+21	3.66	
2S4	stressed creep	NBG-17		1	0.50	30	29.5	3.463	5.09E+21	3.71	2U4
Spacer	Guide/spacer	AXF-5Q		0.25		29	28.875	3.513	5.16E+21	3.77	
2S3	stressed creep	IG-430		1	0.50	28.75	28.25	3.559	5.23E+21	3.82	2U3
Spacer	Guide/spacer	AXF-5Q		0.25		27.75	27.625	3.601	5.29E+21	3.86	
2S2	stressed creep	NBG-18		1	0.50	27.5	27	3.639	5.35E+21	3.90	2U2
Spacer	Guide/spacer	AXF-5Q		0.25		26.5	26.375	3.673	5.40E+21	3.94	
2S1	stressed creep	PCEA		1	0.50	26.25	25.75	3.703	5.44E+21	3.97	2U1
Spacer	Guide/spacer	AXF-5Q		0.25		25.25	25.125	3.729	5.48E+21	4.00	
Plug	Core center plug			1		25	24.5	3.750	5.51E+21	4.02	
Core Center Line											
Plug	Core center plug			1		24	23.5	3.775	5.55E+21	4.05	
GAP	GAP			0.25		23	22.875	3.785	5.56E+21	4.06	
Spacer	Guide/spacer	AXF-5Q		0.25		22.75	22.625	3.788	5.56E+21	4.06	

AGC-1 Channel 2 (NORTH EAST) Layout [2 ksi]											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Companion Sample Position
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
2PB16	Piggyback	NBG-17		0.25	0.50	22.5	22.375	3.790	5.57E+21	4.06	
Spacer	Guide/spacer	AXF-5Q		0.25		22.25	22.125	3.792	5.57E+21	4.07	
2PB17	Piggyback	PCEA		0.25	0.50	22	21.875	3.793	5.57E+21	4.07	FLUX CL
Spacer	Guide/spacer	AXF-5Q		0.25		21.75	21.625	3.793	5.57E+21	4.07	
2PB18	Piggyback	NBG-18		0.25	0.50	21.5	21.375	3.792	5.57E+21	4.07	
Spacer	Guide/spacer	AXF-5Q		0.25		21.25	21.125	3.791	5.57E+21	4.06	
2PB19	Piggyback	IG-430		0.25	0.50	21	20.875	3.788	5.56E+21	4.06	
Spacer	Guide/spacer	AXF-5Q		0.25		20.75	20.625	3.786	5.56E+21	4.06	
2PB20	Piggyback	H-451		0.25	0.50	20.5	20.375	3.782	5.56E+21	4.06	
Spacer	Guide/spacer	AXF-5Q		0.25		20.25	20.125	3.778	5.55E+21	4.05	
2PB21	Piggyback	IG-110		0.25	0.50	20	19.875	3.773	5.54E+21	4.05	
Spacer	Guide/spacer	AXF-5Q		0.25		19.75	19.625	3.767	5.53E+21	4.04	
2PB22	Piggyback	BAN		0.25	0.50	19.5	19.375	3.761	5.52E+21	4.03	
Spacer	Guide/spacer	AXF-5Q		0.25		19.25	19.125	3.753	5.51E+21	4.02	
2U1	unstressed control	PCEA		1	0.50	19	18.5	3.732	5.48E+21	4.00	2S1
Spacer	Guide/spacer	AXF-5Q		0.25		18	17.875	3.706	5.44E+21	3.97	
2U2	unstressed control	NBG-18		1	0.50	17.75	17.25	3.675	5.40E+21	3.94	2S2
Spacer	Guide/spacer	AXF-5Q		0.25		16.75	16.625	3.640	5.35E+21	3.90	

AGC-1 Channel 2 (NORTH EAST) Layout [2 ksi]											
				Dimensions, ins					Nominal Dose		
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Length	Dia	Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	n/cm2 [E>0.1 MeV]	dpa	Companion Sample Position
2U3	unstressed control	IG-430		1	0.50	16.5	16	3.599	5.29E+21	3.86	2S3
Spacer	Guide/spacer	AXF-5Q		0.25		15.5	15.375	3.554	5.22E+21	3.81	
2U4	unstressed control	NBG-17		1	0.50	15.25	14.75	3.504	5.15E+21	3.76	2S4
Spacer	Guide/spacer	AXF-5Q		0.25		14.25	14.125	3.449	5.07E+21	3.70	
2U5	unstressed control	IG-110		1	0.50	14	13.5	3.389	4.98E+21	3.63	2S5
Spacer	Guide/spacer	AXF-5Q		0.25		13	12.875	3.324	4.88E+21	3.56	
2U6	unstressed control	NBG-17		1	0.50	12.75	12.25	3.254	4.78E+21	3.49	2S6
Spacer	Guide/spacer	AXF-5Q		0.25		11.75	11.625	3.179	4.67E+21	3.41	
2U7	unstressed control	IG-110		1	0.50	11.5	11	3.099	4.55E+21	3.32	2S7
Spacer	Guide/spacer	AXF-5Q		0.25		10.5	10.375	3.014	4.43E+21	3.23	
2U8	unstressed control	PCEA		1	0.50	10.25	9.75	2.923	4.29E+21	3.13	2S8
Spacer	Guide/spacer	AXF-5Q		0.25		9.25	9.125	2.827	4.15E+21	3.03	
2U9	unstressed control	IG-430		1	0.50	9	8.5	2.726	4.00E+21	2.92	2S9
Spacer	Guide/spacer	AXF-5Q		0.25		8	7.875	2.619	3.85E+21	2.81	
2U10	unstressed control	NBG-17		1	0.50	7.75	7.25	2.507	3.68E+21	2.69	2S10
Spacer	Guide/spacer	AXF-5Q		0.25		6.75	6.625	2.390	3.51E+21	2.56	
2U11	unstressed control	NBG-18		1	0.50	6.5	6	2.267	3.33E+21	2.43	2S11/12
Spacer	Guide/spacer	AXF-5Q		0.25		5.5	5.375	2.138	3.14E+21	2.29	

AGC-1 Channel 2 (NORTH EAST) Layout [2 ksi]											
				Dimensions, ins					Nominal Dose		
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Length	Dia	Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	n/cm2 [E>0.1 MeV]	dpa	Companion Sample Position
2U12	unstressed control	H-451		1	0.50	5.25	4.75	2.004	2.94E+21	2.15	2S13
Spacer	Guide/spacer	AXF-5Q		0.25		4.25	4.125	1.864	2.74E+21	2.00	
2U13	unstressed control	PCEA		1	0.50	4	3.5	1.719	2.52E+21	1.84	2S14
Spacer	Guide/spacer	AXF-5Q		0.25		3	2.875	1.568	2.30E+21	1.68	
2U14	unstressed control	IG-430		1	0.50	2.75	2.25	1.411	2.07E+21	1.51	2S15
Spacer	Guide/spacer	AXF-5Q		0.25		1.75	1.625	1.249	1.83E+21	1.34	
2PB23	Piggyback	IG-110		0.25	0.50	1.5	1.375	1.182	1.74E+21	1.27	
Spacer	Guide/spacer	AXF-5Q		0.25	0.50	1.25	1.125	1.114	1.64E+21	1.19	
2PB24	Piggyback	NBG-18		0.25	0.50	1	0.875	1.046	1.54E+21	1.12	
Spacer	Guide/spacer	AXF-5Q		0.25	0.50	0.75	0.625	0.976	1.43E+21	1.05	
2PB25	Piggyback	IG-430		0.25	0.50	0.5	0.375	0.906	1.33E+21	0.97	
Spacer	Guide/spacer	AXF-5Q		0.25	0.50	0.25	0.125	0.834	1.23E+21	0.89	End of core

Appendix C

AGC-1 Channel 3 (South-East) Specimen Layout [3 ksi]

AGC-1 Channel 3 (SOUTH-EAST) Layout [3 ksi]											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Companion Sample Position
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
	Insulation										
	Thimble top										
3PB1	Piggyback	NBG-18		0.25	0.50	48	47.875	0.373	5.48E+20	0.40	Top of Core
3PB2	Piggyback	IG-430		0.25	0.50	47.75	47.625	0.426	6.26E+20	0.46	
3PB3	Piggyback	PCEA		0.25	0.50	47.5	47.375	0.479	7.04E+20	0.51	
3PB4	Piggyback	NBG-17		0.25	0.50	47.25	47.125	0.532	7.81E+20	0.57	
3PB5	Piggyback	NBG-18		0.25	0.50	47	46.875	0.584	8.58E+20	0.63	
3PB6	Piggyback	IG-430		0.25	0.50	46.75	46.625	0.636	9.33E+20	0.68	
3PB7	Piggyback	PCEA		0.25	0.50	46.5	46.375	0.687	1.01E+21	0.74	
3PB8	Piggyback	NBG-17		0.25	0.50	46.25	46.125	0.738	1.08E+21	0.79	
3PB9	Piggyback	NBG-18		0.25	0.50	46	45.875	0.788	1.16E+21	0.84	
3PB10	Piggyback	IG-110		0.25	0.50	45.75	45.625	0.838	1.23E+21	0.90	
3PB11	Piggyback	H-451		0.25	0.50	45.5	45.375	0.888	1.30E+21	0.95	
3PB12	Piggyback	NBG-17		0.25	0.50	45.25	45.125	0.937	1.38E+21	1.00	
3PB13	Piggyback	NBG-17		0.25	0.50	45	44.875	0.986	1.45E+21	1.06	
3PB14	Piggyback	PCEA		0.25	0.50	44.75	44.625	1.034	1.52E+21	1.11	
3PB15	Piggyback	NBG-17		0.25	0.50	44.5	44.375	1.082	1.59E+21	1.16	

AGC-1 Channel 3 (SOUTH-EAST) Layout [3 ksi]											
				Dimensions, ins					Nominal Dose		
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Length	Dia	Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	n/cm2 [E>0.1 MeV]	dpa	Companion Sample Position
	Thimble Bottom			0.25		44.25	44.125	1.129	1.66E+21	1.21	
Spacer	Guide/spacer	AXF-5Q		0.25		44	43.875	1.176	1.73E+21	1.26	
3S15	stressed creep	PCEA		1	0.50	43.75	43.25	1.292	1.90E+21	1.39	3U14
Spacer	Guide/spacer	AXF-5Q		0.25		42.75	42.625	1.405	2.06E+21	1.51	
3S14	stressed creep	NBG-18		1	0.50	42.5	42	1.515	2.23E+21	1.62	3U13
Spacer	Guide/spacer	AXF-5Q		0.25		41.5	41.375	1.623	2.38E+21	1.74	
3S13	stressed creep	NBG-17		1	0.50	41.25	40.75	1.727	2.54E+21	1.85	3U12
Spacer	Guide/spacer	AXF-5Q		0.25		40.25	40.125	1.829	2.69E+21	1.96	
3S12	stressed creep	NBG-18		1	0.50	40	39.5	1.928	2.83E+21	2.07	3U11
Spacer	Guide/spacer	AXF-5Q		0.25		39	38.875	2.024	2.97E+21	2.17	
3S11	stressed creep	NBG-18		1	0.50	38.75	38.25	2.117	3.11E+21	2.27	3U11
Spacer	Guide/spacer	AXF-5Q		0.25		37.75	37.625	2.207	3.24E+21	2.37	
3S10	stressed creep	H-451		1	0.50	37.5	37	2.293	3.37E+21	2.46	3U10
Spacer	Guide/spacer	AXF-5Q		0.25		36.5	36.375	2.377	3.49E+21	2.55	
3S9	stressed creep	IG-110		1	0.50	36.25	35.75	2.458	3.61E+21	2.64	3U9
Spacer	Guide/spacer	AXF-5Q		0.25		35.25	35.125	2.535	3.72E+21	2.72	
3S8	stressed creep	NBG-17		1	0.50	35	34.5	2.609	3.83E+21	2.80	3U8
Spacer	Guide/spacer	AXF-5Q		0.25		34	33.875	2.680	3.94E+21	2.87	

AGC-1 Channel 3 (SOUTH-EAST) Layout [3 ksi]											
				Dimensions, ins					Nominal Dose		
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Length	Dia	Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	n/cm2 [E>0.1 MeV]	dpa	Companion Sample Position
3S7	stressed creep	IG-430		1	0.50	33.75	33.25	2.748	4.04E+21	2.95	3U7
Spacer	Guide/spacer	AXF-5Q		0.25		32.75	32.625	2.813	4.13E+21	3.02	
3S6	stressed creep	PCEA		1	0.50	32.5	32	2.874	4.22E+21	3.08	3U6
Spacer	Guide/spacer	AXF-5Q		0.25		31.5	31.375	2.931	4.31E+21	3.14	
3S5	stressed creep	IG-430		1	0.50	31.25	30.75	2.986	4.39E+21	3.20	3U5
Spacer	Guide/spacer	AXF-5Q		0.25		30.25	30.125	3.037	4.46E+21	3.26	
3S4	stressed creep	IG-430		1	0.50	30	29.5	3.084	4.53E+21	3.31	3U4
Spacer	Guide/spacer	AXF-5Q		0.25		29	28.875	3.128	4.59E+21	3.35	
3S3	stressed creep	IG-430		1	0.50	28.75	28.25	3.168	4.65E+21	3.40	3U3
Spacer	Guide/spacer	AXF-5Q		0.25		27.75	27.625	3.205	4.71E+21	3.44	
3S2	stressed creep	NBG-18		1	0.50	27.5	27	3.238	4.76E+21	3.47	3U2
Spacer	Guide/spacer	AXF-5Q		0.25		26.5	26.375	3.268	4.80E+21	3.50	
3S1	stressed creep	H-451		1	0.50	26.25	25.75	3.294	4.84E+21	3.53	3U1
Spacer	Guide/spacer	AXF-5Q		0.25		25.25	25.125	3.316	4.87E+21	3.56	
Plug	Core center plug	AXF-5Q		1		25	24.5	3.334	4.90E+21	3.58	
Core Center Line											
Plug	Core center plug	AXF-5Q		1		24	23.5	3.356	4.93E+21	3.60	
GAP	GAP			0.25		23	22.875	3.365	4.94E+21	3.61	

AGC-1 Channel 3 (SOUTH-EAST) Layout [3 ksi]											
				Dimensions, ins					Nominal Dose		
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Length	Dia	Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	n/cm2 [E>0.1 MeV]	dpa	Companion Sample Position
Spacer	Guide/spacer	AXF-5Q		0.25		22.75	22.625	3.367	4.95E+21	3.61	
3PB16	Piggyback	NBG-17		0.25	0.50	22.5	22.375	3.369	4.95E+21	3.61	
Spacer	Guide/spacer	AXF-5Q		0.25		22.25	22.125	3.370	4.95E+21	3.61	
3PB17	Piggyback	PCEA		0.25	0.50	22	21.875	3.370	4.95E+21	3.61	FLUX CL
Spacer	Guide/spacer	AXF-5Q		0.25		21.75	21.625	3.370	4.95E+21	3.61	
3PB18	Piggyback	NBG-18		0.25	0.50	21.5	21.375	3.369	4.95E+21	3.61	
Spacer	Guide/spacer	AXF-5Q		0.25		21.25	21.125	3.368	4.95E+21	3.61	
3PB19	Piggyback	IG-430		0.25	0.50	21	20.875	3.366	4.94E+21	3.61	
Spacer	Guide/spacer	AXF-5Q		0.25		20.75	20.625	3.363	4.94E+21	3.61	
3PB20	Piggyback	H-451		0.25	0.50	20.5	20.375	3.359	4.93E+21	3.60	
Spacer	Guide/spacer	AXF-5Q		0.25		20.25	20.125	3.355	4.93E+21	3.60	
3PB21	Piggyback	IG-110		0.25	0.50	20	19.875	3.351	4.92E+21	3.59	
Spacer	Guide/spacer	AXF-5Q		0.25		19.75	19.625	3.345	4.91E+21	3.59	
3PB22	Piggyback	BAN		0.25	0.50	19.5	19.375	3.340	4.91E+21	3.58	
Spacer	Guide/spacer	AXF-5Q		0.25		19.25	19.125	3.333	4.90E+21	3.57	
3U1	unstressed control	H-451		1	0.50	19	18.5	3.314	4.87E+21	3.55	3S1
Spacer	Guide/spacer	AXF-5Q		0.25		18	17.875	3.290	4.83E+21	3.53	
3U2	unstressed control	NBG-18		1	0.50	17.75	17.25	3.262	4.79E+21	3.50	3S2

AGC-1 Channel 3 (SOUTH-EAST) Layout [3 ksi]											
				Dimensions, ins					Nominal Dose		
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Length	Dia	Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	n/cm2 [E>0.1 MeV]	dpa	Companion Sample Position
Spacer	Guide/spacer	AXF-5Q		0.25		16.75	16.625	3.231	4.75E+21	3.46	
3U3	unstressed control	IG-430		1	0.50	16.5	16	3.195	4.69E+21	3.43	3S3
Spacer	Guide/spacer	AXF-5Q		0.25		15.5	15.375	3.154	4.63E+21	3.38	
3U4	unstressed control	IG-430		1	0.50	15.25	14.75	3.110	4.57E+21	3.33	3S4
Spacer	Guide/spacer	AXF-5Q		0.25		14.25	14.125	3.061	4.50E+21	3.28	
3U5	unstressed control	IG-430		1	0.50	14	13.5	3.008	4.42E+21	3.22	3S5
Spacer	Guide/spacer	AXF-5Q		0.25		13	12.875	2.950	4.33E+21	3.16	
3U6	unstressed control	PCEA		1	0.50	12.75	12.25	2.888	4.24E+21	3.10	3S6
Spacer	Guide/spacer	AXF-5Q		0.25		11.75	11.625	2.821	4.14E+21	3.02	
3U7	unstressed control	IG-430		1	0.50	11.5	11	2.750	4.04E+21	2.95	3S7
Spacer	Guide/spacer	AXF-5Q		0.25		10.5	10.375	2.674	3.93E+21	2.87	
3U8	unstressed control	NBG-17		1	0.50	10.25	9.75	2.594	3.81E+21	2.78	3S8
Spacer	Guide/spacer	AXF-5Q		0.25		9.25	9.125	2.509	3.69E+21	2.69	
3U9	unstressed control	IG-110		1	0.50	9	8.5	2.420	3.55E+21	2.59	3S9
Spacer	Guide/spacer	AXF-5Q		0.25		8	7.875	2.326	3.42E+21	2.49	
3U10	unstressed control	H-451		1	0.50	7.75	7.25	2.227	3.27E+21	2.39	3S10
Spacer	Guide/spacer	AXF-5Q		0.25		6.75	6.625	2.123	3.12E+21	2.28	
3U11	unstressed control	NBG-18		1	0.50	6.5	6	2.015	2.96E+21	2.16	3S11/12

AGC-1 Channel 3 (SOUTH-EAST) Layout [3 ksi]											
				Dimensions, ins					Nominal Dose		
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Length	Dia	Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	n/cm2 [E>0.1 MeV]	dpa	Companion Sample Position
Spacer	Guide/spacer	AXF-5Q		0.25		5.5	5.375	1.902	2.79E+21	2.04	
3U12	unstressed control	NBG-17		1	0.50	5.25	4.75	1.784	2.62E+21	1.91	3S13
Spacer	Guide/spacer	AXF-5Q		0.25		4.25	4.125	1.661	2.44E+21	1.78	
3U13	unstressed control	NBG-18		1	0.50	4	3.5	1.533	2.25E+21	1.64	3S14
Spacer	Guide/spacer	AXF-5Q		0.25		3	2.875	1.400	2.06E+21	1.50	
3U14	unstressed control	PCEA		1	0.50	2.75	2.25	1.262	1.85E+21	1.35	3S15
Spacer	Guide/spacer	AXF-5Q		0.25		1.75	1.625	1.120	1.64E+21	1.20	
3PB23	Piggyback	PCEA		0.25	0.50	1.5	1.375	1.061	1.56E+21	1.14	
Spacer	Guide/spacer	AXF-5Q		0.25		1.25	1.125	1.002	1.47E+21	1.07	
3PB24	Piggyback	IG-430		0.25	0.50	1	0.875	0.941	1.38E+21	1.01	
Spacer	Guide/spacer	AXF-5Q		0.25		0.75	0.625	0.880	1.29E+21	0.94	
3PB25	Piggyback	PCEA		0.25	0.50	0.5	0.375	0.819	1.20E+21	0.88	
Spacer	Guide/spacer	AXF-5Q		0.25		0.25	0.125	0.756	1.11E+21	0.81	End of core

Appendix D

AGC-1 Channel 4 (South) Specimen Layout [2 ksi]

AGC-1 Channel 4 (SOUTH) Layout [2 ksi]											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Companion Sample Position
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
	Insulation										
	Thimble top										
4PB1	Piggyback	PCEA		0.25	0.50	48	47.875	0.364	5.34E+20	0.39	Top of Core
4PB2	Piggyback	NBG-18		0.25	0.50	47.75	47.625	0.413	6.06E+20	0.44	
4PB3	Piggyback	IG-430		0.25	0.50	47.5	47.375	0.462	6.78E+20	0.49	
4PB4	Piggyback	NBG-17		0.25	0.50	47.25	47.125	0.510	7.49E+20	0.55	
4PB5	Piggyback	PCEA		0.25	0.50	47	46.875	0.558	8.19E+20	0.60	
4PB6	Piggyback	NBG-17		0.25	0.50	46.75	46.625	0.605	8.89E+20	0.65	
4PB7	Piggyback	IG-430		0.25	0.50	46.5	46.375	0.653	9.59E+20	0.70	
4PB8	Piggyback	NBG-18		0.25	0.50	46.25	46.125	0.700	1.03E+21	0.75	
4PB9	Piggyback	PCEA		0.25	0.50	46	45.875	0.746	1.10E+21	0.80	
4PB10	Piggyback	NBG-17		0.25	0.50	45.75	45.625	0.792	1.16E+21	0.85	
4PB11	Piggyback	IG-430		0.25	0.50	45.5	45.375	0.838	1.23E+21	0.90	
4PB12	Piggyback	NGB-17		0.25	0.50	45.25	45.125	0.883	1.30E+21	0.95	
4PB13	Piggyback	IG-110		0.25	0.50	45	44.875	0.928	1.36E+21	1.00	
4PB14	Piggyback	NBG-17		0.25	0.50	44.75	44.625	0.973	1.43E+21	1.04	
4PB15	Piggyback	NBG-17		0.25	0.50	44.5	44.375	1.017	1.49E+21	1.09	

AGC-1 Channel 4 (SOUTH) Layout [2 ksi]											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Companion Sample Position
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
	Thimble Bottom			0.25		44.25	44.125	1.061	1.56E+21	1.14	
Spacer	Guide/spacer	AXF-5Q		0.25		44	43.875	1.104	1.62E+21	1.18	
4S15	stressed creep	PCEA		1	0.50	43.75	43.25	1.211	1.78E+21	1.30	4U14
Spacer	Guide/spacer	AXF-5Q		0.25		42.75	42.625	1.315	1.93E+21	1.41	
4S14	stressed creep	NBG-18		1	0.50	42.5	42	1.417	2.08E+21	1.52	4U13
Spacer	Guide/spacer	AXF-5Q		0.25		41.5	41.375	1.516	2.23E+21	1.63	
4S13	stressed creep	H-451		1	0.50	41.25	40.75	1.613	2.37E+21	1.73	4U12
Spacer	Guide/spacer	AXF-5Q		0.25		40.25	40.125	1.707	2.51E+21	1.83	
4S12	stressed creep	NBG-17		1	0.50	40	39.5	1.798	2.64E+21	1.93	4U11
Spacer	Guide/spacer	AXF-5Q		0.25		39	38.875	1.887	2.77E+21	2.02	
4S11	stressed creep	NBG-17		1	0.50	38.75	38.25	1.973	2.90E+21	2.12	4U11
Spacer	Guide/spacer	AXF-5Q		0.25		37.75	37.625	2.056	3.02E+21	2.20	
4S10	stressed creep	IG-430		1	0.50	37.5	37	2.136	3.14E+21	2.29	4U10
Spacer	Guide/spacer	AXF-5Q		0.25		36.5	36.375	2.214	3.25E+21	2.37	
4S9	stressed creep	IG-110		1	0.50	36.25	35.75	2.288	3.36E+21	2.45	4U9
Spacer	Guide/spacer	AXF-5Q		0.25		35.25	35.125	2.360	3.47E+21	2.53	
4S8	stressed creep	NBG-17		1	0.50	35	34.5	2.429	3.57E+21	2.60	4U8
Spacer	Guide/spacer	AXF-5Q		0.25		34	33.875	2.495	3.66E+21	2.68	

AGC-1 Channel 4 (SOUTH) Layout [2 ksi]											
				Dimensions, ins					Nominal Dose		
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Length	Dia	Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	n/cm2 [E>0.1 MeV]	dpa	Companion Sample Position
4S7	stressed creep	NBG-18		1	0.50	33.75	33.25	2.558	3.76E+21	2.74	4U7
Spacer	Guide/spacer	AXF-5Q		0.25		32.75	32.625	2.617	3.84E+21	2.81	
4S6	stressed creep	PCEA		1	0.50	32.5	32	2.674	3.93E+21	2.87	4U6
Spacer	Guide/spacer	AXF-5Q		0.25		31.5	31.375	2.728	4.01E+21	2.92	
4S5	stressed creep	NBG-18		1	0.50	31.25	30.75	2.778	4.08E+21	2.98	4U5
Spacer	Guide/spacer	AXF-5Q		0.25		30.25	30.125	2.825	4.15E+21	3.03	
4S4	stressed creep	IG-110		1	0.50	30	29.5	2.870	4.21E+21	3.08	4U4
Spacer	Guide/spacer	AXF-5Q		0.25		29	28.875	2.910	4.27E+21	3.12	
4S3	stressed creep	IG-430		1	0.50	28.75	28.25	2.948	4.33E+21	3.16	4U3
Spacer	Guide/spacer	AXF-5Q		0.25		27.75	27.625	2.982	4.38E+21	3.20	
4S2	stressed creep	H-451		1	0.50	27.5	27	3.013	4.43E+21	3.23	4U2
Spacer	Guide/spacer	AXF-5Q		0.25		26.5	26.375	3.041	4.47E+21	3.26	
4S1	stressed creep	PCEA		1	0.50	26.25	25.75	3.065	4.50E+21	3.29	4U1
Spacer	Guide/spacer	AXF-5Q		0.25		25.25	25.125	3.085	4.53E+21	3.31	
Plug	Core center plug			1		25	24.5	3.102	4.56E+21	3.33	
Core Center Line											
Plug	Core center plug			1		24	23.5	3.123	4.59E+21	3.35	
GAP	GAP			0.25		23	22.875	3.130	4.60E+21	3.36	

AGC-1 Channel 4 (SOUTH) Layout [2 ksi]											
				Dimensions, ins					Nominal Dose		
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Length	Dia	Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	n/cm2 [E>0.1 MeV]	dpa	Companion Sample Position
Spacer	Guide/spacer	AXF-5Q		0.25		22.75	22.625	3.133	4.60E+21	3.36	
4PB16	Piggyback	NBG-17		0.25	0.50	22.5	22.375	3.134	4.60E+21	3.36	
Spacer	Guide/spacer	AXF-5Q		0.25		22.25	22.125	3.135	4.61E+21	3.36	
4PB17	Piggyback	PCEA		0.25	0.50	22	21.875	3.136	4.61E+21	3.36	FLUX CL
Spacer	Guide/spacer	AXF-5Q		0.25		21.75	21.625	3.135	4.61E+21	3.36	
4PB18	Piggyback	NBG-18		0.25	0.50	21.5	21.375	3.135	4.60E+21	3.36	
Spacer	Guide/spacer	AXF-5Q		0.25		21.25	21.125	3.133	4.60E+21	3.36	
4PB19	Piggyback	IG-430		0.25	0.50	21	20.875	3.131	4.60E+21	3.36	
Spacer	Guide/spacer	AXF-5Q		0.25		20.75	20.625	3.129	4.60E+21	3.35	
4PB20	Piggyback	H-451		0.25	0.50	20.5	20.375	3.126	4.59E+21	3.35	
Spacer	Guide/spacer	AXF-5Q		0.25		20.25	20.125	3.122	4.59E+21	3.35	
4PB21	Piggyback	IG-110		0.25	0.50	20	19.875	3.118	4.58E+21	3.34	
Spacer	Guide/spacer	AXF-5Q		0.25		19.75	19.625	3.113	4.57E+21	3.34	
4PB22	Piggyback	BAN		0.25	0.50	19.5	19.375	3.107	4.56E+21	3.33	
Spacer	Guide/spacer	AXF-5Q		0.25		19.25	19.125	3.101	4.56E+21	3.33	
4U1	unstressed control	PCEA		1	0.50	19	18.5	3.083	4.53E+21	3.31	4S1
Spacer	Guide/spacer	AXF-5Q		0.25		18	17.875	3.061	4.50E+21	3.28	
4U2	unstressed control	H-451		1	0.50	17.75	17.25	3.036	4.46E+21	3.25	4S2

AGC-1 Channel 4 (SOUTH) Layout [2 ksi]											
				Dimensions, ins					Nominal Dose		
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Length	Dia	Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	n/cm2 [E>0.1 MeV]	dpa	Companion Sample Position
Spacer	Guide/spacer	AXF-5Q		0.25		16.75	16.625	3.006	4.42E+21	3.22	
4U3	unstressed control	IG-430		1	0.50	16.5	16	2.972	4.37E+21	3.19	4S3
Spacer	Guide/spacer	AXF-5Q		0.25		15.5	15.375	2.935	4.31E+21	3.15	
4U4	unstressed control	IG-110		1	0.50	15.25	14.75	2.893	4.25E+21	3.10	4S4
Spacer	Guide/spacer	AXF-5Q		0.25		14.25	14.125	2.847	4.18E+21	3.05	
4U5	unstressed control	NBG-18		1	0.50	14	13.5	2.798	4.11E+21	3.00	4S5
Spacer	Guide/spacer	AXF-5Q		0.25		13	12.875	2.744	4.03E+21	2.94	
4U6	unstressed control	PCEA		1	0.50	12.75	12.25	2.686	3.95E+21	2.88	4S6
Spacer	Guide/spacer	AXF-5Q		0.25		11.75	11.625	2.624	3.85E+21	2.81	
4U7	unstressed control	NBG-18		1	0.50	11.5	11	2.557	3.76E+21	2.74	4S7
Spacer	Guide/spacer	AXF-5Q		0.25		10.5	10.375	2.487	3.65E+21	2.67	
4U8	unstressed control	NBG-17		1	0.50	10.25	9.75	2.412	3.54E+21	2.59	4S8
Spacer	Guide/spacer	AXF-5Q		0.25		9.25	9.125	2.332	3.43E+21	2.50	
4U9	unstressed control	IG-110		1	0.50	9	8.5	2.249	3.30E+21	2.41	4S9
Spacer	Guide/spacer	AXF-5Q		0.25		8	7.875	2.161	3.17E+21	2.32	
4U10	unstressed control	IG-430		1	0.50	7.75	7.25	2.068	3.04E+21	2.22	4S10
Spacer	Guide/spacer	AXF-5Q		0.25		6.75	6.625	1.971	2.90E+21	2.11	
4U11	unstressed control	NBG-17		1	0.50	6.5	6	1.870	2.75E+21	2.01	4S11/12

AGC-1 Channel 4 (SOUTH) Layout [2 ksi]											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Companion Sample Position
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
Spacer	Guide/spacer	AXF-5Q		0.25		5.5	5.375	1.764	2.59E+21	1.89	
4U12	unstressed control	H-451		1	0.50	5.25	4.75	1.654	2.43E+21	1.77	4S13
Spacer	Guide/spacer	AXF-5Q		0.25		4.25	4.125	1.539	2.26E+21	1.65	
4U13	unstressed control	NBG-18		1	0.50	4	3.5	1.419	2.08E+21	1.52	4S14
Spacer	Guide/spacer	AXF-5Q		0.25		3	2.875	1.294	1.90E+21	1.39	
4U14	unstressed control	PCEA		1	0.50	2.75	2.25	1.165	1.71E+21	1.25	4S15
Spacer	Guide/spacer	AXF-5Q		0.25		1.75	1.625	1.032	1.52E+21	1.11	
4PB23	Piggyback	NBG-18		0.25	0.50	1.5	1.375	0.977	1.43E+21	1.05	
Spacer	Guide/spacer	AXF-5Q		0.25	0.50	1.25	1.125	0.921	1.35E+21	0.99	
4PB24	Piggyback	PCEA		0.25	0.50	1	0.875	0.865	1.27E+21	0.93	
Spacer	Guide/spacer	AXF-5Q		0.25	0.50	0.75	0.625	0.808	1.19E+21	0.87	
4PB25	Piggyback	NBG-18		0.25	0.50	0.5	0.375	0.750	1.10E+21	0.80	
Spacer	Guide/spacer	AXF-5Q		0.25	0.50	0.25	0.125	0.691	1.01E+21	0.74	End of core

Appendix E

AGC-1 Channel 5 (South-West) Specimen Layout [3 ksi]

AGC-1 Channel 5 (SOUTH-WEST) Layout [3 ksi]											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Companion Sample Position
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
	Insulation										
	Thimble top										
5PB1	Piggyback	HOPG		0.25	0.50	48	47.875	0.413	6.07E+20	0.44	Top of Core
5PB2	Piggyback	A3		0.25	0.50	47.75	47.625	0.466	6.84E+20	0.50	
5PB3	Piggyback	HLM		0.25	0.50	47.5	47.375	0.519	7.62E+20	0.56	
5PB4	Piggyback	PGX		0.25	0.50	47.25	47.125	0.571	8.38E+20	0.61	
5PB5	Piggyback	PPEA		0.25	0.50	47	46.875	0.622	9.14E+20	0.67	
5PB6	Piggyback	NBG-25		0.25	0.50	46.75	46.625	0.674	9.90E+20	0.72	
5PB7	Piggyback	2020		0.25	0.50	46.5	46.375	0.725	1.06E+21	0.78	
5PB8	Piggyback	PCIB		0.25	0.50	46.25	46.125	0.775	1.14E+21	0.83	
5PB9	Piggyback	BAN		0.25	0.50	46	45.875	0.826	1.21E+21	0.89	
5PB10	Piggyback	NBG-10		0.25	0.50	45.75	45.625	0.875	1.29E+21	0.94	
5PB11	Piggyback	BAN		0.25	0.50	45.5	45.375	0.925	1.36E+21	0.99	
5PB12	Piggyback	PCIB		0.25	0.50	45.25	45.125	0.973	1.43E+21	1.04	
5PB13	Piggyback	2020		0.25	0.50	45	44.875	1.022	1.50E+21	1.10	
5PB14	Piggyback	NBG-25		0.25	0.50	44.75	44.625	1.070	1.57E+21	1.15	
5PB15	Piggyback	PPEA		0.25	0.50	44.5	44.375	1.118	1.64E+21	1.20	

AGC-1 Channel 5 (SOUTH-WEST) Layout [3 ksi]											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Companion Sample Position
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
	Thimble Bottom			0.25		44.25	44.125	1.165	1.71E+21	1.25	
Spacer	Guide/spacer	AXF-5Q		0.25		44	43.875	1.212	1.78E+21	1.30	
5S15	stressed creep	NBG-18		1	0.50	43.75	43.25	1.327	1.95E+21	1.42	5U14
Spacer	Guide/spacer	AXF-5Q		0.25		42.75	42.625	1.439	2.11E+21	1.54	
5S14	stressed creep	NBG-17		1	0.50	42.5	42	1.548	2.27E+21	1.66	5U13
Spacer	Guide/spacer	AXF-5Q		0.25		41.5	41.375	1.655	2.43E+21	1.77	
5S13	stressed creep	IG-110		1	0.50	41.25	40.75	1.759	2.58E+21	1.89	5U12
Spacer	Guide/spacer	AXF-5Q		0.25		40.25	40.125	1.860	2.73E+21	1.99	
5S12	stressed creep	PCEA		1	0.50	40	39.5	1.958	2.88E+21	2.10	5U11
Spacer	Guide/spacer	AXF-5Q		0.25		39	38.875	2.053	3.02E+21	2.20	
5S11	stressed creep	PCEA		1	0.50	38.75	38.25	2.145	3.15E+21	2.30	5U11
Spacer	Guide/spacer	AXF-5Q		0.25		37.75	37.625	2.234	3.28E+21	2.40	
5S10	stressed creep	IG-430		1	0.50	37.5	37	2.320	3.41E+21	2.49	5U10
Spacer	Guide/spacer	AXF-5Q		0.25		36.5	36.375	2.403	3.53E+21	2.58	
5S9	stressed creep	PCEA		1	0.50	36.25	35.75	2.483	3.65E+21	2.66	5U9
Spacer	Guide/spacer	AXF-5Q		0.25		35.25	35.125	2.559	3.76E+21	2.74	
5S8	stressed creep	NBG-18		1	0.50	35	34.5	2.633	3.87E+21	2.82	5U8
Spacer	Guide/spacer	AXF-5Q		0.25		34	33.875	2.703	3.97E+21	2.90	

AGC-1 Channel 5 (SOUTH-WEST) Layout [3 ksi]											
				Dimensions, ins					Nominal Dose		
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Length	Dia	Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	n/cm2 [E>0.1 MeV]	dpa	Companion Sample Position
5S7	stressed creep	H-451		1	0.50	33.75	33.25	2.770	4.07E+21	2.97	5U7
Spacer	Guide/spacer	AXF-5Q		0.25		32.75	32.625	2.833	4.16E+21	3.04	
5S6	stressed creep	NBG-17		1	0.50	32.5	32	2.894	4.25E+21	3.10	5U6
Spacer	Guide/spacer	AXF-5Q		0.25		31.5	31.375	2.951	4.33E+21	3.16	
5S5	stressed creep	NBG-18		1	0.50	31.25	30.75	3.004	4.41E+21	3.22	5U5
Spacer	Guide/spacer	AXF-5Q		0.25		30.25	30.125	3.054	4.49E+21	3.27	
5S4	stressed creep	PCEA		1	0.50	30	29.5	3.101	4.55E+21	3.32	5U4
Spacer	Guide/spacer	AXF-5Q		0.25		29	28.875	3.144	4.62E+21	3.37	
5S3	stressed creep	NBG-17		1	0.50	28.75	28.25	3.184	4.68E+21	3.41	5U3
Spacer	Guide/spacer	AXF-5Q		0.25		27.75	27.625	3.220	4.73E+21	3.45	
5S2	stressed creep	IG-430		1	0.50	27.5	27	3.252	4.78E+21	3.49	5U2
Spacer	Guide/spacer	AXF-5Q		0.25		26.5	26.375	3.281	4.82E+21	3.52	
5S1	stressed creep	IG-110		1	0.50	26.25	25.75	3.306	4.86E+21	3.54	5U1
Spacer	Guide/spacer	AXF-5Q		0.25		25.25	25.125	3.327	4.89E+21	3.57	
Plug	Core center plug	AXF-5Q		1		25	24.5	3.345	4.91E+21	3.59	
Core Center Line											
Plug	Core center plug	AXF-5Q		1		24	23.5	3.365	4.94E+21	3.61	
GAP	GAP			0.25		23	22.875	3.373	4.95E+21	3.62	

AGC-1 Channel 5 (SOUTH-WEST) Layout [3 ksi]											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Companion Sample Position
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
Spacer	Guide/spacer	AXF-5Q		0.25		22.75	22.625	3.375	4.96E+21	3.62	
5PB16	Piggyback	NBG-25		0.25	0.50	22.5	22.375	3.376	4.96E+21	3.62	
Spacer	Guide/spacer	AXF-5Q		0.25		22.25	22.125	3.377	4.96E+21	3.62	
5PB17	Piggyback	2020		0.25	0.50	22	21.875	3.377	4.96E+21	3.62	FLUX CL
Spacer	Guide/spacer	AXF-5Q		0.25		21.75	21.625	3.376	4.96E+21	3.62	
5PB18	Piggyback	PCIB		0.25	0.50	21.5	21.375	3.375	4.96E+21	3.62	
Spacer	Guide/spacer	AXF-5Q		0.25		21.25	21.125	3.373	4.95E+21	3.62	
5PB19	Piggyback	BAN		0.25	0.50	21	20.875	3.371	4.95E+21	3.61	
Spacer	Guide/spacer	AXF-5Q		0.25		20.75	20.625	3.368	4.95E+21	3.61	
5PB20	Piggyback	NBG-10		0.25	0.50	20.5	20.375	3.364	4.94E+21	3.61	
Spacer	Guide/spacer	AXF-5Q		0.25		20.25	20.125	3.360	4.93E+21	3.60	
5PB21	Piggyback	HOPG		0.25	0.50	20	19.875	3.355	4.93E+21	3.60	
Spacer	Guide/spacer	AXF-5Q		0.25		19.75	19.625	3.349	4.92E+21	3.59	
5PB22	Piggyback	A3		0.25	0.50	19.5	19.375	3.343	4.91E+21	3.58	
Spacer	Guide/spacer	AXF-5Q		0.25		19.25	19.125	3.336	4.90E+21	3.58	
5U1	unstressed control	IG-110		1	0.50	19	18.5	3.316	4.87E+21	3.56	5S1
Spacer	Guide/spacer	AXF-5Q		0.25		18	17.875	3.291	4.83E+21	3.53	
5U2	unstressed control	IG-430		1	0.50	17.75	17.25	3.263	4.79E+21	3.50	5S2

AGC-1 Channel 5 (SOUTH-WEST) Layout [3 ksi]											
				Dimensions, ins					Nominal Dose		
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Length	Dia	Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	n/cm2 [E>0.1 MeV]	dpa	Companion Sample Position
Spacer	Guide/spacer	AXF-5Q		0.25		16.75	16.625	3.230	4.74E+21	3.46	
5U3	unstressed control	NBG-17		1	0.50	16.5	16	3.193	4.69E+21	3.42	5S3
Spacer	Guide/spacer	AXF-5Q		0.25		15.5	15.375	3.152	4.63E+21	3.38	
5U4	unstressed control	PCEA		1	0.50	15.25	14.75	3.107	4.56E+21	3.33	5S4
Spacer	Guide/spacer	AXF-5Q		0.25		14.25	14.125	3.057	4.49E+21	3.28	
5U5	unstressed control	NBG-18		1	0.50	14	13.5	3.003	4.41E+21	3.22	5S5
Spacer	Guide/spacer	AXF-5Q		0.25		13	12.875	2.945	4.32E+21	3.16	
5U6	unstressed control	NBG-17		1	0.50	12.75	12.25	2.882	4.23E+21	3.09	5S6
Spacer	Guide/spacer	AXF-5Q		0.25		11.75	11.625	2.814	4.13E+21	3.02	
5U7	unstressed control	H-451		1	0.50	11.5	11	2.742	4.03E+21	2.94	5S7
Spacer	Guide/spacer	AXF-5Q		0.25		10.5	10.375	2.666	3.92E+21	2.86	
5U8	unstressed control	NBG-18		1	0.50	10.25	9.75	2.585	3.80E+21	2.77	5S8
Spacer	Guide/spacer	AXF-5Q		0.25		9.25	9.125	2.499	3.67E+21	2.68	
5U9	unstressed control	PCEA		1	0.50	9	8.5	2.409	3.54E+21	2.58	5S9
Spacer	Guide/spacer	AXF-5Q		0.25		8	7.875	2.314	3.40E+21	2.48	
5U10	unstressed control	IG-430		1	0.50	7.75	7.25	2.214	3.25E+21	2.37	5S10
Spacer	Guide/spacer	AXF-5Q		0.25		6.75	6.625	2.110	3.10E+21	2.26	
5U11	unstressed control	PCEA		1	0.50	6.5	6	2.001	2.94E+21	2.15	5S11/12

AGC-1 Channel 5 (SOUTH-WEST) Layout [3 ksi]											
				Dimensions, ins					Nominal Dose		
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Length	Dia	Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	n/cm2 [E>0.1 MeV]	dpa	Companion Sample Position
Spacer	Guide/spacer	AXF-5Q		0.25		5.5	5.375	1.887	2.77E+21	2.02	
5U12	unstressed control	IG-110		1	0.50	5.25	4.75	1.768	2.60E+21	1.90	5S13
Spacer	Guide/spacer	AXF-5Q		0.25		4.25	4.125	1.644	2.42E+21	1.76	
5U13	unstressed control	NBG-17		1	0.50	4	3.5	1.516	2.23E+21	1.63	5S14
Spacer	Guide/spacer	AXF-5Q		0.25		3	2.875	1.382	2.03E+21	1.48	
5U14	unstressed control	NBG-18		1	0.50	2.75	2.25	1.244	1.83E+21	1.33	5S15
Spacer	Guide/spacer	AXF-5Q		0.25		1.75	1.625	1.100	1.62E+21	1.18	
5PB23	Piggyback	BAN		0.25	0.50	1.5	1.375	1.041	1.53E+21	1.12	
Spacer	Guide/spacer	AXF-5Q		0.25	0.50	1.25	1.125	0.981	1.44E+21	1.05	
5PB24	Piggyback	NBG-25		0.25	0.50	1	0.875	0.921	1.35E+21	0.99	
Spacer	Guide/spacer	AXF-5Q		0.25	0.50	0.75	0.625	0.860	1.26E+21	0.92	
5PB25	Piggyback	PPEA		0.25	0.50	0.5	0.375	0.798	1.17E+21	0.86	
Spacer	Guide/spacer	AXF-5Q		0.25	0.50	0.25	0.125	0.735	1.08E+21	0.79	End of core

Appendix F

AGC-1 Channel 6 (North-West) Specimen Layout [2 ksi]

AGC-1 Channel 6 (NORTH-WEST) Layout [2 ksi]											
				Dimensions, ins					Nominal Dose		
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Length	Dia	Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	n/cm2 [E>0.1 MeV]	dpa	Companion Sample Position
	Insulation										
	Thimble top										
6PB1	Piggyback	NBG-10		0.25	0.50	48	47.875	0.483	7.09E+20	0.52	Top of Core
6PB2	Piggyback	BAN		0.25	0.50	47.75	47.625	0.541	7.95E+20	0.58	
6PB3	Piggyback	PCIB		0.25	0.50	47.5	47.375	0.599	8.80E+20	0.64	
6PB4	Piggyback	2020		0.25	0.50	47.25	47.125	0.657	9.65E+20	0.70	
6PB5	Piggyback	HOPG		0.25	0.50	47	46.875	0.714	1.05E+21	0.77	
6PB6	Piggyback	A3		0.25	0.50	46.75	46.625	0.771	1.13E+21	0.83	
6PB7	Piggyback	HLM		0.25	0.50	46.5	46.375	0.827	1.21E+21	0.89	
6PB8	Piggyback	PGX		0.25	0.50	46.25	46.125	0.883	1.30E+21	0.95	
6PB9	Piggyback	PPEA		0.25	0.50	46	45.875	0.938	1.38E+21	1.01	
6PB10	Piggyback	NBG-25		0.25	0.50	45.75	45.625	0.993	1.46E+21	1.06	
6PB11	Piggyback	NBG-10		0.25	0.50	45.5	45.375	1.048	1.54E+21	1.12	
6PB12	Piggyback	PGX		0.25	0.50	45.25	45.125	1.102	1.62E+21	1.18	
6PB13	Piggyback	HLM		0.25	0.50	45	44.875	1.155	1.70E+21	1.24	
6PB14	Piggyback	A3		0.25	0.50	44.75	44.625	1.208	1.77E+21	1.30	
6PB15	Piggyback	HOPG		0.25	0.50	44.5	44.375	1.261	1.85E+21	1.35	

AGC-1 Channel 6 (NORTH-WEST) Layout [2 ksi]											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Companion Sample Position
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
	Thimble Bottom			0.25		44.25	44.125	1.313	1.93E+21	1.41	
Spacer	Guide/spacer	AXF-5Q		0.25		44	43.875	1.365	2.00E+21	1.46	
6S15	stressed creep	NBG-17		1	0.50	43.75	43.25	1.492	2.19E+21	1.60	6U14
Spacer	Guide/spacer	AXF-5Q		0.25		42.75	42.625	1.616	2.37E+21	1.73	
6S14	stressed creep	IG-110		1	0.50	42.5	42	1.737	2.55E+21	1.86	6U13
Spacer	Guide/spacer	AXF-5Q		0.25		41.5	41.375	1.855	2.72E+21	1.99	
6S13	stressed creep	NBG-18		1	0.50	41.25	40.75	1.970	2.89E+21	2.11	6U12
Spacer	Guide/spacer	AXF-5Q		0.25		40.25	40.125	2.081	3.06E+21	2.23	
6S12	stressed creep	PCEA		1	0.50	40	39.5	2.190	3.22E+21	2.35	6U11
Spacer	Guide/spacer	AXF-5Q		0.25		39	38.875	2.295	3.37E+21	2.46	
6S11	stressed creep	PCEA		1	0.50	38.75	38.25	2.397	3.52E+21	2.57	6U11
Spacer	Guide/spacer	AXF-5Q		0.25		37.75	37.625	2.495	3.66E+21	2.68	
6S10	stressed creep	IG-430		1	0.50	37.5	37	2.590	3.80E+21	2.78	6U10
Spacer	Guide/spacer	AXF-5Q		0.25		36.5	36.375	2.682	3.94E+21	2.88	
6S9	stressed creep	H-451		1	0.50	36.25	35.75	2.770	4.07E+21	2.97	6U9
Spacer	Guide/spacer	AXF-5Q		0.25		35.25	35.125	2.855	4.19E+21	3.06	
6S8	stressed creep	NBG-17		1	0.50	35	34.5	2.937	4.31E+21	3.15	6U8
Spacer	Guide/spacer	AXF-5Q		0.25		34	33.875	3.014	4.43E+21	3.23	

AGC-1 Channel 6 (NORTH-WEST) Layout [2 ksi]											
				Dimensions, ins					Nominal Dose		
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Length	Dia	Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	n/cm2 [E>0.1 MeV]	dpa	Companion Sample Position
6S7	stressed creep	IG-430		1	0.50	33.75	33.25	3.088	4.54E+21	3.31	6U7
Spacer	Guide/spacer	AXF-5Q		0.25		32.75	32.625	3.159	4.64E+21	3.39	
6S6	stressed creep	NBG-18		1	0.50	32.5	32	3.226	4.74E+21	3.46	6U6
Spacer	Guide/spacer	AXF-5Q		0.25		31.5	31.375	3.289	4.83E+21	3.53	
6S5	stressed creep	H-451		1	0.50	31.25	30.75	3.348	4.92E+21	3.59	6U5
Spacer	Guide/spacer	AXF-5Q		0.25		30.25	30.125	3.404	5.00E+21	3.65	
6S4	stressed creep	PCEA		1	0.50	30	29.5	3.455	5.08E+21	3.71	6U4
Spacer	Guide/spacer	AXF-5Q		0.25		29	28.875	3.503	5.15E+21	3.76	
6S3	stressed creep	NBG-18		1	0.50	28.75	28.25	3.547	5.21E+21	3.80	6U3
Spacer	Guide/spacer	AXF-5Q		0.25		27.75	27.625	3.587	5.27E+21	3.85	
6S2	stressed creep	IG-430		1	0.50	27.5	27	3.623	5.32E+21	3.88	6U2
Spacer	Guide/spacer	AXF-5Q		0.25		26.5	26.375	3.655	5.37E+21	3.92	
6S1	stressed creep	NBG-17		1	0.50	26.25	25.75	3.683	5.41E+21	3.95	6U1
Spacer	Guide/spacer	AXF-5Q		0.25		25.25	25.125	3.707	5.44E+21	3.97	
Plug	Core center plug			1		25	24.5	3.726	5.47E+21	4.00	
Core Center Line											
Plug	Core center plug			1		24	23.5	3.749	5.51E+21	4.02	
GAP	GAP			0.25		23	22.875	3.757	5.52E+21	4.03	

AGC-1 Channel 6 (NORTH-WEST) Layout [2 ksi]											
				Dimensions, ins					Nominal Dose		
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Length	Dia	Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	n/cm2 [E>0.1 MeV]	dpa	Companion Sample Position
Spacer	Guide/spacer	AXF-5Q		0.25		22.75	22.625	3.760	5.52E+21	4.03	
6PB16	Piggyback	HOPG		0.25	0.50	22.5	22.375	3.761	5.52E+21	4.03	
Spacer	Guide/spacer	AXF-5Q		0.25		22.25	22.125	3.762	5.53E+21	4.03	
6PB17	Piggyback	A3		0.25	0.50	22	21.875	3.762	5.53E+21	4.03	FLUX CL
Spacer	Guide/spacer	AXF-5Q		0.25		21.75	21.625	3.762	5.53E+21	4.03	
6PB18	Piggyback	HLM		0.25	0.50	21.5	21.375	3.760	5.52E+21	4.03	
Spacer	Guide/spacer	AXF-5Q		0.25		21.25	21.125	3.758	5.52E+21	4.03	
6PB19	Piggyback	PGX		0.25	0.50	21	20.875	3.756	5.52E+21	4.03	
Spacer	Guide/spacer	AXF-5Q		0.25		20.75	20.625	3.752	5.51E+21	4.02	
6PB20	Piggyback	PPEA		0.25	0.50	20.5	20.375	3.748	5.51E+21	4.02	
Spacer	Guide/spacer	AXF-5Q		0.25		20.25	20.125	3.744	5.50E+21	4.01	
6PB21	Piggyback	H-451		0.25	0.50	20	19.875	3.738	5.49E+21	4.01	
Spacer	Guide/spacer	AXF-5Q		0.25		19.75	19.625	3.732	5.48E+21	4.00	
6PB22	Piggyback	A3		0.25	0.50	19.5	19.375	3.725	5.47E+21	3.99	
Spacer	Guide/spacer	AXF-5Q		0.25		19.25	19.125	3.717	5.46E+21	3.99	
6U1	unstressed control	NBG-17		1	0.50	19	18.5	3.695	5.43E+21	3.96	6S1
Spacer	Guide/spacer	AXF-5Q		0.25		18	17.875	3.668	5.39E+21	3.93	
6U2	unstressed control	IG-430		1	0.50	17.75	17.25	3.637	5.34E+21	3.90	6S2

AGC-1 Channel 6 (NORTH-WEST) Layout [2 ksi]											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Companion Sample Position
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
Spacer	Guide/spacer	AXF-5Q		0.25		16.75	16.625	3.601	5.29E+21	3.86	
6U3	unstressed control	NBG-18		1	0.50	16.5	16	3.560	5.23E+21	3.82	6S3
Spacer	Guide/spacer	AXF-5Q		0.25		15.5	15.375	3.514	5.16E+21	3.77	
6U4	unstressed control	PCEA		1	0.50	15.25	14.75	3.464	5.09E+21	3.71	6S4
Spacer	Guide/spacer	AXF-5Q		0.25		14.25	14.125	3.409	5.01E+21	3.66	
6U5	unstressed control	H-451		1	0.50	14	13.5	3.349	4.92E+21	3.59	6S5
Spacer	Guide/spacer	AXF-5Q		0.25		13	12.875	3.284	4.82E+21	3.52	
6U6	unstressed control	NBG-18		1	0.50	12.75	12.25	3.214	4.72E+21	3.45	6S6
Spacer	Guide/spacer	AXF-5Q		0.25		11.75	11.625	3.140	4.61E+21	3.37	
6U7	unstressed control	IG-430		1	0.50	11.5	11	3.060	4.49E+21	3.28	6S7
Spacer	Guide/spacer	AXF-5Q		0.25		10.5	10.375	2.975	4.37E+21	3.19	
6U8	unstressed control	NBG-17		1	0.50	10.25	9.75	2.885	4.24E+21	3.09	6S8
Spacer	Guide/spacer	AXF-5Q		0.25		9.25	9.125	2.790	4.10E+21	2.99	
6U9	unstressed control	H-451		1	0.50	9	8.5	2.690	3.95E+21	2.88	6S9
Spacer	Guide/spacer	AXF-5Q		0.25		8	7.875	2.585	3.80E+21	2.77	
6U10	unstressed control	IG-430		1	0.50	7.75	7.25	2.474	3.63E+21	2.65	6S10
Spacer	Guide/spacer	AXF-5Q		0.25		6.75	6.625	2.359	3.46E+21	2.53	
6U11	unstressed control	PCEA		1	0.50	6.5	6	2.238	3.29E+21	2.40	6S11/12

AGC-1 Channel 6 (NORTH-WEST) Layout [2 ksi]											
				Dimensions, ins					Nominal Dose		
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Length	Dia	Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	n/cm2 [E>0.1 MeV]	dpa	Companion Sample Position
Spacer	Guide/spacer	AXF-5Q		0.25		5.5	5.375	2.111	3.10E+21	2.26	
6U12	unstressed control	NBG-18		1	0.50	5.25	4.75	1.979	2.91E+21	2.12	6S13
Spacer	Guide/spacer	AXF-5Q		0.25		4.25	4.125	1.842	2.71E+21	1.97	
6U13	unstressed control	IG-110		1	0.50	4	3.5	1.699	2.50E+21	1.82	6S14
Spacer	Guide/spacer	AXF-5Q		0.25		3	2.875	1.551	2.28E+21	1.66	
6U14	unstressed control	NBG-17		1	0.50	2.75	2.25	1.397	2.05E+21	1.50	6S15
Spacer	Guide/spacer	AXF-5Q		0.25		1.75	1.625	1.238	1.82E+21	1.33	
6PB23	Piggyback	2020		0.25	0.50	1.5	1.375	1.172	1.72E+21	1.26	
Spacer	Guide/spacer	AXF-5Q		0.25	0.50	1.25	1.125	1.106	1.62E+21	1.19	
6PB24	Piggyback	HLM		0.25	0.50	1	0.875	1.039	1.53E+21	1.11	
Spacer	Guide/spacer	AXF-5Q		0.25	0.50	0.75	0.625	0.971	1.43E+21	1.04	
6PB25	Piggyback	PCIB		0.25	0.50	0.5	0.375	0.902	1.32E+21	0.97	
Spacer	Guide/spacer	AXF-5Q		0.25	0.50	0.25	0.125	0.832	1.22E+21	0.89	End of core

Appendix G

AGC-1 Central Channel Specimen Layout [2 ksi]

AGC-1 Channel CENTER Layout											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Comments
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
CPB1	Piggyback	HOPG		0.25	0.5	48	47.875	0.388	5.69E+20	0.42	Top of Core
CPB2	Piggyback	A3 Matrix		0.25	0.5	47.75	47.625	0.444	6.52E+20	0.48	
CPB3	Piggyback	HLM		0.25	0.5	47.5	47.375	0.499	7.33E+20	0.54	On SiC TM
CPB4	Piggyback	PGX		0.25	0.5	47.25	47.125	0.554	8.14E+20	0.59	On SiC TM
CPB5	Piggyback	PPEA		0.25	0.5	47	46.875	0.609	8.94E+20	0.65	On SiC TM
CPB6	Piggyback	NBG-25		0.25	0.5	46.75	46.625	0.663	9.74E+20	0.71	On SiC TM
CPB7	Piggyback	2020		0.25	0.5	46.5	46.375	0.717	1.05E+21	0.77	On SiC TM
CPB8	Piggyback	PCIB		0.25	0.5	46.25	46.125	0.770	1.13E+21	0.83	On SiC TM
CPB9	Piggyback	BAN		0.25	0.5	46	45.875	0.823	1.21E+21	0.88	On SiC TM
CPB10	Piggyback	NGB-10		0.25	0.5	45.75	45.625	0.876	1.29E+21	0.94	On SiC TM
CPB11	Piggyback	HOPG		0.25	0.5	45.5	45.375	0.928	1.36E+21	1.00	
CPB12	Piggyback	A3 Matrix		0.25	0.5	45.25	45.125	0.980	1.44E+21	1.05	
CPB13	Piggyback	HLM		0.25	0.5	45	44.875	1.031	1.51E+21	1.11	On SiC TM
CPB14	Piggyback	PGX		0.25	0.5	44.75	44.625	1.082	1.59E+21	1.16	On SiC TM
CPB15	Piggyback	PPEA		0.25	0.5	44.5	44.375	1.133	1.66E+21	1.21	On SiC TM
CPB16	Piggyback	NBG-25		0.25	0.5	44.25	44.125	1.183	1.74E+21	1.27	On SiC TM

AGC-1 Channel CENTER Layout											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Comments
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
CPB17	Piggyback	2020		0.25	0.5	44	43.875	1.232	1.81E+21	1.32	On SiC TM
CPB18	Piggyback	PCIB		0.25	0.5	43.75	43.625	1.281	1.88E+21	1.37	On SiC TM
CPB19	Piggyback	BAN		0.25	0.5	43.5	43.375	1.330	1.95E+21	1.43	On SiC TM
CPB20	Piggyback	NGB-10		0.25	0.5	43.25	43.125	1.378	2.02E+21	1.48	On SiC TM
CPB21	Piggyback	HOPG		0.25	0.5	43	42.875	1.426	2.09E+21	1.53	
CPB22	Piggyback	A3 Matrix		0.25	0.5	42.75	42.625	1.474	2.16E+21	1.58	
CPB23	Piggyback	HLM		0.25	0.5	42.5	42.375	1.520	2.23E+21	1.63	On SiC TM
CPB24	Piggyback	PGX		0.25	0.5	42.25	42.125	1.567	2.30E+21	1.68	On SiC TM
CPB25	Piggyback	PPEA		0.25	0.5	42	41.875	1.613	2.37E+21	1.73	On SiC TM
CPB26	Piggyback	NBG-25		0.25	0.5	41.75	41.625	1.658	2.44E+21	1.78	On SiC TM
CPB27	Piggyback	2020		0.25	0.5	41.5	41.375	1.704	2.50E+21	1.83	On SiC TM
CPB28	Piggyback	PCIB		0.25	0.5	41.25	41.125	1.748	2.57E+21	1.87	On SiC TM
CPB29	Piggyback	BAN		0.25	0.5	41	40.875	1.792	2.63E+21	1.92	On SiC TM
CPB30	Piggyback	NGB-10		0.25	0.5	40.75	40.625	1.836	2.70E+21	1.97	On SiC TM
CPB31	Piggyback	HOPG		0.25	0.5	40.5	40.375	1.879	2.76E+21	2.01	
CPB32	Piggyback	A3 Matrix		0.25	0.5	40.25	40.125	1.922	2.82E+21	2.06	
CPB33	Piggyback	HLM		0.25	0.5	40	39.875	1.964	2.89E+21	2.11	On SiC TM
CPB34	Piggyback	PGX		0.25	0.5	39.75	39.625	2.006	2.95E+21	2.15	On SiC TM

AGC-1 Channel CENTER Layout											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Comments
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
CPB35	Piggyback	PPEA		0.25	0.5	39.5	39.375	2.047	3.01E+21	2.20	On SiC TM
CPB36	Piggyback	NBG-25		0.25	0.5	39.25	39.125	2.088	3.07E+21	2.24	On SiC TM
CPB37	Piggyback	2020		0.25	0.5	39	38.875	2.128	3.13E+21	2.28	On SiC TM
CPB38	Piggyback	PCIB		0.25	0.5	38.75	38.625	2.168	3.18E+21	2.32	On SiC TM
CPB39	Piggyback	BAN		0.25	0.5	38.5	38.375	2.208	3.24E+21	2.37	On SiC TM
CPB40	Piggyback	NGB-10		0.25	0.5	38.25	38.125	2.246	3.30E+21	2.41	On SiC TM
CPB41	Piggyback	HOPG		0.25	0.5	38	37.875	2.285	3.36E+21	2.45	
CPB42	Piggyback	A3 Matrix		0.25	0.5	37.75	37.625	2.323	3.41E+21	2.49	
CPB43	Piggyback	HLM		0.25	0.5	37.5	37.375	2.360	3.47E+21	2.53	On SiC TM
CPB44	Piggyback	PGX		0.25	0.5	37.25	37.125	2.397	3.52E+21	2.57	On SiC TM
CPB45	Piggyback	PPEA		0.25	0.5	37	36.875	2.433	3.57E+21	2.61	On SiC TM
CPB46	Piggyback	NBG-25		0.25	0.5	36.75	36.625	2.469	3.63E+21	2.65	On SiC TM
CPB47	Piggyback	2020		0.25	0.5	36.5	36.375	2.504	3.68E+21	2.68	On SiC TM
CPB48	Piggyback	PCIB		0.25	0.5	36.25	36.125	2.539	3.73E+21	2.72	On SiC TM
CPB49	Piggyback	BAN		0.25	0.5	36	35.875	2.573	3.78E+21	2.76	On SiC TM
CPB50	Piggyback	NGB-10		0.25	0.5	35.75	35.625	2.607	3.83E+21	2.79	On SiC TM
CPB51	Piggyback	HOPG		0.25	0.5	35.5	35.375	2.640	3.88E+21	2.83	
CPB52	Piggyback	A3 Matrix		0.25	0.5	35.25	35.125	2.673	3.93E+21	2.87	

AGC-1 Channel CENTER Layout											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Comments
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
CPB53	Piggyback	HLM		0.25	0.5	35	34.875	2.705	3.97E+21	2.90	On SiC TM
CPB54	Piggyback	PGX		0.25	0.5	34.75	34.625	2.736	4.02E+21	2.93	On SiC TM
CPB55	Piggyback	PPEA		0.25	0.5	34.5	34.375	2.767	4.06E+21	2.97	On SiC TM
CPB56	Piggyback	NBG-25		0.25	0.5	34.25	34.125	2.798	4.11E+21	3.00	On SiC TM
CPB57	Piggyback	2020		0.25	0.5	34	33.875	2.828	4.15E+21	3.03	On SiC TM
CPB58	Piggyback	PCIB		0.25	0.5	33.75	33.625	2.857	4.20E+21	3.06	On SiC TM
CPB59	Piggyback	BAN		0.25	0.5	33.5	33.375	2.886	4.24E+21	3.09	On SiC TM
CPB60	Piggyback	NGB-10		0.25	0.5	33.25	33.125	2.914	4.28E+21	3.12	On SiC TM
CPB61	Piggyback	HOPG		0.25	0.5	33	32.875	2.942	4.32E+21	3.15	
CPB62	Piggyback	A3 Matrix		0.25	0.5	32.75	32.625	2.969	4.36E+21	3.18	
CPB63	Piggyback	HLM		0.25	0.5	32.5	32.375	2.996	4.40E+21	3.21	On SiC TM
CPB64	Piggyback	PGX		0.25	0.5	32.25	32.125	3.022	4.44E+21	3.24	On SiC TM
CPB65	Piggyback	PPEA		0.25	0.5	32	31.875	3.048	4.48E+21	3.27	On SiC TM
CPB66	Piggyback	NBG-25		0.25	0.5	31.75	31.625	3.073	4.51E+21	3.29	On SiC TM
CPB67	Piggyback	2020		0.25	0.5	31.5	31.375	3.097	4.55E+21	3.32	On SiC TM
CPB68	Piggyback	PCIB		0.25	0.5	31.25	31.125	3.121	4.58E+21	3.35	On SiC TM
CPB69	Piggyback	BAN		0.25	0.5	31	30.875	3.144	4.62E+21	3.37	On SiC TM
CPB70	Piggyback	NGB-10		0.25	0.5	30.75	30.625	3.167	4.65E+21	3.40	On SiC TM

AGC-1 Channel CENTER Layout											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Comments
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
CPB71	Piggyback	HOPG		0.25	0.5	30.5	30.375	3.189	4.68E+21	3.42	
CPB72	Piggyback	A3 Matrix		0.25	0.5	30.25	30.125	3.210	4.72E+21	3.44	
CPB73	Piggyback	HLM		0.25	0.5	30	29.875	3.231	4.75E+21	3.46	On SiC TM
CPB74	Piggyback	PGX		0.25	0.5	29.75	29.625	3.251	4.78E+21	3.49	On SiC TM
CPB75	Piggyback	PPEA		0.25	0.5	29.5	29.375	3.271	4.80E+21	3.51	On SiC TM
CPB76	Piggyback	NBG-25		0.25	0.5	29.25	29.125	3.290	4.83E+21	3.53	On SiC TM
CPB77	Piggyback	2020		0.25	0.5	29	28.875	3.309	4.86E+21	3.55	On SiC TM
CPB78	Piggyback	PCIB		0.25	0.5	28.75	28.625	3.327	4.89E+21	3.57	On SiC TM
CPB79	Piggyback	BAN		0.25	0.5	28.5	28.375	3.344	4.91E+21	3.59	On SiC TM
CPB80	Piggyback	NGB-10		0.25	0.5	28.25	28.125	3.361	4.94E+21	3.60	On SiC TM
CPB81	Piggyback	HOPG		0.25	0.5	28	27.875	3.377	4.96E+21	3.62	
CPB82	Piggyback	A3 Matrix		0.25	0.5	27.75	27.625	3.393	4.98E+21	3.64	
CPB83	Piggyback	HLM		0.25	0.5	27.5	27.375	3.407	5.00E+21	3.65	On SiC TM
CPB84	Piggyback	PGX		0.25	0.5	27.25	27.125	3.422	5.03E+21	3.67	On SiC TM
CPB85	Piggyback	PPEA		0.25	0.5	27	26.875	3.435	5.05E+21	3.68	On SiC TM
CPB86	Piggyback	NBG-25		0.25	0.5	26.75	26.625	3.448	5.07E+21	3.70	On SiC TM
CPB87	Piggyback	2020		0.25	0.5	26.5	26.375	3.461	5.08E+21	3.71	On SiC TM
CPB88	Piggyback	PCIB		0.25	0.5	26.25	26.125	3.473	5.10E+21	3.72	On SiC TM

AGC-1 Channel CENTER Layout											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Comments
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
CPB89	Piggyback	BAN		0.25	0.5	26	25.875	3.484	5.12E+21	3.74	On SiC TM
CPB90	Piggyback	NGB-10		0.25	0.5	25.75	25.625	3.494	5.13E+21	3.75	On SiC TM
CPB91	Piggyback	HOPG		0.25	0.5	25.5	25.375	3.504	5.15E+21	3.76	
CPB92	Piggyback	A3 Matrix		0.25	0.5	25.25	25.125	3.514	5.16E+21	3.77	
CPB93	Piggyback	HLM		0.25	0.5	25	24.875	3.522	5.17E+21	3.78	On SiC TM
CPB94	Piggyback	PGX		0.25	0.5	24.75	24.625	3.530	5.19E+21	3.79	On SiC TM
CPB95	Piggyback	PPEA		0.25	0.5	24.5	24.375	3.538	5.20E+21	3.79	On SiC TM
CPB96	Piggyback	NBG-25		0.25	0.5	24.25	24.125	3.544	5.21E+21	3.80	On SiC TM
CPB97	Piggyback	2020		0.25	0.5	24	23.875	3.550	5.21E+21	3.81	On SiC TM
CPB98	Piggyback	PCIB		0.25	0.5	23.75	23.625	3.556	5.22E+21	3.81	On SiC TM
CPB99	Piggyback	BAN		0.25	0.5	23.5	23.375	3.561	5.23E+21	3.82	On SiC TM
CPB100	Piggyback	NGB-10		0.25	0.5	23.25	23.125	3.565	5.24E+21	3.82	On SiC TM
CPB101	Piggyback	HOPG		0.25	0.5	23	22.875	3.568	5.24E+21	3.83	
CPB102	Piggyback	A3 Matrix		0.25	0.5	22.75	22.625	3.571	5.24E+21	3.83	
CPB103	Piggyback	HLM		0.25	0.5	22.5	22.375	3.573	5.25E+21	3.83	On SiC TM
CPB104	Piggyback	PGX		0.25	0.5	22.25	22.125	3.574	5.25E+21	3.83	On SiC TM
CPB105	Piggyback	PPEA		0.25	0.5	22	21.875	3.575	5.25E+21	3.83	On SiC TM
CPB106	Piggyback	NBG-25		0.25	0.5	21.75	21.625	3.575	5.25E+21	3.83	On SiC TM

AGC-1 Channel CENTER Layout											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Comments
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
CPB107	Piggyback	2020		0.25	0.5	21.5	21.375	3.575	5.25E+21	3.83	On SiC TM
CPB108	Piggyback	PCIB		0.25	0.5	21.25	21.125	3.573	5.25E+21	3.83	On SiC TM
CPB109	Piggyback	BAN		0.25	0.5	21	20.875	3.571	5.25E+21	3.83	On SiC TM
CPB110	Piggyback	NGB-10		0.25	0.5	20.75	20.625	3.569	5.24E+21	3.83	On SiC TM
CPB111	Piggyback	HOPG		0.25	0.5	20.5	20.375	3.566	5.24E+21	3.82	
CPB112	Piggyback	A3 Matrix		0.25	0.5	20.25	20.125	3.562	5.23E+21	3.82	
CPB113	Piggyback	HLM		0.25	0.5	20	19.875	3.557	5.22E+21	3.81	On SiC TM
CPB114	Piggyback	PGX		0.25	0.5	19.75	19.625	3.551	5.22E+21	3.81	On SiC TM
CPB115	Piggyback	PPEA		0.25	0.5	19.5	19.375	3.545	5.21E+21	3.80	On SiC TM
CPB116	Piggyback	NBG-25		0.25	0.5	19.25	19.125	3.539	5.20E+21	3.79	On SiC TM
CPB117	Piggyback	2020		0.25	0.5	19	18.875	3.531	5.19E+21	3.79	On SiC TM
CPB118	Piggyback	PCIB		0.25	0.5	18.75	18.625	3.523	5.17E+21	3.78	On SiC TM
CPB119	Piggyback	BAN		0.25	0.5	18.5	18.375	3.514	5.16E+21	3.77	On SiC TM
CPB120	Piggyback	NGB-10		0.25	0.5	18.25	18.125	3.504	5.15E+21	3.76	On SiC TM
CPB121	Piggyback	HOPG		0.25	0.5	18	17.875	3.494	5.13E+21	3.75	
CPB122	Piggyback	A3 Matrix		0.25	0.5	17.75	17.625	3.483	5.12E+21	3.73	
CPB123	Piggyback	HLM		0.25	0.5	17.5	17.375	3.471	5.10E+21	3.72	On SiC TM
CPB124	Piggyback	PGX		0.25	0.5	17.25	17.125	3.459	5.08E+21	3.71	On SiC TM

AGC-1 Channel CENTER Layout											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Comments
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
CPB125	Piggyback	PPEA		0.25	0.5	17	16.875	3.446	5.06E+21	3.69	On SiC TM
CPB126	Piggyback	NBG-25		0.25	0.5	16.75	16.625	3.432	5.04E+21	3.68	On SiC TM
CPB127	Piggyback	2020		0.25	0.5	16.5	16.375	3.417	5.02E+21	3.66	On SiC TM
CPB128	Piggyback	PCIB		0.25	0.5	16.25	16.125	3.402	5.00E+21	3.65	On SiC TM
CPB129	Piggyback	BAN		0.25	0.5	16	15.875	3.385	4.97E+21	3.63	On SiC TM
CPB130	Piggyback	NGB-10		0.25	0.5	15.75	15.625	3.369	4.95E+21	3.61	On SiC TM
CPB131	Piggyback	HOPG		0.25	0.5	15.5	15.375	3.351	4.92E+21	3.59	
CPB132	Piggyback	A3 Matrix		0.25	0.5	15.25	15.125	3.333	4.89E+21	3.57	
CPB133	Piggyback	HLM		0.25	0.5	15	14.875	3.313	4.87E+21	3.55	On SiC TM
CPB134	Piggyback	PGX		0.25	0.5	14.75	14.625	3.294	4.84E+21	3.53	On SiC TM
CPB135	Piggyback	PPEA		0.25	0.5	14.5	14.375	3.273	4.81E+21	3.51	On SiC TM
CPB136	Piggyback	NBG-25		0.25	0.5	14.25	14.125	3.252	4.78E+21	3.49	On SiC TM
CPB137	Piggyback	2020		0.25	0.5	14	13.875	3.230	4.74E+21	3.46	On SiC TM
CPB138	Piggyback	PCIB		0.25	0.5	13.75	13.625	3.207	4.71E+21	3.44	On SiC TM
CPB139	Piggyback	BAN		0.25	0.5	13.5	13.375	3.183	4.68E+21	3.41	On SiC TM
CPB140	Piggyback	NGB-10		0.25	0.5	13.25	13.125	3.159	4.64E+21	3.39	On SiC TM
CPB141	Piggyback	HOPG		0.25	0.5	13	12.875	3.134	4.60E+21	3.36	
CPB142	Piggyback	A3 Matrix		0.25	0.5	12.75	12.625	3.108	4.56E+21	3.33	

AGC-1 Channel CENTER Layout											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Comments
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
CPB143	Piggyback	HLM		0.25	0.5	12.5	12.375	3.081	4.53E+21	3.30	On SiC TM
CPB144	Piggyback	PGX		0.25	0.5	12.25	12.125	3.053	4.48E+21	3.27	On SiC TM
CPB145	Piggyback	PPEA		0.25	0.5	12	11.875	3.025	4.44E+21	3.24	On SiC TM
CPB146	Piggyback	NBG-25		0.25	0.5	11.75	11.625	2.996	4.40E+21	3.21	On SiC TM
CPB147	Piggyback	2020		0.25	0.5	11.5	11.375	2.966	4.36E+21	3.18	On SiC TM
CPB148	Piggyback	PCIB		0.25	0.5	11.25	11.125	2.936	4.31E+21	3.15	On SiC TM
CPB149	Piggyback	BAN		0.25	0.5	11	10.875	2.904	4.27E+21	3.11	On SiC TM
CPB150	Piggyback	NGB-10		0.25	0.5	10.75	10.625	2.872	4.22E+21	3.08	On SiC TM
CPB151	Piggyback	HOPG		0.25	0.5	10.5	10.375	2.839	4.17E+21	3.04	
CPB152	Piggyback	A3 Matrix		0.25	0.5	10.25	10.125	2.805	4.12E+21	3.01	
CPB153	Piggyback	HLM		0.25	0.5	10	9.875	2.771	4.07E+21	2.97	On SiC TM
CPB154	Piggyback	PGX		0.25	0.5	9.75	9.625	2.735	4.02E+21	2.93	On SiC TM
CPB155	Piggyback	PPEA		0.25	0.5	9.5	9.375	2.699	3.96E+21	2.89	On SiC TM
CPB156	Piggyback	NBG-25		0.25	0.5	9.25	9.125	2.662	3.91E+21	2.85	On SiC TM
CPB157	Piggyback	2020		0.25	0.5	9	8.875	2.625	3.85E+21	2.81	On SiC TM
CPB158	Piggyback	PCIB		0.25	0.5	8.75	8.625	2.586	3.80E+21	2.77	On SiC TM
CPB159	Piggyback	BAN		0.25	0.5	8.5	8.375	2.547	3.74E+21	2.73	On SiC TM
CPB160	Piggyback	NGB-10		0.25	0.5	8.25	8.125	2.506	3.68E+21	2.69	On SiC TM

AGC-1 Channel CENTER Layout											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Comments
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
CPB161	Piggyback	HOPG		0.25	0.5	8	7.875	2.465	3.62E+21	2.64	
CPB162	Piggyback	A3 Matrix		0.25	0.5	7.75	7.625	2.423	3.56E+21	2.60	
CPB163	Piggyback	HLM		0.25	0.5	7.5	7.375	2.381	3.50E+21	2.55	On SiC TM
CPB164	Piggyback	PGX		0.25	0.5	7.25	7.125	2.337	3.43E+21	2.51	On SiC TM
CPB165	Piggyback	PPEA		0.25	0.5	7	6.875	2.293	3.37E+21	2.46	On SiC TM
CPB166	Piggyback	NBG-25		0.25	0.5	6.75	6.625	2.248	3.30E+21	2.41	On SiC TM
CPB167	Piggyback	2020		0.25	0.5	6.5	6.375	2.202	3.23E+21	2.36	On SiC TM
CPB168	Piggyback	PCIB		0.25	0.5	6.25	6.125	2.155	3.16E+21	2.31	On SiC TM
CPB169	Piggyback	BAN		0.25	0.5	6	5.875	2.107	3.09E+21	2.26	On SiC TM
CPB170	Piggyback	NGB-10		0.25	0.5	5.75	5.625	2.058	3.02E+21	2.21	On SiC TM
CPB171	Piggyback	HOPG		0.25	0.5	5.5	5.375	2.009	2.95E+21	2.15	
CPB172	Piggyback	A3 Matrix		0.25	0.5	5.25	5.125	1.959	2.88E+21	2.10	
CPB173	Piggyback	HLM		0.25	0.5	5	4.875	1.908	2.80E+21	2.05	On SiC TM
CPB174	Piggyback	PGX		0.25	0.5	4.75	4.625	1.856	2.73E+21	1.99	On SiC TM
CPB175	Piggyback	PPEA		0.25	0.5	4.5	4.375	1.803	2.65E+21	1.93	On SiC TM
CPB176	Piggyback	NBG-25		0.25	0.5	4.25	4.125	1.749	2.57E+21	1.88	On SiC TM
CPB177	Piggyback	2020		0.25	0.5	4	3.875	1.695	2.49E+21	1.82	On SiC TM
CPB178	Piggyback	PCIB		0.25	0.5	3.75	3.625	1.639	2.41E+21	1.76	On SiC TM

AGC-1 Channel CENTER Layout											
Location in Capsule	Sample Type	Graphite Grade	Specimen ID	Dimensions, ins		Cumulative stack distance from Core bottom	Sample mid line distance from core bottom	Fast Flux, 10^14 n/cm2-s [E>0.1MeV]	Nominal Dose		Comments
				Length	Dia				n/cm2 [E>0.1 MeV]	dpa	
CPB179	Piggyback	BAN		0.25	0.5	3.5	3.375	1.583	2.33E+21	1.70	On SiC TM
CPB180	Piggyback	NGB-10		0.25	0.5	3.25	3.125	1.526	2.24E+21	1.64	On SiC TM
CPB181	Piggyback	HOPG		0.25	0.5	3	2.875	1.468	2.16E+21	1.57	
CPB182	Piggyback	A3 Matrix		0.25	0.5	2.75	2.625	1.409	2.07E+21	1.51	
CPB183	Piggyback	HLM		0.25	0.5	2.5	2.375	1.349	1.98E+21	1.45	On SiC TM
CPB184	Piggyback	PGX		0.25	0.5	2.25	2.125	1.289	1.89E+21	1.38	On SiC TM
CPB185	Piggyback	PPEA		0.25	0.5	2	1.875	1.227	1.80E+21	1.32	On SiC TM
CPB186	Piggyback	NBG-25		0.25	0.5	1.75	1.625	1.165	1.71E+21	1.25	On SiC TM
CPB187	Piggyback	2020		0.25	0.5	1.5	1.375	1.101	1.62E+21	1.18	On SiC TM
CPB188	Piggyback	PCIB		0.25	0.5	1.25	1.125	1.037	1.52E+21	1.11	On SiC TM
CPB189	Piggyback	BAN		0.25	0.5	1	0.875	0.972	1.43E+21	1.04	On SiC TM
CPB190	Piggyback	NGB-10		0.25	0.5	0.75	0.625	0.906	1.33E+21	0.97	On SiC TM
CPB191	Piggyback	HOPG		0.25	0.5	0.5	0.375	0.839	1.23E+21	0.90	
CPB192	Piggyback	A3 Matrix		0.25	0.5	0.25	0.125	0.771	1.13E+21	0.83	Core Bottom

Appendix H

AGC-1 Capsule Drawings

Appendix I

Structural Evaluation of the ATR Advanced Graphite Creep Experiment AGC-1

Document ID:EDF-5925
Revision ID:0
Effective Date:May 2006
Draft

Engineering Design File

Structural Evaluation of the ATR Advanced Graphite Creep Experiment AGC-1

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The INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance.

ENGINEERING DESIGN FILE

EDF No.: 5925 EDF Rev. No.: 0 Project File No.: 23747

1. Title: Structural Evaluation of the ATR Advanced Graphite Creep Experiment AGC-1

2. Index Codes:
Building/Type TRA 670 SSC ID N/A Site Area 533

3. NPH Performance Category: PC 4 or ☐ N/A

4. EDF Safety Category: SC or ☐ N/A SCC Safety Category: CG or ☐ N/A

5. Summary:

6. Review (R) and Approval (A) and Acceptance (Ac) Signatures:
(See instructions for definitions of terms and significance of signatures.)

	R/A	Typed Name/Organization	Signature	Date
Performer/ Author	N/A	B. D. Hawkes Applied Mechanics & SD		
Performer/ Author	N/A	S. D. Snow Applied Mechanics & SD		
Technical Checker	R	M. E. Nitzel Applied Mechanics & SD		
Independent Peer Reviewer	R	T. E. Rahl Applied Mechanics & SD		
Manager	A	C. C. O'Brien Applied Mechanics & SD		
Requestor (if applicable)	Ac	R. L. Bratton Nuclear Materials Disp & Eng		
Approver	A	S. R. Jensen RTC Seismic Review		
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12. NRC related? ☐ Yes ☒ No

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EDF No.: 5925 EDF Rev. No.: 0 Project File No.: 23747

1. Title: Structural Evaluation of the ATR Advanced Graphite Creep Experiment AGC-1			
2. Index Codes:			
Building/Type TRA 670	SSC ID N/A	Site Area 533	
13. Registered Professional Engineer's Stamp (if required) N/A			

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1. PURPOSE

The Advanced Graphite Creep Experiment (AGC-1) has been designed for installation into the Advanced Test Reactor (ATR) at the Idaho National Laboratory (INL) Reactor Technology Complex (RTC). The purpose of this EDF is to document the structural evaluation of the components of the AGC-1 experiment. This will include an evaluation of the test facility assembly including the reactor penetration components.

2. SCOPE

This EDF applies only to the AGC-1 facility experiment components as listed above. Evaluations of the gas and other control systems external to the reactor were not performed herein.

3. SAFETY CATEGORY & GOVERNING CODES

The safety categories for the various components in this AGC-1 experiment were defined in the Technical & Functional Requirements document (Ref.1). Those components subjected to reactor pressure (top head seal plug, hanger rod, capsule boundaries, etc.) are categorized as Safety Class (SC). The gas control system is specified as Safety Significant (SS), while the pneumatic rams, graphite support plates, and the heat shield are listed as Low Safety Consequence (LSC). Internal components such as pushrods, load cells, graphite body and specimens, and stainless steel guide plates are considered Consumer Grade (CG).

The reactor penetration is greater than 3 inches in diameter and will be evaluated to the requirements of the ASME Boiler and Pressure Vessel Code (hereafter referred to as the ASME Code) Section III, Class 1 (Ref.2).

The hanger rod and capsule boundaries will be evaluated according to the requirements of the ASME Code Section III, Class 3 (Ref.3).

The gas lines and hanger rod assembly external to the reactor will be evaluated to the requirements of ANSI B31.1 (Ref.4).

Low Safety Class and Consumer Grade components will be evaluated using industry standard design codes.

4. NATURAL PHENOMENA HAZARDS PERFORMANCE CATEGORY

Per Reference 1, the reactor penetration, hanger rod, and capsule pressure boundary components shall be evaluated for Natural Phenomena Hazards Performance Category 4 (PC-4) requirements.

5. STRUCTURE, SYSTEM, OR COMPONENT (SSC) DESCRIPTION

The AGC-1 experiment begins with the hanger rod assembly outside of the reactor. This hanger rod assembly is threaded into the experiment top head seal plug which is clamped to reactor at the top head closure plate with a standard loop seal flange. Welded to the reactor side of the top head seal plug is the in-vessel hanger rod extension tube, followed by four transition tubes (all 5-inch diameter tubing) which are about 12-1/2 feet in total length. Those in-vessel

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hanger rod tubes then join through a reducer to the capsule facility body (2-1/2 inch diameter tubing), which is about 12-1/2 feet in total length. The capsule facility body passes through the reactor core area by way of the South Flux Trap, where it terminates just beyond the core region. Figure 1 shows the AGC-1 experiment assembly in the ATR vessel. Figure 2 shows the AGC-1 experiment assembly.

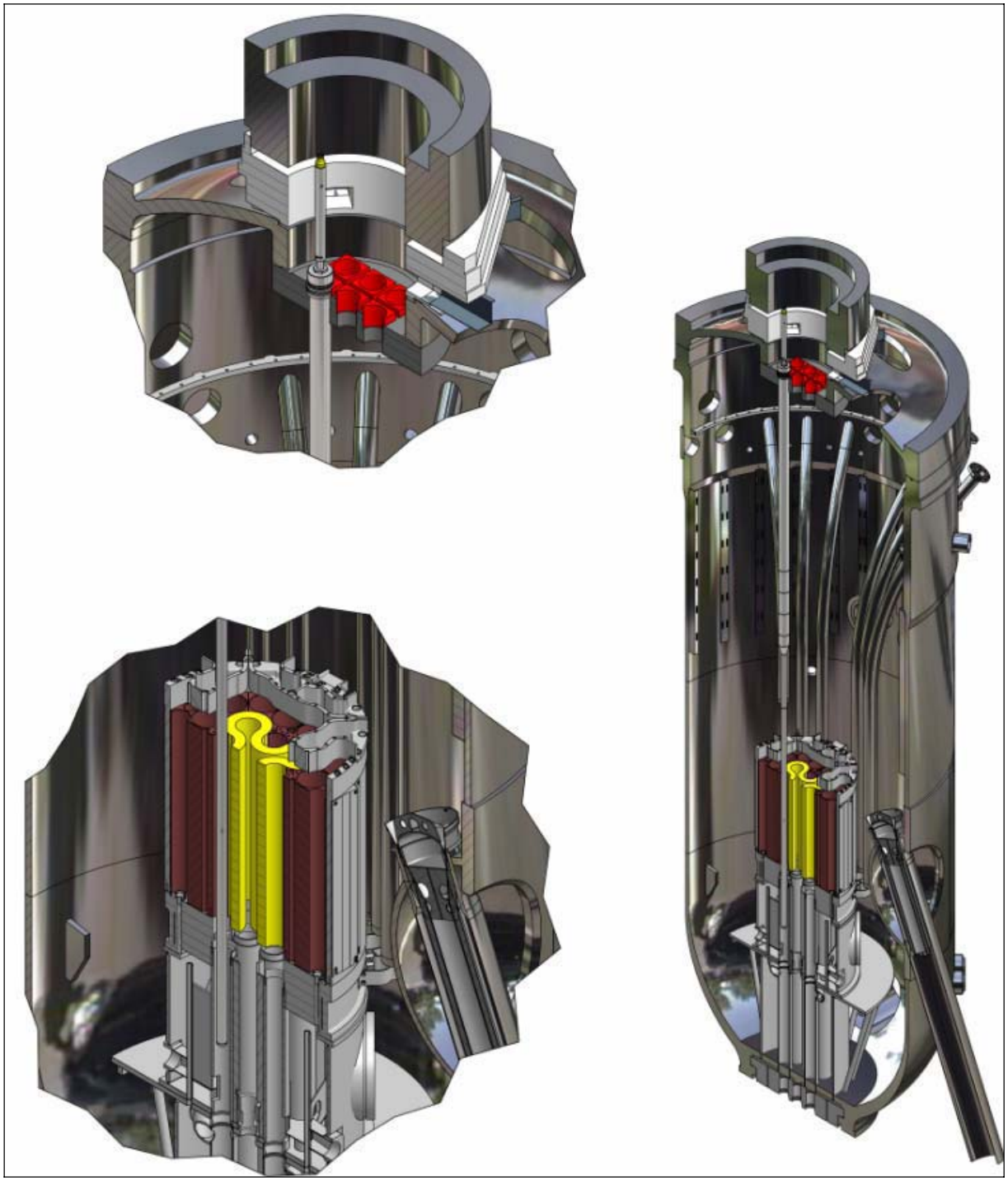

Figure 1. Advanced test reactor with the AGC-1 experiment assembly installed.

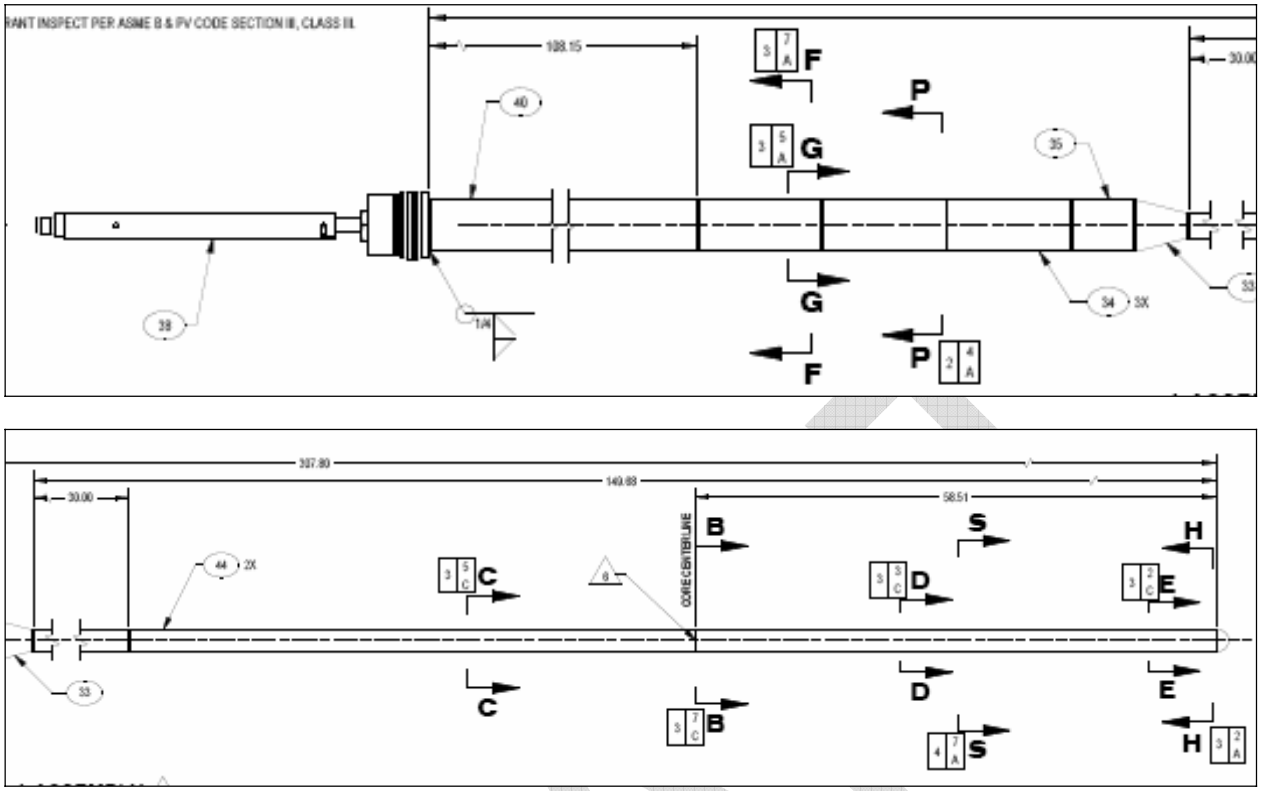

Figure 2. AGC-1 experiment assembly.

Within the capsule facility body are seven channels of graphite specimens, specimen holders, a heat shield, gas lines, thermocouples, and other related components. Actuators are placed in the hanger rod transition tubes and in the bottom of the capsule facility body to allow for load and movement to be applied, by way of push rods, to six of the seven graphite specimen channels.

The hanger rod assembly, top head seal plug, in-reactor hanger rod extension and transition tubes, and capsule facility body are all made of stainless steel (SST). Components within the experiment are made primarily of SST, graphite, or Haynes 230.

The next two sections list the design drawings and materials employed in this evaluation.

6. DRAWINGS

Table 1. INL design drawings.

Drawing Number	Drawing Title	Revision
630427	ATR Advanced Graphite Test Graphite Component Details	Draft
630428	ATR 7 Hole Graphite Test Stainless Steel Component Assemblies and Details	Draft
630429	ATR 7 Hole Graphite Test Hanger Rod Assemblies and Details	Draft
630430	ATR 7 Hole Graphite Test Capsule Facility Assembly	Draft
630431	ATR Advanced Graphite Test Graphite Specimen Stack-up Arrangements	Draft
630432	Advanced Graphite Test (AGC) Transitioned Thermal Heat Shield Details and Assembly	Draft
630434	ATR Advanced Graphite Capsule (AGC) Capsule Facility In-Core Pressure Boundary Tube	Draft
120438	ATR Reactor Vessel Top Head Closure Plate and Instrument Thimbles	8
120446	ATR Reactor Vessel Top & Bottom Closure Plate Penetration Closures and Seals	3
443027	ATR South and East Chopped Dummy In-Pile Tube Assembly	6

"Draft" drawings were not yet released at the time of this evaluation.

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7. MATERIALS

The primary components of the AGC-1 experiment that were specifically evaluated herein employed the following materials:

- Hanger Rod Assembly: 304 SST (ASME SA-240 and SA-213, Dwg. 630429)
- Top Head Seal Plug: 304 SST (ASME SA-240, Dwg. 630429)
- Loop Seal Flange: 304 SST (Dwg. 120446)
- Loop Seal Flange Bolts or Studs: 304 SST (SA-193, Dwg. 120446 Notes 2 & 8)
- Hanger Rod Extension Tube: 304 SST (ASME SA-213, Dwg. 630430)
- Hanger Rod Transition Tubes: 304 SST (ASME SA-213, Dwg. 630428)
- Funnel Transition Tube: 304 SST (ASME SA-213, Dwg. 630428)
- Transition Funnel: 304 SST (ASME SA-479, Dwg. 630428)
- Capsule Facility Body: 304 SST (ASME SA-213, Dwg. 630430)
  [In-core pressure boundary tube: 304 SST (ASME SA-213, Dwg. 630434)]
- Test Facility Bottom Cap: 304 SST (ASME SA-479, Dwg. 630428)
- Upper Cylinder Mounting Plates: 304 SST (ASME SA-240, Dwg. 630428)
- Push Rod Alignment Plates: 304 SST (ASME SA-240, Dwg. 630428)
- Upper Cylinder Push Rods/Bars: 304 SST (ASME SA-479, Dwg. 630428)
- Upper Cylinder Load Cell Attach Bolts: 304 SST (ASME SA-479, Dwg. 630428)
- Lower Spacer Tube: 304 SST (ASME SA-213, Dwg. 630428)
- Capsule Bottom Plate: 304 SST (ASME SA-479, Dwg. 630428)
- Graphite Components: graphite (POCO AXF-5Q1, Dwg. 630427)
- Heat Shield: Haynes 230 (Dwg. 630432)
- Channel Through Tubes: 304L SST (ASME SA-213, Dwg. 630430)
- Gas Lines: 304L SST (ASME SA-213, Dwg. 630430)

The following tables list the material properties that were employed in the evaluation of these primary components and assemblies.

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Table 2. Material properties for 304 and 304L stainless steels.

Material Property		Material Properties at Temperature			
		100 °F	180 °F	200 °F	240 °F
Thermal Expansion άT (in./ft.) going from 70 °F to specified temperature[1]		0.003	0.0116	0.014	0.0188
Modulus of Elasticity E ($x10^6$ psi)[2]		28.3	27.7	27.6	27.4
Minimum Yield Strength S_y (ksi)[3]	304	30.0	25.7	25.0	23.9
	304L	25.0	21.9	21.4	20.4
Design Stress Intensity for Class 1 Components S_m (ksi)[4]	304	20.0	20.0	20.0	20.0
	304L	16.7	16.7	16.7	16.7
	304 Bolts[6]	10.0	8.6	8.3	8.0
Allowable Stress for Class 3 Components S (ksi)[5]	304	20.0	20.0	20.0	20.0
	304L	16.7	16.7	16.7	16.7
Allowable Stress for B31.1 Components S (ksi)[7]	304	18.8	16.3	15.7	15.1
	304L	15.7	13.9	13.4	12.8

All Table properties found in Ref. 5 except for B31.1 properties which were found in Ref. 4.
1. Table TE-1 for Group 3 materials.
2. Table TM-1 for Group G materials.
3. Table Y-1
4. Table 2A.
5. Table 1A.
6. Table 4.
7. ASME B31.1, Table A-3.

Table 3. Material properties for Haynes 230 alloy.

Material Property	Material Properties at Temperature		
	100 °F	200 °F	400 °F
Mean Coefficient of Thermal Expansion going from 70 °F to specified temperature (in./in.- °F)	-	.0000065	.0000069
Modulus of Elasticity E ($x10^6$ psi)	30.6	30.1	29.3
Typical Yield Strength S_y (ksi)	61.3		
Typical Ultimate Strength S_u (ksi)	121.6		

Properties specified by the manufacturer (www.haynesintl.com).

The Table 3 properties were published by the manufacturer (Haynes International). Haynes 230 is used in constructing the thermal heat shield and will not experience any pressure loadings. The heat shield must merely remain in place and intact to be acceptable. No ASME Code evaluation is required for the heat shield.

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Table 4. Material properties for graphite POCO AXF-5Q.

Quality | Environment | Privacy Policy | Sitemap | Site Search

Poco Graphite

MSDS | Literature | EDM | Silicon Carbide | Graphite | Thermal Mgmt | About POCO

POCOSTORE.com | Applications | **Materials** | Products | Post-Processing | Distributors

Languages: | English | 中文

Semiconductor
- GRADE CHART
- COMPARE
- CZR-1,-2
- DFP-1,-2
- DFP-1C
- FM-1,-2
- HPD-1,-2
- PLS-1,-2
- SCF-1,-2
- SFG-1,-2
- TRA-1,-2
- ZEE-2

Industrial
- GRADE CHART
- COMPARE
- ACF-10Q
- **AXF-5Q**
- AXF-5QC
- AXM-5Q
- AXZ-5Q
- TM
- XT
- ZXF-5Q
- JET-2

Glassmate
- GRADE CHART
- COMPARE
- CXT
- GM
- HT
- LT
- SR

CLEANING INFO

PURITY INFO

AXF-5Q			
Particle Size		***Tensile Strength (1)***	
microns	5	N/mm^2	62
µ·inches	200	psi	9,000
Pore Size		***Modulus of Elasticity***	
microns	0.8	N/mm^2	11,000
µ·inches	32	psi x 10^6	1.6
Total Porosity		***Tensile Strain***	
% volume	20	to Failure %	0.95
Open Porosity		***Hardness***	
% of total	80	SSH	74
Apparent Density		***Electrical Resistivity***	
g/cc	1.78	µ·ohm·cm	1,470
lb/in^3	0.0641	µ·ohm·in	580
Compressive Strength		***Coefficient of Thermal Expansion***	
N/mm^2	138	microns/m °C	7.9
psi	20,000	µ·in/in °F	4.4
Flexural Strength		***Thermal Conductivity***	
N/mm^2	86	watts/m K	95
psi	12,500	BTU·ft/hr·ft^2·°F	55

Related Applications
- Biomedical
- Fuel Cells

Related Materials
- AXF-5QC

http://www.poco.com/us/Graphite/axf.asp (Manufacturer: POCO Graphite)

The Table 4 properties were published by the manufacturer. This graphite will be used in the lower graphite spacer, the lower and upper graphite specimen holders, the graphite specimen separators (stop blocks), and graphite spacer and push rods. These components are not required to meet ASME Code requirements, but will be evaluated using the above properties and engineering judgment (i.e., maintenance of a factor of safety against material failure).

The manufacturer does not list higher temperature properties for this graphite. However, Reference 6 states that the compressive strength increases (to almost double the room temperature value) with temperature up to about 2500 deg. C. (4500 deg. F.). Strength also increases with irradiation (Ref.7).

8. LOADS

8.1 Design Load Conditions

8.1.1 Reactor Vessel Penetration Components

The design conditions for the reactor vessel penetration components are:

- Design Life: 1.5 years for seal plug, 14 years for loop seal flange and bolts (Ref. 1)
- Design Temperature: 240 °F (Ref. 8)
- Design Pressure: 390 psig in reactor, 0 psig external to reactor (Ref. 8)
- Corrosion Allowance: zero (Ref. 1)

8.1.2 In-Vessel Pressure Boundary Components

The design conditions for the hanger rod extension and transition tubes and the capsule boundary components are:

- Design Life: 1.5 years (Ref. 1)
- Design Temperature: 240 °F (Ref. 8)
- Design Pressure: 390 psig external pressure (Ref. 8), 200 psig internal pressure (Ref. 1)
- Corrosion Allowance: zero (Ref. 1)
- Sustained loadings under design conditions include flow-induced vibrations, flow lift/drag, and a 100 psig pressure drop across the core (flow velocity past capsule of 27.1 ft/sec., Ref. 9).

8.1.3 Gas Lines (In-Vessel) and Hanger Rod Assembly (Out-of-Reactor) Components

The design conditions for the gas lines and hanger rod assembly (out-of-reactor) components are:

- Design Life: 14 years (Ref. 1)
- Design Temperature: Gas Lines at 240 °F (Ref. 8)
  Hanger Rod Assembly at 240 °F (conservative)
- Design Pressure: Gas Lines at 250 psig internal, 0 psig external (Ref. 1)
  Hanger Rod Assembly- 0 psig internal and external (Ref. 1)
- Corrosion Allowance: zero (Ref. 1)

8.2 Service Level Conditions

8.2.1 Service Level Conditions (Level A - Normal Operation)

- Design Pressure: 390 psi reactor pressure (Ref. 8)
- Operating Temperature: 125°F reactor (Ref. 8)

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- Startup-to-Steady State-to-Shutdown Frequency: 18 per year (Ref. 8)

8.2.2 Level B (Upset) Service Conditions

- Pressure: 429 psi reactor pressure (10% overpressure, Ref. 8)
- Temperature: 240°F reactor (Ref. 8)
- Frequency: 30 per year (Ref. 8)

8.2.3 Level C (Emergency) Service Conditions

- Pressure: 468 psi reactor pressure (20% overpressure, Ref. 8)
- Temperature: 240°F reactor (Ref. 8)
- Frequency: 10 times per 20 year period (Ref. 8)

8.2.4 Level D (Faulted) Service Conditions

- ATR Seismic Event, Performance Category 4 (PC-4)

For a number of years the ATR Safe Shutdown Event (SSE) was defined (Ref. 10) using USNRC Regulatory Guide 1.60 Response Spectra (Ref. 11) scaled to 0.24g zero period acceleration (zpa horizontal, and 0.16 g's zpa vertical), with Pressure Vessel Research Council (PVRC) damping (ASME Code Case N-411-1, Ref. 12, which was a 5% damping curve transitioning to 2% damping curve). The Regulatory Guide 1.60 spectra were used because site-specific spectra were not available. Numerous experiments have been evaluated using that ATR SSE definition (e.g., Ref.'s 13 and 14). More recently, the ASME Code discarded the PVRC damping in favor of Appendix N damping (Ref. 15, Table N-1230-1, or 5% damping for piping).

Currently, site-specific PC-4 rock spectra (Ref. 16) are available for the Test Reactor Area [name recently changed to Reactor Technology Complex (RTC)] and are recommended for use by the TRA Seismic Review team (Ref. 17). These site-specific spectra are to be used with an amplification factor (1.25) on PC-4 SSCs per DOE-STD-1020 (Ref. 18), though the TRA Seismic Review Team has more recently allowed for a lower amplification factor (1.0, per Ref. 19). However, this current analysis used the 1.25 amplification factor to ensure conservatism. (Note that because the ATR vessel is supported on a substantial concrete structure which is founded on bedrock, no further amplification was deemed applicable.)

Figure 3 shows the comparison of the Reg. Guide 1.60 horizontal spectra, scaled to 0.24 g's zpa, and the site-specific rock spectra with the PC-4 scale factor of 1.25. Both use 5% damping. Figure 4 shows the same for the vertical spectra. From these figures it can be seen that neither spectra entirely envelopes the other. This current analysis of the AGC-1 experiment conservatively enveloped both spectra by following the Reg. Guide 1.60 spectra until it met the rock spectra, and then following the rock spectra (switching back to the Reg. Guide 1.60 spectra at 50 Hz. for horizontal only). Table 5 shows the enveloping spectra points that were employed in this AGC-1 experiment evaluation.

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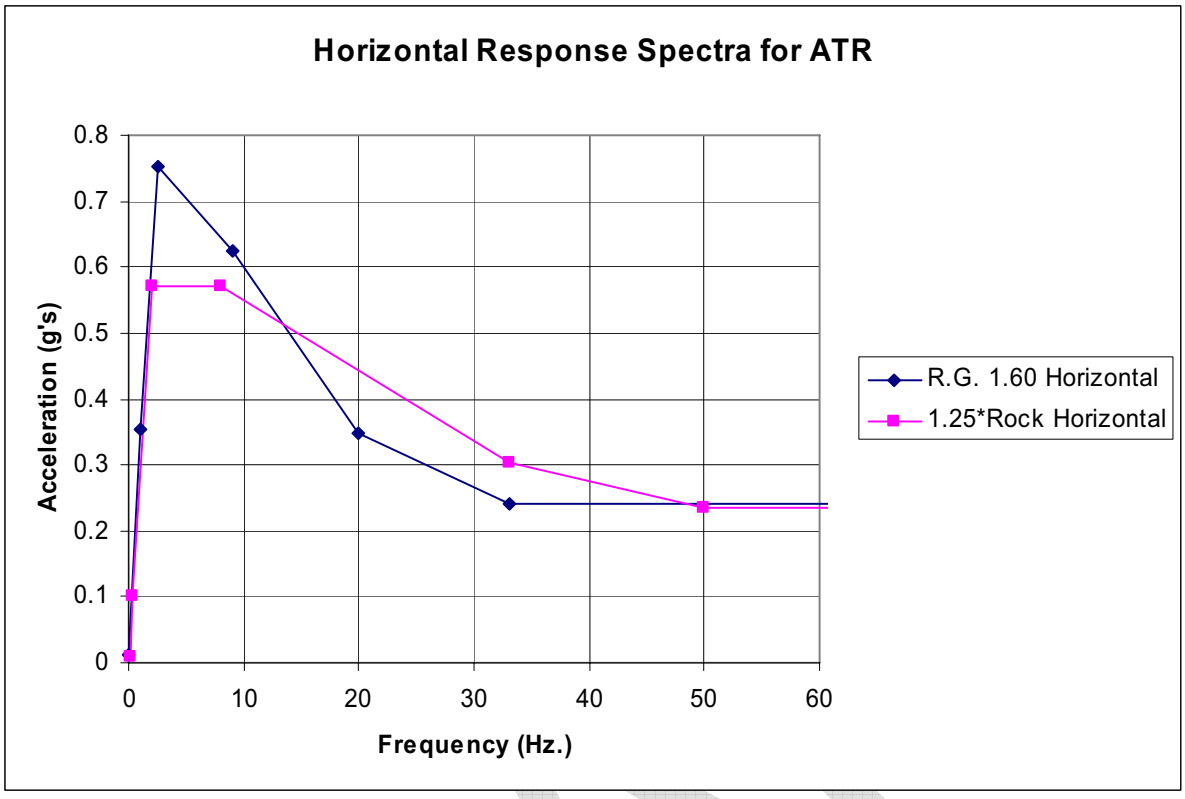

Figure 3. Comparison of horizontal response spectra, 5% damping.

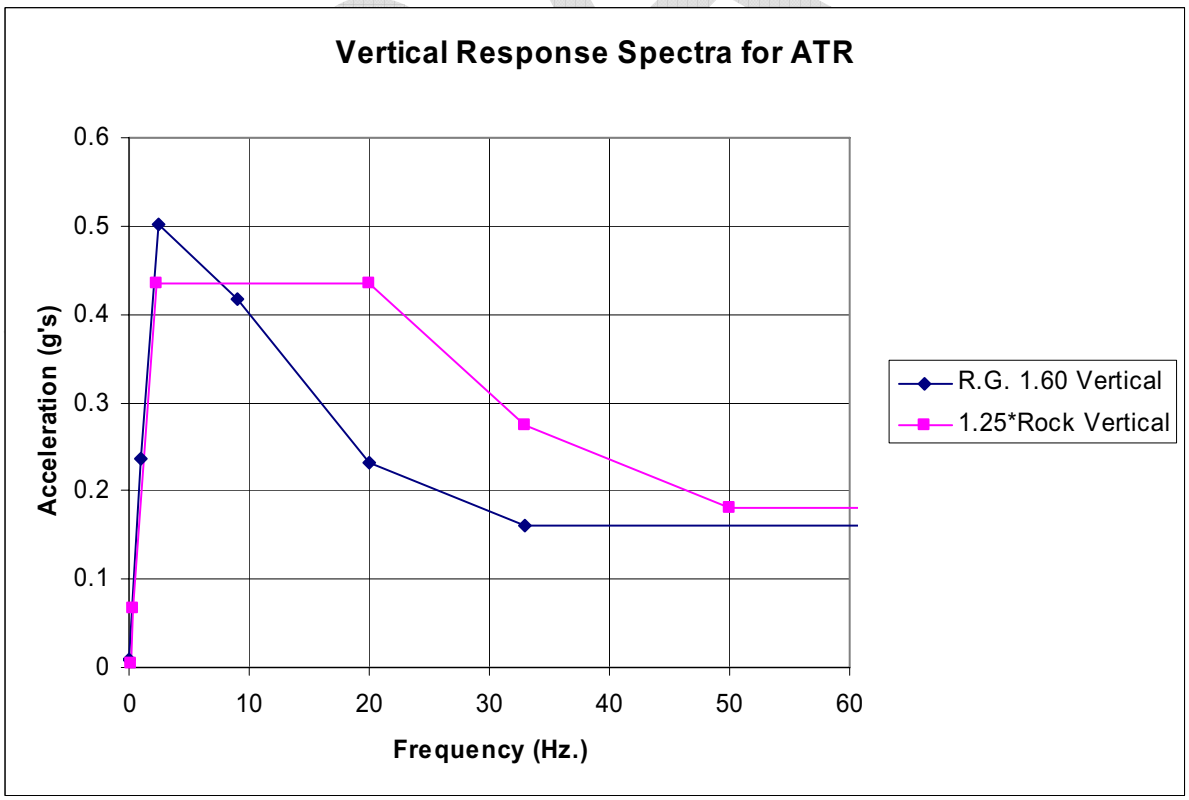

Figure 4. Comparison of vertical spectra, 5% damping.

Table 5. Enveloping response spectra for the ATR seismic event.

Frequency (Hz.)	Horizontal Accelerations (g), 5% Damping		Frequency (Hz.)	Vertical Accelerations (g), 5% Damping
0.001	0.013		0.001	0.009
1.0	0.354		1.0	0.236
2.5	0.751		2.5	0.501
9.0	0.626		7.63	0.435
13.5	0.512		20.0	0.435
33.0	0.303		33.0	0.274
50.0	0.240		50.0	0.180
100.0	0.240		100.0	0.180

9. ASSUMPTIONS

Assumptions used within the evaluation will be stated when employed.

10. ACCEPTANCE CRITERIA

The ASME Code, Section III, Subsection NB (Ref. 2), is used for Class 1 Components. ASME Code, Section III, Subsection ND (Ref. 3) is the governing code for Class 3 components which include most of the in-vessel components. The gas lines and hanger rod Assembly outside of the reactor must meet the ASME B31.1 (Power Piping) Code requirements (Ref. 4).

11. CALCULATIONS

Calculations are contained in the Appendices.

- Appendix A – Computer Software Validation & Verification
- Appendix B – ASME Code and Non-Code - Calculations
- Appendix C – Component Weights
- Appendix D – ASME Code - Computer Calculations
- Appendix E – Other Computer Calculations
- Appendix F – Thermal Stress Analysis of the Capsule Reactor Core Components

12. CONCLUSIONS

The calculations show that all components meet their respective code requirements for the specified design conditions and service levels.

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13. RECOMMENDATIONS

None.

14. ANALYSIS PLAN

This analysis plan was agreed to by the customer's representative (R. L. Bratton) at the beginning of the analysis efforts.

Objective:

Provide structural analysis in support of the AGC-1 experiment to meet the applicable requirements for its installation and operation in the Advanced Test Reactor (ATR) south flux trap.

Work Scope:

Evaluate the reactor penetration, the in-reactor capsule facility pressure boundary, and the in-capsule structural components.

Requirements (and SSC Category):

Reactor Vessel Penetration – ASME B&PV Code Section III, Class 1, 2001 Ed. w/2003 Addenda, (Safety Class)

Capsule Boundaries – ASME B&PV Code Section III, Class 3, 2001 Ed. w/ 2002 Addenda, (Low Safety Consequence)

Gas Lines and Hanger Rod Assembly (out-of reactor) - ASME B31.1, 1998 Ed., (Consumer Grade)

Loads environment and conditions as defined in the T&FR.

Performance Category (seismic loadings):

Performance Category 4 (PC-4, per T&FR).

Assumptions:

Thermal loadings to be provided by the project.

Controlling Documents:

INL Drawings 630427, 630428, 630429, 630430, and 630431 - all in draft form at this time.

Technical & Functional Requirements (T&FR) document – in draft form at this time.

Calculation Software:

ABAQUS/Standard Version 6.4-1, PipeStress Version 3.5.1 +026, and I-DEAS Version 10 (all currently validated and verified per MCP-3039).

Required Reviews:

Technical Checker (per MCP-2374) and Independent Peer Reviewer (Per MCP-2374, required for seismic calculations).

Deliverables:

Engineering Design File (EDF) report.

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15. REFERENCES

1 T&FR-XXX, *Functional and Operational Requirements for the AGC-1 Irradiation Test*, Draft.

2 ASME Boiler and Pressure Vessel Code, Section III, Division 1, *Subsection NB – Class 1 Components*, 2001 Ed. with 2003 Addenda, American Society of Mechanical Engineers.

3 ASME Boiler and Pressure Vessel Code, Section III, Division 1, *Subsection ND – Class 3 Components*, 2001 Ed. with 2002 Addenda, American Society of Mechanical Engineers.

4 ASME B31.1, *Power Piping*, 1998 Ed., American Society of Mechanical Engineers.

5 ASME Boiler and Pressure Vessel Code, Section II, *Part D – Material Properties*, 2001 Ed. with 2002 Addenda, American Society of Mechanical Engineers.

6 *Mechanical Properties of Artificial Graphites – A Survey Report*, ORNL-4327, December 1968, Oak Ridge National Laboratory.

7 R. J. Price, *Mechanical Properties of Graphite for High-Temperature Gas-Cooled Reactors: A Review*, General Atomic Report GA-A13524, 9/22/1975.

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9 Flow data provided by R. G. Ambrosek on June 2, 2005.

10 V. W. Gorman, *Recommended Interim Safe Shutdown Earthquake Criteria for ATR*, PG-T-89-012, May 1989.

11 U.S. Atomic Regulatory Commission, Regulatory Guide 1.60, *Design Response Spectra for Seismic Design of Nuclear Power Plants*, Rev. 1, December 1973.

12 ASME Boiler and Pressure Vessel Code, Code Case N-411-1, *Alternate Damping Values for Response Spectra Analysis of Class 1, 2, and 3 Piping*, Section III, Div. 1, 2/20/1986.

13 S. D. Snow, *Structural Evaluation of the ATR Irradiation Capsule Experiment (ICE) Test and Facility*, EDF TRA-ATR-1275, Rev. 0, Nov. 1997.

14 R. K. Blandford, *Structural Evaluation of the ATR Multiple Irradiation Capsule Experiment (MICE) Test Train, Facility and Support Equipment*, EDF-TRA-ATR-1512, Rev. 0, 10/1999.

15 ASME Boiler and Pressure Vessel Code, Section III, *Division 1 – Appendices*, 2001 Edition, American Society of Mechanical Engineers.

16 Payne, S. J., et al., *Development of Probabilistic Design Basis Earthquake (DBE) Parameters for Moderate and High Hazard Facilities at INEEL*, INEL/EXT-99-0075, Rev. 2, June 1, 2002.

17 T. A. Thatcher email of 1/22/2004, *Seismic Team (ICARE 35644) Draft Guidance*.

18 DOE Standard, *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities*, DOE-STD-1020-2002, January 2002.

19 S. R. Jensen email of 4/3/2006, *Updated Guidance on RTC Seismic Analysis*.

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Appendix A

Computer Software Validation & Verification

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- ABAQUS/Standard Version 6.4-1 (Ref. 16)
  -Tracking Number 125097
  -EDF-4549, *ABAQUS Version 6.4-1 Standard and Explicit Validation and Verification*, Feb. 2004
  - Computer Used: Tomcat
- I-DEAS 10 (Ref. 17)
  -Tracking Number 112379
  -EDF-3883, *Mechanical and Structural Engineering Software Validation for I-DEAS 10*, Mar. 2004
  -Computer Used: ZION
- PipeStress Version3.5.1+026 (Ref. 18)
  -Tracking Number 176056
  -EDF-5719, *Validation of PIPESTRESS Version 3.5.1+026 Piping Analysis Software on INL Computers ZION and MIRA*, Aug. 2005.
  -Computer Used: MIRA

Software Justification

ABAQUS, I-DEAS 10, and PipeStress were each used for this analysis because (1) they are readily available, and (2) they were designed and purchased to perform the type of analyses for which they were used herein.

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Appendix B

ASME Code & Non-Code - Calculations

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B1. Reactor Vessel Penetration Components (Class 1)

The reactor vessel penetration components for the Advanced Graphite Creep Experiment AGC-1 consists of the following items: one loop seal flange with four attachment bolts (3/4 in.-10UNC, or studs with nuts), and one top head seal plug.

The top head seal plug rests on a ledge within the reactor top head closure plate (Ref. drawings 120438 and 120446). Movement upward is impeded by the loop seal flange which is bolted to the reactor top head closure plate. The AGC-1 facility is welded to the seal plug on the in-reactor side. All reactor pressure boundary components (seal plug, loop seal flange and bolting) must meet the ASME B&PV Code, Section III, Class 1 requirements (Ref. B1).

B1.1 Top Head Seal Plug Evaluation

The seal plug is basically a 10-inch long 304 stainless steel bar, 6-1/2-inches maximum diameter, with a 1.39-inch diameter through hole. Design loadings on the seal plug are as follows:

(1) Load from AGC-1 facility assembly weight minus buoyancy (see Appendix C):
[the self-weight of the seal plug plus the weight in-reactor and out-of-reactor (hanger rod assembly) components, calculated at 347 lbs, minus the buoyancy of the in-vessel components, at 135 lbs, gives a total net weight acting on the seal plug of 204 lbs],

$W_{net} := 211 \cdot lbf$ — W_{net} = wet weight of facility (from weights calculation section - Appendix C)

(2) Load from reactor design pressure:

$P_d := 390 \cdot \frac{lbf}{in^2}$ — P_d = reactor design pressure

$D_{max} := 6.0 \cdot in$ — D_{max} = O.D. of reactor top head closure plate penetration for the seal plug

$F_{rp} := P_d \cdot \frac{\pi}{4} \cdot \left(D_{max}^2\right)$ — F_{rp} = force due to reactor design pressure on seal plug

$F_{rp} = 11027\, lbf$

(3) Load from loop seal flange attachment bolts:

$f_{torque} := 55 \cdot ft \cdot lbf$ — f_{torque} = torque on bolts (Ref.'s B2 & B3)

$D_{bolt} := 0.75 \cdot in$ — D_{bolt} = bolt O.D.

$F_{bolt} := \frac{f_{torque}}{0.2 \cdot D_{bolt}}$ — F_{bolt} = force per bolt

$F_{bolt} = 4400\, lbf$

B1.1.1 Check Ledge on Reactor Closure Plate and Seal Plug

Design Conditions: The dimensions of the overlap between the seal plug and the reactor top head penetration are as follows:

$D_{rth} := 6.0 \cdot in$ D_{rth} = reactor top head penetration diameter

$D_{spl} := 6.28 \cdot in$ D_{spl} = seal plug ledge outer diameter

The maximum bearing stress on the reactor top head penetration ledge is:

$$\sigma_{rledge} := \frac{W_{net} + 4 \cdot F_{bolt}}{\frac{\pi}{4} \cdot \left(D_{spl}^2 - D_{rth}^2\right)}$$

σ_{rledge} = bearing stress on reactor ledge

$$\sigma_{rledge} = 6595\,psi$$

(Note that the bearing stress due to weight and bolt preloading plus the reactor design pressure would be less than calculated above because the pressure force is upward directed.)

The allowable bearing stress (NB-3227.1) is the yield strength (S_y) of the reactor top head and seal plug material (both 304 stainless steel) at the design temperature (240 F), which is 23.9 ksi (Ref. Table 2 from report main body). The calculated bearing stress above is less than the allowable of 23.9 ksi. This indicates that the bearing stress in the reactor top head and seal plug is acceptable.

The seal plug must also be checked to assure that a ring of plug material (through the seal region) does not shear off under these design loads.

$t_{shear} := 2.75 \cdot in$ t_{shear} = thickness of seal plug from the reactor ledge through the sealing region

$$\tau_{plug} := \frac{W_{net} + 4 \cdot F_{bolt}}{\pi \cdot D_{rth} \cdot t_{shear}}$$

τ_{plug} = shear stress through seal plug

$$\tau_{plug} = 344\,psi$$

The allowable shear stress (NB-3227.2) is 60% of S_m (20 ksi as listed in Table 2 of the report main body), or 12 ksi. This allowable shear stress exceeds that calculated above.

:Top head seal plug ledge is acceptable for design conditions.

Service Levels A through C Conditions: Service Levels A through C conditions for the seal plug include increased reactor pressures only. Pressure loads would only reduce the loading on the plug/plate ledge.

:Top head seal plug ledge is acceptable for Service Levels A through C conditions.

Service Level D Conditions:
The Service Level D condition includes the specified ATR SSE event. The AGC-1 experiment components are not expected to see much more than zero period acceleration in the vertical direction (0.16g's). This would create vertical forces on the seal plug/closure plate that would be negligible in comparison to the loop seal flange attachment bolts preload. Horizontal seismic motion would be transferred directly to the reactor top head closure plate through the base of the seal plug. As far as fatigue is concerned, it will be shown in the loop seal flange evaluation that service temperature and normal pressure conditions and fluctuations are such that a fatigue evaluation is not necessary. This applies to the seal plug as well.

:Top head seal plug ledge is acceptable for Service Level D conditions.

B1.1.2 Overall Seal Plug Structure Evaluation

Design Conditions: The seal plug is a 4.75-inch to 6.5-inch diameter stainless steel bar, 10 inches long, with one 1.39-inch diameter centered through hole. The design loadings would create, in a worst case, compressive membrane stresses in the plug body of:

$D_{4.75} := 4.75 \cdot in$ $D_{4.75}$ = minimum diameter of seal plug

$D_{1.39} := 1.39 \cdot in$ $D_{1.39}$ = seal plug through hole diameter

$$\sigma_m := \frac{W_{net} + F_{rp} + 4 \cdot F_{bolt}}{\frac{\pi}{4} \cdot \left(D_{4.75}^2 - D_{1.39}^2\right)}$$

σ_m = compressive membrane stress

$$\sigma_m = 1780\,psi$$

The allowable membrane stress (NB-3221.1) is S_m, which is 20 ksi (per Table 2 of the main report. This is much greater than the calculated membrane stress above.

:Top head seal plug overall structure is acceptable for design conditions.

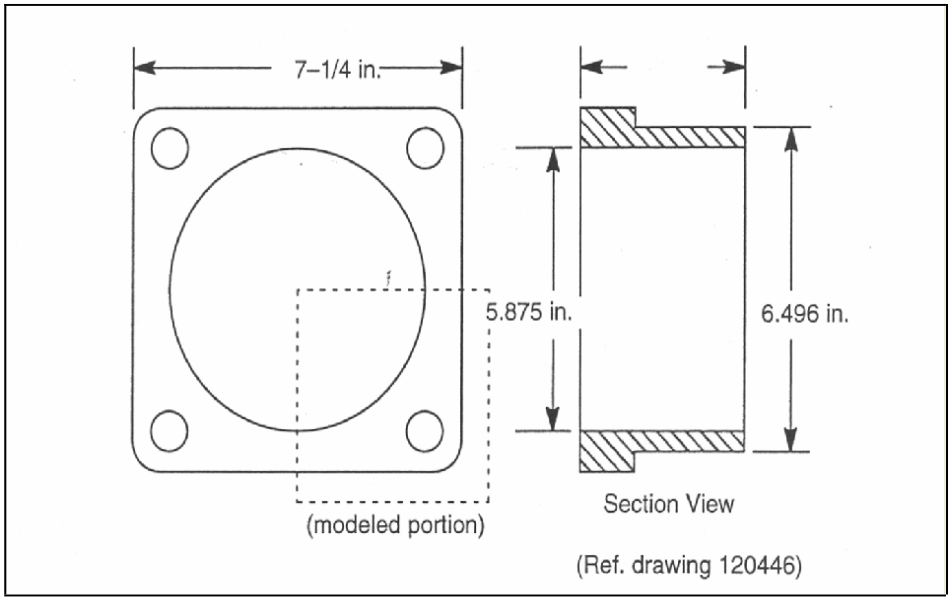
Service Level A through D Conditions: The seal plug will only see an increase in reactor pressure for Service Levels A through C conditions. However, that pressure increase (10% and 20%) will not significantly increase the design-calculated compressive membrane stress. The Service Level D event is the ATR seismic event. Since the seal plug is very sturdy in comparison to the in-vessel hanger rod extension/transition tube and capsule tube, any seismic loads that are carried by those in-vessel components will be carried as a much lower stress level in the seal plug. A detailed evaluation of the seal plug under seismic loads is not considered necessary. As far as fatigue is concerned, it will be shown in the loop seal flange evaluation that service temperature and normal pressure conditions and fluctuations are such that a fatigue evaluation is not required.

:Top head seal plug overall structure is acceptable for Service Level A through D conditions.

B1.2 Loop Seal Flange and Attachment Bolts Evaluation

B1.2.1 Loop Seal Flange Evaluation

The ASME Code, Section III, Subsection NB-3647 defines the requirements for the pressure design of flanged joints. However, the loop seal flange is not designed like the type of flanges that this section addresses. It expects regular piping-type flanges or blanks. The following sketch shows the configuration of the loop seal flange.



The loop seal flange sees reactor pressure by way of the seal plug as a "ring" load. It appears more appropriate to evaluate this loop seal flange under the rules of NB-3220 "Stress Limits for Other than Bolts."

Design Conditions: The design loadings on this flange are due to the reactor pressure load of 390 psig transmitted through the top head seal plug, minus the weight of the ACG-1 facility assembly, plus the preload torques on the flange bolts. That gives a total load of:

$F_{flange} := F_{rp} - W_{net} + 4 \cdot F_{bolt}$ F_{flange} = total design load on flange

$F_{flange} = 28416\,lbf$

Reference B2 employed a finite element model to evaluate this loop seal flange under a ring load of 33,167 lbf. The resulting maximum stress intensity due to primary bending plus peak stresses was 12,400 psi. Because that evaluation was performed using linear analysis methods, the equivalent stress in the loop seal flange used for the AGC-1 experiment would be:

$\sigma_f := \frac{F_{flange}}{33167 \cdot lbf} \cdot 12400 \cdot psi$ σ_f = primary bending plus peak stress in flange

$\sigma_f = 10624\,psi$

The ASME Code allows for the basic stress intensity at 20 ksi (Table 2 of report main body) for general primary membrane stress intensity alone (NB-3221.1) The allowable for membrane plus bending is even higher ($1.5S_m$ giving 30 ksi, NB-3221.3) This flange experiences a maximum stress intensity level that is below the allowable value under design conditions.

:Loop seal flange is acceptable for design conditions.

Service Level A Conditions: Weight and pressure loadings during normal operation are enveloped by the design conditions. Thermal growth of components is not impeded by the structure, so Service Level A thermal conditions do not affect the flange. However, fatigue concerns must be evaluated.

Fatigue Investigation

The loop seal flange is governed by the rules for Class 1 components. However, a full fatigue analysis does not need to be performed provided that it can be shown that the requirements of NB-3222.4(d) are satisfied. Those requirement are:

<u>Atmospheric to Service Pressure Cycle</u>

$S_m := 20000 \cdot psi$ S_m = allowable design stress intensity

$S_a := 3 \cdot S_m$ S_a = alternating stress

$S_a = 60000\,psi$

$N_{allowed} := 15000$ — $N_{allowed}$ = allowed lifetime cycles (Fig. I-9.2.1)

$N_{actual} := 18 \cdot \frac{cycles}{year} \cdot 14 \cdot year$ — N_{actual} = actual cycles = 252 cycles

For conservatism, use N_{actual} = 1000 cycles.

:Allowed cycles are much greater than the actual cycles. OK.

Normal Service Pressure Fluctuation

$S_{a10_6} := 28000 \cdot psi$ — S_{a10_6} = stress at 10^6 service cycles

$P_f := \frac{P_d}{3} \cdot \frac{S_{a10_6}}{S_m}$ — P_f = pressure fluctuation

$P_f = 182\,psi$

Normal service pressure fluctuation will not exceed 182 psi. OK.

Temperature Difference - Startup and Shutdown

$S_{a1000} := 80000 \cdot psi$ — S_{a1000} = alternating stress at 1000 service cycles (Fig. I-9.2.1)

$E := 27400000 \cdot psi$ — E = modulus of elasticity at 240 F (Table 2 of main report)

$\alpha := 9.23 \cdot 10^{-6}$ — α = instantaneous thermal expansion coefficient (in./in./F)

$\Delta T_{ss} := \frac{S_{a1000}}{2 \cdot E \cdot \alpha}$ — ΔT_{ss} = maximum allowed temperature difference between any two adjacent points during startup or shutdown

$\Delta T_{ss} = 158\ F$

Maximum temperature difference will not exceed 158 deg. F between two adjacent points. OK.

Temperature Difference - Normal Service

$\Delta T_{ns} := \frac{S_{a10_6}}{2 \cdot E \cdot \alpha}$ — ΔT_{ns} = maximum allowed temperature difference between any two adjacent points during normal service

$\Delta T_{ns} = 55\ F$

Maximum temperature difference between any two adjacent points will not exceed 55 deg. F. OK.

Temperature Difference - Dissimilar Materials

Not applicable - no dissimilar materials. OK.

Mechanical Loads

Mechanical loads exclude pressure, but do include piping reactions. This design is such that the flange will not carry the piping loads (they are transferred through the top head seal plug into the reactor top head closure plate directly). The only other load that the flange will carry is due to the bolt preload torque - which is constant (not cyclic). OK.

:Loop seal flange does not require analysis for cyclical service, and is therefore acceptable for Service Level A conditions.

Service Level B Conditions: Service Level B conditions are only slightly increased over design conditions due to the specified 10% overpressure. However, this overpressure only increases the total flange load by 4%. This is considered acceptable without further evaluation. Service Level B fatigue conditions are enveloped by the Service Level A fatigue evaluation.

:Loop seal flange is acceptable for Service Level B conditions.

Service Level C Conditions: Service Level C conditions include an overpressure event of 468 psi with a design frequency of 10 times every 20 years. This is a 20% pressure increase over design, but only 8% increase in the total flange load. Flange stresses will only increase by 8% because of this overpressure, which will still be below the design allowable stress values (Service Level C stress limits are at or greater than design limits). Service Level C stress levels in the flnage are therefore acceptable. Note that the fatigue evaluation under Service Level A conditions allowed for a range of pressure fluctuations of 182 psi. This Service Level C overpressure event falls within that allowable pressure fluctuation range.

:Loop seal flange is acceptable for Service Level C conditions.

Service Level D Conditions: The Service Level D conditions include the ATR seismic event. Because of the fit between the seal plug and the reactor head, horizontal and moment loadings will not be transferred into the seal flange. The calculation in Appendix D resulted in negligibly small upward vertical loadings on the seal plug, and thus the flange.

:Loop seal flange is acceptable for Service Level D conditions.

B1.2.2 Loop Seal Flange Attachment Bolts Evaluation

Design Conditions: The ASME Code (NB-3231) indicates that the stresses in the bolts (3/4-in.-10UNC) due only to the design pressure load must be less than the basic allowable stress (8000 psi at 240 deg. F, from Table 2 in main report). (Appendix E of the ASME Code is not applicable to this loop seal flange since the flange is not required to compress a gasket - seal is maintained by o-rings on the seal plug.) Note that these may not be bolts, but studs with nuts. If existing studs are used, then the stud material is still expected to be 304 SST as noted in the report main body. The nuts would then be SA-194 Grade 8 (see Ref. 22 listed in Reference B2). The following evaluation will apply to both bolts and studs with nuts. The design pressure will create the following primary stress:

$A_{bolt} := 0.334 \cdot in^2$

A_{bolt} = tensile area of 3/4-inch bolt

$$\sigma_{bolt_design} := \frac{\frac{F_{rp}}{4}}{A_{bolt}}$$

σ_{bolt_design} = primary stress in bolts under design pressure, where the tensile area of a 3/4-inch bolt is 0.334 in.^2

$$\sigma_{bolt_design} = 8254\,psi$$

The above design stress is 3% above the allowable stress value of 8000 psi. This will be considered acceptable. (This is consistent with the conclusions of Ref. B2.) The normal operating temperature of these bolts will be no more than 125 deg. F, at which temperature the allowable stress is 10000 psi.

:Loop seal flange bolts are considered acceptable for Design Conditions.

Service Level A Conditions: The ASME Code (NB-3232) indicates that the loop seal flange bolts must be able to carry actual service loads due to bolt preload, weight, and pressure with stresses below two times the basic allowable stress. The service loadings on the bolts, and the resulting average tensile stresses are:

$F_{bolt} = 4400\,lbf$

F_{bolt} = preload in each bolt, calculated previously

Calculate the load due to pressure:

$L_b := 1.25 \cdot in$

L_b = length of bolt not engaged in threads (1.25-inches flange thickness)

$$K_b := A_{bolt} \cdot \frac{E}{L_b}$$

K_b = stiffness of bolt

$$A_m := \frac{1}{4} \cdot \frac{\pi}{4} \cdot \left(6.497^2 - 5.875^2\right) \cdot in^2$$

A_m = area of narrow part of flange

$$A_m = 1.511\,in^2$$

$L_m := 1.25 \cdot in$

L_m = length of flange under bolt

$$K_m := A_m \cdot \frac{E}{L_m}$$

K_m = stiffness of flange

$E = 27400000\,psi$

$$F_{rp_bolts} := \frac{F_{rp}}{4} \cdot \left(\frac{K_b}{K_b + K_m}\right)$$

F_{rp_bolts} = load actually transferred into each bolt

$$F_{rp_bolts} = 499\,lbf$$

$$F_{bolt_total} := F_{bolt} + F_{rp_bolts} + \frac{-W_{net}}{4}$$ F_{bolt_total} = maximum bolt load per bolt

$F_{bolt_total} = 4846\,lbf$ Per Bolt

$$\sigma_{bolt_Level_A} := \frac{F_{bolt_total}}{A_{bolt}}$$ $\sigma_{bolt_Level_A}$ = Level A stress in each bolt

$\sigma_{bolt_Level_A} = 14510\,psi$

The allowable stress level of 2 times S_m (at 240 deg. F), or 2 * 8000 psi = 16,000 psi, exceeds the above Service Level A stress.

:Loop seal flange attachment bolts with a 55 ft.-lbf preload torque are acceptable under Service Level A conditions.

Service Level A Fatigue Evaluation: The ASME Code (NB-3232.3) indicates that the bolts that are installed on components that meet all the conditions of NB-3222.4(d) require no fatigue evaluation. The above flange analysis shows that those conditions are met.

:Service Level A fatigue conditions are satisfied.
:Loop seal flange bolts (or studs with nuts) are acceptable for Service Level A conditions.

Service Level B Conditions: Service Level B conditions are the same as for Level A but with the specified 10% overpressure (429 psig). This will increase the bolt stresses as caculated next:

$$F_{bolt_Level_B} := F_{bolt} + F_{rp_bolts} \cdot \frac{429}{390} + \frac{-W_{net}}{4}$$

$F_{bolt_Level_B} = 4896\,lbf$ $F_{bolt_Level_B}$ = Level B forces in bolts

$$\sigma_{bolt_Level_B} := \frac{F_{bolt_Level_B}}{A_{bolt}}$$ $\sigma_{bolt_Level_B}$ = Level B stress in each bolt

$\sigma_{bolt_Level_B} = 14659\,psi$

The above Level B stress in the bolts is below the Code allowable of 16,000 psi (NB-3233).

The addition of 30 cycles of 429 psi per year for a 14 year life is insignificant as far as fatigue is concerned.

:Loop seal flange bolts (or studs with nuts) are acceptable for Service Level B conditions.

Service Level C Conditions: Service Level C conditions include a reactor overpressure event of 468 psi designed to occur 10 times in a 20 year period This will increase the bolt stresses by:

$$F_{bolt_Level_C} := F_{bolt} + F_{rp_bolts} \cdot \frac{468}{390} + \frac{-W_{net}}{4}$$

$$F_{bolt_Level_C} = 4946.119\,lbf$$

$F_{bolt_Level_C}$ = Level B forces in bolts

$$\sigma_{bolt_Level_C} := \frac{F_{bolt_Level_C}}{A_{bolt}}$$

$\sigma_{bolt_Level_C}$ = Level C stress in each bolt

$$\sigma_{bolt_Level_C} = 14809\,psi$$

The above Level C stress in the bolts is below the Code allowable of 16,000 psi (NB-3234).

The addition of 10 cycles of 468 psi per year for a 14 year life is insignificant as far as fatigue is concerned.

:Loop seal bolts (or studs with nuts) are acceptable for Service Level C conditions.

Service Level D Conditions: Service Level D conditions include the specified ATR seismic event. This event should not load the flange bolts since the piping loads are transferred directly into the reactor upper head closure plate through the seal plug.

:Loop seal flange bolts (or studs with nuts) are acceptable for Service Level D conditions.

:Top head closure assembly meets the ASME Code structural requirements.

B2. Capsule Boundary Components (Class 3)

B2.1 Check Component Minimum Thicknesses

The pressure boundary of the in-vessel components include the hanger rod extension and transition tubes, the funnel transition tube, the transition funnel, the capsule facility body, and the bottom cap. A check for minimum thickness on these components will be performed next. (A maximum of 200 psig internal and 390 psig external design pressures are defined for these components.)

B2.1.1 Check Hanger Rod Extension & Transition Tubes, and the Transition Funnel Thickness

Because the design external pressure is so much larger than the internal pressure, it is suspected that external pressure will control the design and will therefore be checked first.

Design Conditions - External Pressure: The hanger rod extension & transition tubes and the transition funnel are made of 304 stainless steel. Following the requirements of the ASME Code, ND-3133.3 (Ref. B4, as directed by ND-3641.2) for tubular products under external pressure:

$D_{o_hrt} := 5.00 \cdot in$ — D_{o_hrt} = outside diameter of hanger rod extension & transition tubes, funnel transition tube

$t_{hrt} := 0.188 \cdot in$ — t_{hrt} = nominal thickness of these tubes

$\frac{D_{o_hrt}}{t_{hrt}} = 26.5957$ — Diameter-to-thickness ratio >10

$L_{hret} := 108.15 \cdot in$ — L_{hret} = maximum unsupported length of hanger rod extension tube

$L_{hrtt} := 12 \cdot in$ — L_{hrtt} = maximum unsupported length of hanger rod transition tubes (funnel transition tube enveloped by the transition tubes)

$\frac{L_{hret}}{D_{o_hrt}} = 21.63$ — Length-to-diameter ratio for extension tube

$\frac{L_{hrtt}}{D_{o_hrt}} = 2.4$ — Length-to-diameter ratio for transition tubes

$A_{hret} := 0.0017$ — A_{hret} from Figure G (Section II, Part D, extension tube)

$A_{hrtt} := 0.0045$ — A_{hrtt} from Figure G (transition tubes)

$B_{hret} := 9500 \cdot psi$ — B_{hret} from Figure HA-1 (Section II, Part D, @ 240 F., extension tube)

$B_{hrtt} := 11500 \cdot psi$ — B_{hrtt} from Figure HA-1 (Section II, Part D, transition tubes)

The "B" value for the extension tube, because of its length, is lower than for transition tubes. Only the hanger rod extension tube and its B_{hret} value will be used now.

$$P_{a_hret} := \frac{4}{3} \cdot \frac{B_{hret}}{\frac{D_{o_hrt}}{t_{hrt}}}$$

P_{a_hrt} = maximum allowable external pressure on hanger rod extension tube

$$P_{a_hret} = 476\,psi$$

The above shows that a 5-inch diameter tube made of 304 stainless steel, 108 inches long with a 0.188-inch thick wall, can support 476 psig external pressure and satisfy the ASME Code for Class 3 components. This is greater than the design pressure of 390 psig. OK.

Check the hanger rod extension & transition tubes and the funnel transition tube as cylinders under compressive load due to the external design pressure on the bottom cap and transition funnel (ND-3133.6).

Two equations must be checked:

(1) Calculate the compressive stress and compare to the design allowable stress level.

$$F_c := P_d \cdot \frac{\pi}{4} \cdot D_{o_hrt}^2 \qquad F_c = 7658\,lbf$$

F_c = compressive force on tubes due to design pressure

$$\sigma_{hrt_comp} := \frac{F_c}{\frac{\pi}{4} \cdot \left[D_{o_hrt}^2 - \left(D_{o_hrt} - 2 \cdot t_{hrt}\right)^2\right]}$$

σ_{hrt_comp} = compressive stress on tubes

$$\sigma_{hrt_comp} = 2694\,psi$$

(The above is conservative since the design pressure acts only on the transition funnel, and is 100 psig lower on the bottom cap due to the pressure drop across the core.)

The above calculated compressive stress due to the external design pressure on the hanger rod extension & transition tubes and the funnel transition tube is below the Class 3 allowable stress S of 20 ksi (304 SST) at 240 deg. F from Table 2 of the main report body). OK

(2) Use tables:

$$A_{hrt_c} := \frac{0.125}{\frac{\frac{D_{o_hrt}}{2}}{t_{hrt}}} \qquad A_{hrt_c} = 0.009$$

A_{hrt_c} value used to enter external pressure table

$$B_{hret_c} := 12300 \cdot psi$$

B_{hret_c} from Table HA-1 (Section II, Part D, extension tube 304 SST)

The compressive stress in these tubes is less than the B_{hret_c} value calculated above. OK

:Hanger rod extension & transition tubes and funnel transition tube with a 0.188-inch wall thickness are acceptable for the compressive stresses caused by the design pressure.

Design Conditions - Internal Pressure: Following the requirements of the ASME Code, ND-3641.1 for piping under internal pressure, the minimum thickness is calculated as follows:

$E_{joint} := 0.80$ — E_{joint} = weld joint efficiency per Table 3613.4-1

$y := 0.4$ — y = required coefficient

$P_{des_int} := 200 \cdot psi$ — P_{des_int} = internal design pressure

$S_{c3L} := 20000 \cdot psi$ — S_{c3L} = allowable Class 3 stress for 304L pipe

$$t_{min} := \frac{P_{des_int} \cdot D_{o_hrt}}{2 \cdot \left(S_{c3L} \cdot E_{joint} - P_{des_int} \cdot y\right)}$$

t_{min} = minimum thickness to support the internal design pressure

$$t_{min} = 0.031\,in$$

Clearly, the internal pressure is adequately carried by the 0.188-inch thick extension and transition tubes.

:Hanger rod extension & transition tubes and funnel transition tube with a 0.188-inch wall thickness are acceptable for design internal pressure conditions.

In addition to the internal pressure load, the maximum line cylinder load of 6 * 600 lbf, or 3600 lbf, will be applied to these tubes as a tensile load. If this occurs with the external design pressure, it will be entirely negated by that compressive load. Alone, this 3600 lbf tensile load will create the following stress in the transition tubes:

$$\sigma_{t_hrtt} := \frac{3600 \cdot lbf}{\pi \cdot D_{o_hrt} \cdot t_{hrt}} \qquad \sigma_{t_hrtt} = 1219\,psi$$

σ_{t_hrtt} = tensile stress in hanger rod transition tubes under the maximum line cylinder loading

The above tensile load is very low, expecially when compared to the basic Class 3 allowable stress of 20 ksi for 304 SST materials.

:Hanger rod and funnel transition tubes with a 0.188-inch wall thicknes are acceptable for the maximum cylinder line loads.

Service Level A Conditions: The Service Level A conditions are enveloped by the design conditions.

:Hanger rod extension and transition tubes with a 0.188-inch wall thickness meet the Level A conditions.

Service Level B Conditions: The Service Level B conditions only include a 10% increase in external design pressure, or 429 psig. However, the design calculations showed that the allowable external pressure to prevent buckling was:

$P_{a_hret} = 476\,psi$

which is greater than the 429 psig Level B condition.

:Hanger rod extension and transition tubes with a 0.188-inch wall thickness meet the Level B conditions.

Service Level C Conditions: The Service Level D conditions only include a 20% increase in external design pressure, or 468 psig. This pressure is also less than the allowable external pressure calculated for design conditions.

:Hanger rod extension and transition tubes with a 0.188-inch wall thickness meet the Level C conditions.

Service Level D Conditions: The results of the Service Level D conditions evaluation on the hanger rod extension and transition tubes will be discussed in Appendix D.

B2.1.2 Check Capsule Facility Body Thickness

Because the design external pressure is so much larger than the internal pressure, it is suspected that external pressure will control the design and will therefore be checked first.

Design Conditions - External Pressure: The capsule facility body is made of 304 stainless steel, about 150 inches long, and with an outer diameter of 2.5 inches. About half of the length has a wall thickness of 0.120 inches while the other half has a thickness of 0.188 inches but with thirteen grooves on the inner diameter (referred to as the "in-core pressure boundary tube"). The minimum thickness of this grooved tube is 0.115 inches. It will be conservative to use the minimum thickness of 0.115 inches for the following calculations. Following the requirements of the ASME Code, ND-3133.3 (as directed by ND-3641.2) for tubular products under external pressure:

$D_{o_cfb} := 2.500 \cdot in$ — D_{o_cfb} = outside diameter of capsule facility body

$t_{cfb} := 0.115 \cdot in$ — t_{cfb} = minimum thickness of capsule facility body

$\frac{D_{o_cfb}}{t_{cfb}} = 21.7391$ — Diameter-to-thickness ratio

$L_{cfb} := 150 \cdot in$ — L_{cfb} = maximum unsupported length of capsule facility body - assumed unsupported on its entire length - very conservative.

$\frac{L_{cfb}}{D_{o_cfb}} = 60$ — Length-to-diameter ratio

$A_{cfb} := 0.0025$ — A_{cfb} from Figure G (Section II, Part D)

$B_{cfb} := 10500 \cdot psi$ — B_{cfb} from Figure HA-1 (Section II, Part D)

$$P_{a_cfb} := \frac{4}{3} \cdot \frac{B_{cfb}}{\frac{D_{o_cfb}}{t_{cfb}}}$$

P_{a_cfb} = maximum allowable external pressure on capsule facility body

$$P_{a_cfb} = 644\,psi$$

The above maximum allowable external pressure on the capsule facility body exceeds the ATR design pressure of 390 psig.

:Capsule facility body minimum thickness is sufficient for carrying the design pressure as an external load.

Check the capsule facility as a cylinder under compressive load due to the design pressure on the bottom cap (ND-3133.6).

Two equations must be checked:
(1) Calculate the compressive stress and compare to the design allowable stress level.

$$F_{c_cfb} := \left(P_d - 100 \cdot psi\right) \cdot \frac{\pi}{4} \cdot D_{o_cfb}^{\ 2} \qquad F_{c_cfb} = 1424\,lbf$$

F_{c_cfb} = compressive force on capsule facility body

$$\sigma_{cfb_comp} := \frac{F_{c_cfb}}{\frac{\pi}{4} \cdot \left[D_{o_cfb}^{\ 2} - \left(D_{o_cfb} - 2 \cdot t_{cfb}\right)^2\right]}$$

σ_{cfb_comp} = compressive stress

$$\sigma_{cfb_comp} = 1652\,psi$$

The above calculated compressive stress due to the design pressure on the capsule facility body lower cap is below the Class 3 allowable stress S of 20 ksi (304 SST) at 240 deg. F (from Table 2 of the main report body). OK

(2) Use tables:

$$A_{cfb_c} := \frac{0.125}{\frac{\frac{D_{o_cfb}}{2}}{t_{cfb}}}$$

A_{cfb_c} value used to enter external pressure table

$$A_{cfb_c} = 0.0115$$

$$B_{cfb_c} := 12000 \cdot psi$$

B_{cfb_c} from Table HA-1 (Section II, Part D)

The compressive stress in the capsule facility body is less than the B_{cfb_c} value calculated above. OK

:Capsule facility body is acceptable for the compressive stresses caused by the design external pressure.

Design Conditions - Internal Pressure: Following the requirements of the ASME Code, ND-3641.1 for piping under internal pressure, the minimum thickness is calculated as follows:

$E_{joint} = 0.8$ — E_{joint} = weld joint efficiency per Table 3613.4-1

$y = 0.4$ — y = required coefficient

$P_{des_int} = \blacksquare\,psi$ — P_{des_int} = internal design pressure

$S_{c3} := 20000 \cdot psi$ — S_{c3} = allowable Class 3 stress for 304 pipe

$$t_{min_i} := \frac{P_{des_int} \cdot D_{o_hrt}}{2 \cdot \left(S_{c3} \cdot E_{joint} - P_{des_int} \cdot y\right)}$$

t_{min_i} = minimum thickness to support the internal design pressure

$$t_{min_i} = 0.031\,in$$

Clearly, the internal pressure is adequately carried by capsule facility body.

:Capsule facility body is acceptable for design internal pressure conditions.

Note that the line cylinders, discussed later, may apply a maximum combined tensile load of 600 lbf * 6 cylinders, or 3600 lbf, to the capsule facility body. If this maximum line cylinder load occurs with the external pressure load, it will entirely negate that axial compressive load. If the line cylinder maximum load occurs alone, the resulting tensile stresses will exist in the capsule facility body:

$$\sigma_{cfb_cylinders} := \frac{3600 \cdot lbf}{\pi \cdot D_{o_cfb} \cdot t_{cfb}}$$

$\sigma_{cfb_cylinders}$ = tensile stress in capsule facility body under the line cylinder maximum load

$$\sigma_{cfb_cylinders} = 3986\,psi$$

The above maximum tension stress in the capsule faciltiy body under the maximum line cylinder loading is well below the 20 ksi Class 3 basic allowable stress for the 304 SST material.

:Capsule facility body is accepable under the maximum line cylinder tension loading.

Service Level A Conditions: The Service Level A conditions are enveloped by the design conditions.

:Capsule facility body meets the Level A conditions.

Service Level B Conditions: The Service Level B conditions only include a 10% increase in external design pressure, or 429 psig. However, the design calculations showed that the allowable external pressure to prevent buckling was:

$P_{a_cfb} = 644\,psi$

which is greater than the 429 psig Level B condition.

:Capsule facility body meets the Level B conditions.

Service Level C Conditions: The Service Level D conditions only include a 20% increase in external design pressure, or 468 psig. This pressure is also less than the allowable external pressure calculated for design conditions.

:Capsule facility body meets the Level C conditions.

Service Level D Conditions: The results of the Service Level D conditions evaluation on the capsule facility body will be discussed in Appendix D.

B2.1.3 Check Transition Funnel Thickness

The 304 stainless steel transition funnel has a 5-inch outer diameter on one end and a 2.5-inch diameter on the other end, is 0.225-inches thick, and is 5.375-inches long. Because of the hanger rod alignment plate, welded at the large end of this funnel, the funnel is supported against buckling on that end. The funnel thickness (0.225-inch) also exceeds that of the hanger rod tubes (3/16-inch) and the capsule facility body (0.120-inch). Therefore, the transition funnel is expected to support a much greater external pressure load than the hanger rod tubes and the capsule facility body. However, the following calculation will assume no support at the large end of the funnel.

Design Conditions - External Pressure: The transition funnel is made of 304 stainless steel. Following the requirements of the ASME Code, ND-3133.4(e) for conical sections under external pressure:

$D_{lf} := 5.000 \cdot in$ — D_{lf} = diameter of funnel large end

$t_{lf} := 0.225 \cdot in$ — t_{lf} = nominal thickness of funnel

$\frac{D_{lf}}{t_{lf}} = 22.2222$ — Diameter-to-thickness ratio

$L_{lf} := 5.375 \cdot in$ — L_{lf} = length of funnel.

$\frac{L_{lf}}{D_{lf}} = 1.075$ — Length-to-diameter ratio

$A_{lf} := 0.013$ — A_{lf} from Figure G (Section II, Part D)

$B_{lf} := 125000 \cdot psi$ — B_{lf} from Figure HA-1 (Section II, Part D)

$P_{a_lf} := \frac{4}{3} \cdot \frac{B_{lf}}{\frac{D_{lf}}{t_{lf}}}$ — P_{a_lf} = maximum allowable external pressure on transition funnel

$P_{a_lf} = 7500\,psi$

The above maximum allowable external pressure on the transition funnel exceeds the ATR design pressure.

:Transition funnel design is sufficient for carrying the design external pressure.

Design Conditions - Internal Pressure: The transition funnel must have the required thickness for the internal design pressure, as calculated using ASME Code, ND-3324.9:

$$\alpha_f := \tan\left(\frac{\frac{4.550-2.050}{2}}{5.375}\right) \qquad \alpha_f = 13.5701\,\text{deg}$$

α_f = angle of funnel

$P_{des_int} = 200\,\text{psi}$ — P_{des_int} = internal design pressure

$S_{c3L} = 20000\,\text{psi}$ — S_{c3L} = Class 3 allowable stress for 304

$E_{joint} = 0.8$ — E_{joint} = joint efficiency

$$t_{c_int} := \frac{P_{des_int} \cdot D_{lf}}{2 \cdot \cos(\alpha) \cdot \left(S_{c3L} \cdot E_{joint} - 0.6 \cdot P_{des_int}\right)}$$

t_{c_int} = required thickness for internal pressure

$$t_{c_int} = 0.031\,\text{in}$$

The above thickness required for carrying the internal design pressure is well below the funnel thickness of 0.225-in.

:Transition funnel design is acceptable for design internal pressure conditions.

Note that the maximum load of the line cylinders of 6 * 600 lbf, or 3600 lbf, will also be carried through the funnel. The previous sections showed that the capsule facility body and the hanger rod tubes carried that load with low resulting stresses. The funnel, which is thicker than the attaching tubes, will also carry that load with low resulting tensile stresses. No further calculations will be performed on the funnel under the line cylinder loads.)

Service Level A Conditions: The Service Level A conditions are enveloped by the design conditions.

:Transition funnel meets the Level A conditions.

Service Level B Conditions: The Service Level B conditions only include a 10% increase in external design pressure, or 429 psig. However, the design calculations showed that the allowable external pressure to prevent buckling was:

$P_{a_lf} = 7500\,\text{psi}$

which is greater than the 429 psig Level B condition.

:Transition funnel meets the Level B conditions.

Service Level C Conditions: The Service Level D conditions only include a 20% increase in external design pressure, or 468 psig. This pressure is also less than the allowable external pressure calculated for design conditions.

:Transition funnel meets the Level C conditions.

Service Level D Conditions: The results of the Service Level D conditions evaluation on the transition funnel will be discussed in Appendix D.

B2.1.4 Check Capsule Bottom Cap Thickness

The bottom cap is solid 304 stainless steel, and clearly very stout when compared to the capsule facility body to which it is attached. Thickness is considered acceptable without further calculations.

B2.2 Check Component Welds

The in-vessel components are welded together at several locations: hanger rod extension tube to the seal plug, hanger rod extension tube to the hanger rod transition tube, transition tubes together, hanger rod transition tube to the funnel transition tube, funnel transition tube to transition funnel, transition funnel to capsule facility body, capsule facility body welds, capsule facility body to end cap. NB-3661 indicates that because these are piping welds, that the requirements of NB-4200 are in force with girth butt welded joints being either type 1, 2, or 3 (ND-4245).

B2.2.1 Weld: Seal Plug-to-Hanger Rod Extension Tube

The weld that attaches the hanger rod extension tube to the seal plug is identified as a full penetration groove weld with a 1/4-inch fillet cap (Dwg. 630430). This weld could be viewed as a single butt welded joint with the use of a backing ring (Type 2 per ND-4245, albeit a huge backing ring) with an additional fillet weld. This is considered an acceptable Class 3 weld.

B2.2.2 Welds: Transition Tubes

The weld that attaches the hanger rod extension tube to the first transition tube, the weld between transition tubes, and the weld between the funnel transition tube and the transition funnel, are identified as full penetration groove welds (Dwg. 630430) ground flush. These welds are Type 2 welds per ND-4245 because of the built-in backing provided by the upper cylinder mounting plates and the push rod alignment plates that span these joints. These are considered acceptable Class 3 welds.

B2.2.3 Weld: Transition Funnel-to-Capsule Facility Body

The weld that attaches the transition funnel to the capsule facility body is identified as a full penetration groove weld (Dwg. 630430) ground flush. This weld is a Type 3 weld per ND-4245 because of no built-in backing. This is considered an acceptable Class 3 weld.

B2.2.4 Weld: Capsule Facility Body-to-End Cap

The weld that attaches the capsule facility body to the end cap is identified as a full penetration groove weld (Dwg. 630430) ground flush. This weld is a Type 2 weld per ND-4245 because of the built-in backing provided as part of the end cap. This is considered an acceptable Class 3 weld.

B2.2.5 Welds: Capsule Facility Body

The weld that connects two pieces of the capsule facility body at the lowest hanger rod alignment plate is a full-penetration groove weld (Dwg. 630430) ground flush. This weld is a Type 2 weld per ND-4245 because of the built-in backing provided by the alignment plate that spans this joint. This is considered an acceptable Class 3 weld.

B2.3 Calculate Flow-Induced Loads

The capsule facility body will see reactor coolant flow in cross flow and paralled flow as follows.

B2.3.1 Coolant Cross Flow

Coolant flow occurs in a cross flow orientation from the top of the core to a maximum level of 4.5 feet above the core, at a rate of 5.5 feet/second (Ref.'s B5 & B6). However, the capsule facility body is within the chopped dummy in-pile tube in that region. [The chopped dummy in-pile tube (Ref. Dwg. 443027) begins 2 inches above the locater tie (which is at 4-feet and 7-inches above the top of the core) and passes through the 4-ft. long core section and on another 12 feet.] The chopped dummy in-pile tube is a 3-inch Sch. 160 aluminum pipe, machined to include external fins and through slots, as well as other features. It is expected that any loading due to coolant cross flow on the chopped dummy in-pile tube will be supported by the tube itself, and that transfer of any such loading to the AGC-1 capsule facility body will be negligibly small.

:Loading on the capsule facility body due to coolant cross flow is negligible.

B2.3.2 Coolant Parallel Flow

Coolant flow will occur between the outside of the AGC-1 capsule facility body and the inside diameter of the chopped dummy in-pile tube in a parallel flow orientation. This will create two loadings on the capsule facility body: transverse loading due to vibration, and flow drag.

Vibration: The radial gap between the capsule facility body and the chopped dummy in-pile tube is 0.062-inches. (Actually, as far as the capsule body is concerned, spacers on the body will eliminate the gap at regular intervals.) The in-vessel portion of this experiment (hanger rod extension and transition tubes and the capsule facility body) is about 24-1/2 feet long and is suspended from the top head seal plug. In this configuration, the assembly looks like a very long cantilever beam fixed at the top end and free until it enters the chopped dummy in-pile tube. At that point, the capsule facility body is regularly supported in all transverse directions, with a 0.062-inch radial gap between supports. This small gap will limit the vibration potential of the assembly due to parallel-flowing coolant and the resulting stresses to negligible levels.

:Vibration due to parallel flow is not considered a problem.

Flow Drag: The coolant flowing parallel to the capsule facility body will create a drag force. The magnitude of that force will be estimated as follows (Ref. B7):

$\rho_c := 9.34 \cdot 10^{-5} \cdot \frac{lbf \cdot sec^2}{in^4}$ — ρ_c = mass density of coolant (at 240 F under pressure)

$V_c := 27.1 \cdot \frac{ft}{sec}$ — V_c = velocity of coolant (Ref. B8)

$L_{total} := 134.75 \cdot in$

L_{total} = total length of capsule facility body subject to parallel flow (57 in. above core, 48 in. through core, 29.75 in. below core)

$\mu_c := 3.472 \cdot 10^{-8} \cdot lbf \cdot \frac{s}{in^2}$

μ_c = dynamic viscosity of coolant (liquid at 240 F)

$R_{el} := \frac{\rho_c \cdot V_c \cdot L_{total}}{\mu_c}$

R_{el} = Reynold's number

$R_{el} = 117881722$

A Reynold's number of less than $5x10^5$ is laminar in flow, turbulent in flow if greater. The Reynold's number calculated is clearly turbulent.

$C_D := \frac{0.074}{R_{el}^{0.2}}$

C_D = drag coefficient (Ref. B7, Eqn. 7.18)

$C_D = 0.0018$

$A_D := \pi \cdot D_{o_cfb} \cdot L_{total}$

A_D = drag area (surface area of capsule body)

$A_D = 1058 in^2$

$F_{Drag} := \frac{1}{2} \cdot C_D \cdot \rho_c \cdot V_c^2 \cdot A_D$

F_{Drag} = drag force

$F_{Drag} = 9.4 lbf$

The above flow drag force will create the following tensile stress in the capsule facility body:

$\sigma_{Drag} := \frac{F_{Drag}}{\frac{\pi}{4} \cdot \left[D_{o_cfb}^2 - \left(D_{o_cfb} - 2 \cdot t_{cfb}\right)^2\right]}$

σ_{Drag} = capsule facility body tensile stress due to drag force

$\sigma_{Drag} = 11 psi$

This tensile stress in the capsule facility body due to the parallel flow-induced drag force is negligible.

:Loading on the capsule facility body due to coolant parallel flow is negliglble.

B3. ATR Gas Lines and Hanger Rod Assembly (out-of-reactor) Components (B31.1 Evaluation)

B3.1 Gas System Lines

The gas system is not designed at this stage but will be in the future. The only evaluation of the gas system that will be performed herein is a check for the minimum required wall thickness for the tubing (Dwg. 630430) that will run through the seal plug, through the hanger rod extension and transition sections, and into the capsule facility capsule. Only design conditions will be evaluated. This tubing is specified as 304L SST.

$D_{o_g} := 0.0625 \cdot in$ — D_{o_g} = gas tubing O.D.

$t_g := 0.010 \cdot in$ — t_g = tubing wall thickness

$P_{d_g} := 250 \cdot psi$ — P_{d_g} = gas system design pressure

$S_g := 12800 \cdot psi$ — S_g = allowable stress for 304L SST at 240 F, per ASME B31.1 (Ref. 9)

$y_g := 0.4$ — y_g = per ASME B31.1 Table 104.1.2(A)

$E_g := 1.0$ — E_g = joint effeciency, assume 1

$$t_m := \frac{P_{d_g} \cdot D_{o_g}}{2 \cdot \left(S_g \cdot E_g + P_{d_g} \cdot y_g\right)}$$

t_m = minimum thickness to support the design pressure, eqn. (3) per ASME B31.1

$$t_m = 0.0006\,in$$

The minimum thickness t_m to support the design pressure is less than the actual thickness t_g.

:Gas system 1/6-inch diameter by 0.010-inch thick tubing is acceptable under design conditions.

B3.2 Hanger Rod Assembly (out-of-reactor)

No evaluation on the hanger rod assembly outside of the reactor will be performed because the design conditions do not provide any appreciable loading conditions. Connections for gas lines and other components are contained within that assembly. The appropriate time for any evaluation of those components would be when the gas system design has been completed.

B4. Other Component Evaluations

The following components are inside of the pressure boundary of this design. Therefore, the ASME Code requirements do not have to be met for these components (though they may be used to judge component adequacy in performing the intended functions).

B4.1 Evaluate Components Under Upper Cylinder Loads

Inside of the capsule facility are pnumatic line cylinders. The components that are loaded by these line cylinders are as follows:

-upper cylinder mounting plates (to be evaluated after the push rods)
-upper push bar
-load cell attachment bolt and load cell
-upper push rod
-compressed specimen stack (graphite push rod, specimen stack)
-graphite specimen separators (stop blocks)
-lower graphite specimen holder
-lower graphite spacer
-capsule bottom plate
-lower spacer tube
-capsule bottom cap

This section will evaluate these components under the upper cylinder loadings.

B4.1.1 Upper Push Bars

Calculate line cylinder force

$PF := 2.4 \cdot in^2$ — PF = power factor (the piston area) of the upper line cylinder (1-3/4" Bimba Original Line cylinder, SR-242-P-V)

$P_{ulc} := 250 \cdot psi$ — P_{ulc} = upper line cylinder maximum allowable working pressure (per manufacturer)

$F_{ulc} := PF \cdot P_{ulc}$ — F_{ulc} = line cylinder maximum output force at the maximum allowable working pressure

$F_{ulc} = 600\,lbf$

$\Delta_{off} := 0.695 \cdot in$ — Δ_{off} = distance between line cylinder centerline and push rod centerline

Calculate push bar area and section modulus

$L_{pb} := 0.695 \cdot in$ — L_{pb} = length of push bar cross-section minus the radius ends

$W_{pb} := 0.5 \cdot in$ — W_{pb} = overall width of push bar cross-section

$R_{pb} := 0.25 \cdot in$ — R_{pb} = radius of push bar cross-section ends

$A_{pb} := L_{pb} \cdot W_{pb} + \pi \cdot R_{pb}^2$

A_{pb} = area of push bar

$A_{pb} = 0.5438\,in^2$

$Z_{pb} := \frac{W_{pb} \cdot (L_{pb} + 2 \cdot R_{pb})^2}{6}$

Z_{pb} = approximate section modulus of push bar (This value is slightly non-conservative, but will be considered acceptable if the bending stress in the push bar is low.)

$Z_{pb} = 0.119\,in^3$

Calculate stresses in push bar

$\sigma_{a_pb} := \frac{F_{ulc}}{A_{pb}}$

σ_{a_pb} = axial stress in push bar

$\sigma_{a_pb} = 1103\,psi$

$\sigma_{b_pb} := \frac{F_{ulc} \cdot \Delta_{off}}{Z_{pb}}$

σ_{b_pb} = bending stress in push bar

$\sigma_{b_pb} = 3504\,psi$

$\sigma_{pb} := \sigma_{a_pb} + \sigma_{b_pb}$

σ_{pb} = maximum combined stress in push bar

$\sigma_{pb} = 4607\,psi$

The above maximum combined stress in the upper push bar is well below the yield strength of 304 SST (23.9 ksi) at 240 deg. F (see Table 2 in report main body). (No buckling calculation will be performed because these bars are so short - just under 17 inches long.)

:Upper push bars are acceptable.

What force might be lost through friction as the push bar passes through the mounting/alignment plates?

Summing moments about one of the plates and equating to zero, the horizontal reaction force on the next plate is:

$F_{r_pb} := \frac{F_{ulc} \cdot \Delta_{off}}{12 \cdot in}$

F_{r_pb} = reaction force on plate 12 inches away from first plate

$F_{r_pb} = 34.75\,lbf$

Summing horizontal forces gives the same horizontal reaction force at the first plate. The loss due to friction would then be:

$\mu_{pb} := 0.25$

μ_{pb} = coefficient of friction between the push bar and the mounting/alignment plate assuming a very smooth finish on each component

$F_{loss} := 2 \cdot F_{r_pb} \cdot \mu_{pb}$

$F_{loss} = 17\,lbf$

F_{loss} = total loss of force due to friction

The above loss in each line cylinder force due to friction on the push bar is acceptably small.

B4.1.2 Load Cell Atachment Bolts and Load Cells

Each load cell attachment bolt and load cell will see the maximum line cylinder axial loading of 600 lbf. The minimum cross-section is in the 1/2-inch threads (13 threads per inch) of the load cell and bolt. The compressive stress on this cross-section is:

$A_{min} := 0.1419 \cdot in^2$

A_{min} = tensile stress area

$\sigma_{lca_bolt} := \frac{F_{ulc}}{A_{min}}$

σ_{lca_bolt} = compressive stress in bolt/load cell at 1/2-inch thread cross-section

$\sigma_{lca_bolt} = 4228\,psi$

The above compressive stress on a 304 SST attachment bolt is low (yield is 23.9 ksi at 240 F, see Table 2 of report main body.) The load cells are rated for 2000 lbf.

:Load cell attachment bolts and load cells are acceptable.

B4.1.3 Upper Push Rods

Because the upper push bars pass through two mounting/alignment plates, the moment caused by the offset line cylinder has been reacted out at these two plates. Only the upper cylinder axial force is applied to the upper push rods.

$D_{pr} := 0.563 \cdot in$

D_{pr} = diameter of push rods through most of length (only the bottom 0.333 inches of rod is reduced to 0.472 inches in diameter.

$L_{lpr} := 77.261 \cdot in$

L_{lpr} = length of long push rods

$L_{spr} := 65.483 \cdot in$

L_{spr} = length of short push rods

The longest unsupported length of these push rods is between the alignment plate at the top of the transition funnel and the alignment plate in the capsule facility body, at 35.375 inches. First, check these push rods for buckling.

$L_{s_eff} := 35.375 \cdot in$

L_{s_eff} = maximum unsupported push rod length

$A_{pr} := \frac{\pi}{4} \cdot D_{pr}^{2}$

$A_{pr} = 0.2489\,in^2$

A_{pr} = area of push rods

$I_{pr} := \frac{\pi}{64} \cdot D_{pr}^{4}$

$I_{pr} = 0.0049\,in^4$

I_{pr} = moment of inertia of push rods

$r_{pr} := \left(\frac{I_{pr}}{A_{pr}}\right)^{\frac{1}{2}}$

$r_{pr} = 0.1407\,in$

r_{pr} = radius of gyration of push rods

$K_f := 0.75$

K_f = end condition factor [Ref. 10, AISC ASD Table C-C2.1, average of case (a) and case (d)]

$K_f \cdot \frac{L_{s_eff}}{r_{pr}} = 188$

KL/R is a slenderness ratio

$F_y := 23900 \cdot psi$

F_y = yield strength of 304 SST at 240 deg. F

$E = 27400000\,psi$

E = modulus of elasticity at 240 deg. F

$C_c := \left(2 \cdot \pi^2 \cdot \frac{E}{F_y}\right)^{\frac{1}{2}}$

$C_c = 150$

C_c = comparison equation against the slenderness ratio to dertermine the applicable equation for limiting compressive stresses

Because KL/r > Cc, the following equation applies to limit the compressive stress in the push rods to prevent buckling.

$F_a := 12 \cdot \pi^2 \cdot \frac{E}{23 \cdot \left[\left(K_f\right) \cdot \frac{L_{s_eff}}{r_{pr}}\right]^2}$

$F_a = 3971\,psi$

F_a = maximum allowable compressive stress in rods to prevent buckling

The maximum load on these push rods is 600 lbf of compressive force (see above).

$F_{ulc} = 600\,lbf$ F_{ulc} = 600 lbf push rod force

$\sigma_{upr} := \frac{F_{ulc}}{A_{pr}}$ $\sigma_{upr} = 2410\,psi$ $\sigma\upsilon_{pr}$ = compressive stress in push rod due to 600 lbf load

The above axial stress in the upper push bars (σ_{upr}) is below the value above which buckling would occur (F_a).

:Upper push rods are acceptable.

B4.1.4 Upper Cylinder Mounting Plates

The two upper cylinder mounting plates (Dwg. 630428), which are 4.800-inch diameter 1/4-inch thick 304 SST plate, with three1-inch diameter mounting holes, three 0.625-inch diameter air line holes, one 0.750-inch diameter center hole, and three slots for push bars (lower plate only), sits on a small ledge in the end of the hanger rod extension and transition tubes. This positioning causes the upper cylinder mounting plate to act as a backing ring for the butt weld that joins a hanger rod extension tube to a transition tube or that joins the two transition tubes.

The bearing stress on the plate and tube ledges under the load of three upper cylinders applying 600 lbf on their respective push rods is:

$$\sigma_{ucmp_b} := \frac{3 \cdot F_{ulc}}{\frac{\pi}{4} \cdot \left[(4.800 \cdot in)^2 - \left(D_{o_hrt} - 2 \cdot t_{hrt}\right)^2 \right]}$$

σ_{ucmp_b} = bearing stress on ledge

$$\sigma_{ucmp_b} = 1382\,psi$$

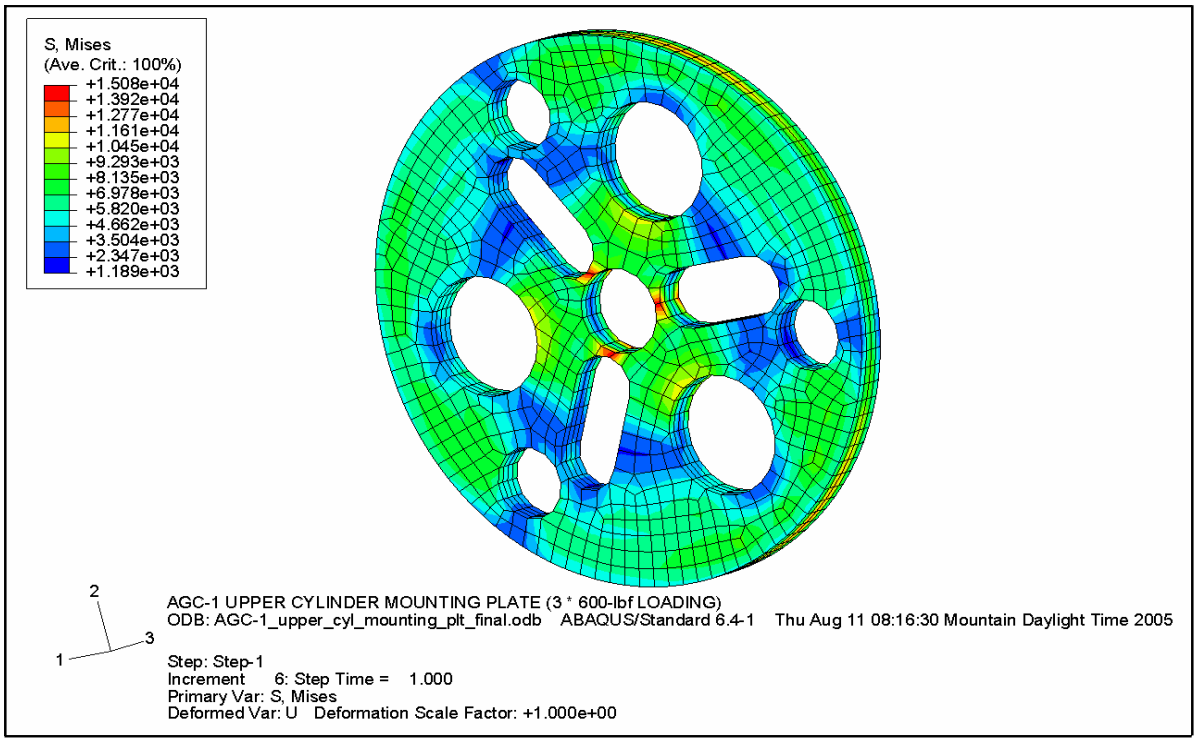
The above bearing stress is negligible. Bearing stress is not a problem.

The bending stress in the plate due to the load of the three upper cylinders applying 600 lbf on their respective push bars/push rods, will be evaluated using finite element methods.

The mounting plate was modeled and evaluated in ABAQUS/Standard Version 6.4-1 running on computer "Tomcat" (see Appendix A for validation documentation and Appendix E for the model file) using 2,828 solid elements (type C3D8R, 4 through the thickness), with the middle of the outside edge simply supported, and with 600 lbf applied on the three mounting holes (1800 lbf total).

The results show that the highest von Mises stress is at 15,080 psi and occurs at the ligaments between the three slots and the center hole (on the surface only) and at the perimeter weld. The bulk of the plate experiences von Mises stresses that are 10,000 psi or less. This is below the yield strength of 304 SST of 23.9 ksi (at 240 F, see Table 2 of main report) and is considered acceptable.

:Upper cylinder mounting plates are acceptable under the maximum 3 * 600 lbf max. line cylinder loading.



Upper cylinder mounting plate (lower plate).

B4.1.5 Specimen Stack - Graphite Push Rods and Specimens

Upper Graphite Push Rods

An upper graphite push rod (dwg. 630427, 0.500-inch O.D., 15.431-inches long) is positioned in the upper graphite specimen holder on each of the six compressed specimen stacks such that the top of a graphite pushrod is about 3-3/4 inches below the top of the holder. This places 15-inches of the graphite push rod in a cylindrical hole that is 0.505-inches in diameter. Because of this positioning, the bottom about 5 inches of this graphite push rod is below the top of the reactor core. Each push rod will experience a compressive force equal to the maximum output of an upper line cylinder, or 600 lbf.

Check bearing stress in the graphite rod where the upper stainless steel push rod contacts it:

$D_{upr_c} := 0.472 \cdot in$

D_{upr_c} = diameter of upper steel push rod at the end that contacts the graphite push rod

$D_{ugpr_od} := 0.500 \cdot in$

D_{ugpr_od} = O.D. of upper graphite push rod

$D_{ugpr_idb} := 0.285 \cdot in$

D_{ugpr_idb} = I.D. of upper graphite push rod at contacting (bearing) end

$D_{ugpr_id} := 0.252 \cdot in$

D_{ugpr_id} = I.D. in main body of upper graphite push rod

$$A_{ugpr_overlap} := \frac{\pi}{4} \cdot \left(D_{upr_c}^{2} - D_{ugpr_idb}^{2}\right)$$

$A_{ugpr_overlap}$ = area of overlap for bearing contact on graphite rod

$$A_{ugpr_overlap} = 0.1112\, in^2$$

$$\sigma_{ugpr_b} := \frac{F_{ulc}}{A_{ugpr_overlap}}$$

σ_{ugpr_b} = bearing stress in upper graphite push rod

$$\sigma_{ugpr_b} = 5397\, psi$$

The compressive strength of this graphite (POCO AXF-5Q) at room temperature is 20,000 psi (per Table 4 of report main body). Therefore, at room temperature (70 deg. F) this bearing stress is well below the compressive strength. Per Reference 6 of the report main body, the compressive strength will increase (to almost double the room temperature value) with increasing temperature up to about 2500 deg. C.

Check the main body compressive stress in the upper graphite push rod:

$$A_{ugpr} := \frac{\pi}{4} \cdot \left(D_{ugpr_od}^{2} - D_{ugpr_id}^{2}\right)$$

A_{ugpr} = area of upper graphite push rod through the main body

$$A_{ugpr} = 0.1465\, in^2$$

$$\sigma_{ugpr} := \frac{F_{ulc}}{A_{ugpr}}$$

σ_{ugpr} = compressive stress in main body of upper graphite push rod

$$\sigma_{ugpr} = 4096\, psi$$

The above compressive stress in the main body of the upper graphite push rod is well below the compressive strength at room temperature (70 deg. F) of 20,000 psi (per Table 4 of report main body). The lower end of this push rod may be heated because it is just below the top of the core. However, the compressive strength increases with increasing temperature to about 2500 deg. C. This push rod is acceptable.

Check buckling in the upper graphite push rod:
The graphite push rod cannot buckle in the classical column buckling mode because it is basically supported at its outer diameter (with a 0.0025-inch radial gap) through its entire length. Additionally, the ratio of the outer radius to the thickness is 2, indicating that this looks like a very thick-walled member which would be not be subject to local wall buckling. Column buckling and local wall buckling at compressive stresses well below the material compressive strength are not a concern.

:Graphite push rods are acceptable.

Graphite Specimens

The purpose of this experiment is to place a load on the graphite specimens for a period of time and evaluate the creep. The compressive stress on the specimens due to the 600 lbf line cylinder load is:

$D_{cs} := 0.501 \cdot in$ $\quad$ D_{cs} = average diameter of specimen

$A_{cs} := \frac{\pi}{4} \cdot D_{cs}^{2}$ $\quad$ A_{cs} = area of specimen

$A_{cs} = 0.1971\, in^{2}$

$\sigma_{cs} := \frac{F_{ulc}}{A_{cs}}$ $\quad$ σ_{cs} = compressive stress on specimen

$F_{ulc} = 600\, lbf$

$\sigma_{cs} = 3044\, psi$

The target maximum stress for these specimens is 3000 psi. This is acceptable.

B4.1.6 Specimen Separators (Stop Blocks)

The specimen separators transfer the upper line cylinder load into the top of the lower graphite specimen holder. The specimen separator, or stop block, will experience a compressive stress through the main body as well as a bearing stress on the ledge in the lower graphite specimen holder.

$D_{sb_min} := 0.472 \cdot in$ — D_{sb_min} = minimum diameter of block

$D_{sb_max} := 0.625 \cdot in$ — D_{sb_max} = maximum diameter of block

$D_{lgsh_th} := 0.506 \cdot in$ — D_{lgsh_th} = hole diameter in lower graphite specimen holder - through hole

$A_{sb_c} := \frac{\pi}{4} \cdot D_{sb_min}^2$ — A_{sb_c} = stop block area for compressive stresses

$A_{sb_c} = 0.175\, in^2$

$A_{sb_b} := \frac{\pi}{4} \cdot \left(D_{sb_max}^2 - D_{lgsh_th}^2\right)$ — A_{sb_b} = stop block bearing area on lower graphite specimen holder

$A_{sb_b} = 0.1057\, in^2$

$\sigma_{sb_c} := \frac{F_{ulc}}{A_{sb_c}}$ — σ_{sb_c} = maximum compressive stress in stop block

$\sigma_{sb_c} = 3429\, psi$

$\sigma_{sb_b} := \frac{F_{ulc}}{A_{sb_b}}$ — σ_{sb_b} = maximum bearing stress in stop block

$\sigma_{sb_b} = 5676\, psi$

The above compressive and bearing stresses in the stop block are well below the compressive strength at room temperature (70 deg. F) of 20,000 psi (per Table 4 of report main body). Per Reference 6 of the report main body, the compressive strength will increase (to almost double the room temperature value) with increasing temperature up to about 2500 deg. C.

:Specimen separators (stop blocks) are acceptable.

B4.1.7 Lower Graphite Specimen Holder

The lower graphite specimen holder will carry the load from six upper line cylinders through the stop blocks to the lower graphite spacer. The bearing stress on the lower graphite specimen holder is that calculated for the stop blocks. Additionally, the compressive stress through the main body of the lower graphite specimen holder will be lower than the bearing stress.

:Lower graphite specimen holder is acceptable.

B4.1.8 Lower Graphite Spacer

The lower graphite spacer will carry the load from the six upper line cylinders (applied through the lower graphite specimen holder). This spacer is below the reactor core and will be cooler and is somewhat thicker (larger outer envelope diameter) than the specimen holder. Therefore, because the compressive stresses in the lower graphite specimen holder were acceptable, those compressive stresses in the main body of the lower graphite spacer will also be acceptable.

The lower graphite spacer rests on the capsule bottom plate. The capsule bottom plate is flat, with channels cut into it for gas flow purposes. Most of the area of the bottom surface of the lower graphite spacer will be supported by the bottom plate, thus minimizing the bearing stresses. (For comparative purposes, the bearing area of the lower graphite spacer on the bottom plate is, by inspection, much greater than the total bearing area of the six specimen separators. Therefore, the bearing stress on the bottom of the lower graphite separator will be less than that of the specimen separators - which stress was shown acceptable.)

:Lower graphite spacer is acceptable.

B4.1.9 Capsule Bottom Plate

As discussed in the previous section, the lower graphite spacer rests on the capsule bottom plate. The bottom plate sits on a ledge in the top of the lower spacer tube which is supported by the bottom cap. The capsule bottom plate (Dwg. 630428) is 3/4-inches thick, made of 304 SST, and has an O.D. of 2.148-inches, six through holes at 0.313-inches diameter (one under each perimeter specimen stack), and six outside perimeter slots of a 0.095-inch radius.

The outer diameter-to-thickness ratio (2.148 / 0.75) for the bottom plate is less than 3, which means that it will respond to the load from the six upper line cylinders through the lower graphite spacer with negligible bending. Compressive stresses will also be small. The only stress of significance on this bottom plate will be in bearing where it sits on the ledge in the lower spacer tube. The bearing stress is calculated as follows:

$D_{o_lst} := 2.230 \cdot in$ — D_{o_lst} = outside diameter of lower spacer tube

$D_{o_bp} := 2.148 \cdot in$ — D_{o_bp} = outside diameter of bottom plate

$D_{i_lst} := 2.010 \cdot in$ — D_{i_lst} = inside diameter of spacer tube

$F_{ulc} = 600\,lbf$

$$\sigma_{lst_b} := \frac{6 \cdot F_{ulc}}{\frac{\pi}{4} \cdot \left(D_{o_bp}^2 - D_{i_lst}^2\right)}$$

σ_{lst_b} = bearing stress on lower spacer tube ledge for the bottom plate

$\sigma_{lst_b} = 7988\,psi$

The capsule bottom plate and the lower spacer tube are made of 304 SST which has a minimum yield strength of 23.9 ksi at 240 deg. F. The above bearing stress is below that yield strength.

:Capsule bottom plate is acceptable.

B4.1.10 Lower Spacer Tube

The lower spacer tube will be loaded by the force of all six upper cylinders through the bottom plate and into the top ledge in the tube. This will cause bearing stresses on the ledge and compressive stresses in the tube. The previous section showed that the bearing stresses were acceptably low. The lower spacer tube is made of 304 SST.

Check buckling in the lower spacer tube under the six upper line cylinder loads:

$$\sigma_{lst_c} := \frac{6 \cdot F_{ulc}}{\frac{\pi}{4} \cdot \left(D_{o_lst}^2 - D_{i_lst}^2\right)}$$

σ_{lst_c} = compressive stress on lower spacer tube

$\sigma_{lst_c} = 4914\,psi$

Using ND-3133.6 (Cylinders Under Axial Compression) as a guide to determine if the lower spacer tube will buckle under this loading/compressive stress:

$$t_{lst} := \frac{D_{o_lst} - D_{i_lst}}{2}$$

t_{lst} = thickness of lower spacer tube

$t_{lst} = 0.110\,in$

$$R_{lst} := \frac{D_{i_lst}}{2}$$

R_{lst} = inside radius

$R_{lst} = 1.005\,in$

$$A_{lst} := \frac{0.125}{\frac{R_{lst}}{t_{lst}}} \qquad A_{lst} = 0.0137$$

A_{lst} = value to enter charts with

$B_{lst} := 12500 \cdot psi$

B = value from Figure HA-1 (ASME Code Section II, Part D)

The lower spacer tube compressive stress (σ_{lst_c}) is less than that allowed (B_{lst}) for a Class 3 component to prevent buckling. Tube will not buckle.

:Lower spacer tube is acceptable.

B4.1.11 Capsule Bottom Cap

The bottom cap is a Class 3 component and was previously evaluated and accepted. This calculation will merely calculate the stress in the attachment weld under the load of 6 upper cylinders pushing at maximum force each. This weld is a full penetration groove weld.

$F_{ulc} = 600\,lbf$

$$\sigma_{bc_w} := \frac{6 \cdot F_{ulc}}{\frac{\pi}{4} \cdot \left[D_{o_cfb}^{2} - \left(D_{o_cfb} - 2 \cdot t_{cfb}\right)^{2}\right]}$$

σ_{bc_w} = tensile stress in weld

$\sigma_{bc_w} = 4178\,psi$

The weld stress calculated above is small when compared to the Class 3 allowable stress for 304 SST of 20,000 psi at 240 deg. F.

:Bottom cap weld under the maximum load of six upper cylinders is acceptable.

B4.2 Evaluate Lower Cylinder Push Rods

The lower cylinders are 9/16-inch Bimba Original Line cylinders (SR-022-P-V) with a maximum delivered force (250 psi maximum allowable working pressure times the piston area of 0.25) of 63 lbf each. The lower cylinder pushrods are made of graphite. The compressive stress in these rods under the maximum load from a lower cylinder is:

$D_{lcpr} := 0.435 \cdot in$

D_{lcpr} = diameter of lower push rod

$$A_{lcpr} := \frac{\pi}{4} \cdot D_{lcpr}^{2}$$

A_{lcpr} = area of lower push rod cross-section

$A_{lcpr} = 0.1486\,in^{2}$

$F_{llc} := 0.25 \cdot in^{2} \cdot 250 \cdot psi$

F_{llc} = lower line cylinder maximum force

$F_{llc} = 62.5\,lbf$

$$\sigma_{lcpr} := \frac{F_{llc}}{A_{lcpr}}$$

σ_{lcpr} = compressive stress on lower push rod

$\sigma_{lcpr} = 421\,psi$

The compressive stress calculated above (σ_{lcpr}) is negligible.

:Lower push rods are acceptable.

(Note that the lower line cylinders will not be operated at the same time as the upper line cylinders. Their purpose is merely to move the specimen stacks enough to assure that the specimens have not swelled to the point of binding in the specimen holders.)

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Appendix C

Component Weights

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C1. Caclulation of Capsule Facility Component Weights

C1.1 Hanger Rod Extension & Transition Tubes and Funnel Transition Tube (Tube, 5-in. O.D., 0.188-in. wall, 304 SST, Dwg. 630430 & 630428)

$L_{HRET} := 108.15 \cdot in$ — L_{HRET} = length of the hanger rod extension tube

$L_{hr} := \left(L_{HRET} + 3 \times 12 \cdot in + 6 \cdot in\right)$ — L_{hr} = total length of hanger rod extension tube, 3 transition tubes, and one funnel transition tube

$L_{hr} = 150.15\,in$

$t_w := 0.188 \cdot in$ — t_w = wall thickness

$D_o := 5 \cdot in$ — D_o = outside diameter of tube

$D_i := 5 \cdot in - 2 \cdot t_w$ — D_i = inside diameter of tube

$A_{hr} := \frac{\pi}{4} \cdot \left(D_o^2 - D_i^2\right)$ — A_{hr} = area of hanger rod tube cross-section

$A_{hr} = 2.842\,in^2$

$\rho_{304sst} := 0.285 \cdot \frac{lbf}{in^3}$ — ρ_{304sst} = weight density of 304 stainless steel

$W_{hr} := L_{hr} \cdot A_{hr} \cdot \rho_{304sst}$ — W_{hr} = total weight of hanger rod extension and transition tubes

$W_{hr} = 121.62\,lbf$

C1.2 Transition Funnel (304 SST, Dwg. 630428)

$R_o := 2.500 \cdot in$ — R_o = outside radius at larger end

$t_{tf} := 0.225 \cdot in$ — t_{tf} = wall thickness

$R_i := R_o - t_{tf}$ — R_i = inside radius at larger end

$R_i = 2.275\,in$

$r_o := 1.25 \cdot in$ — r_o = outside radius at smaller end

$r_i := r_o - t_{tf}$ — r_i = inside radius at smaller end

$r_i = 1.025\,in$

$h_{tf} := 5.375 \cdot in$ — h_{tf} = height of funnel

$$V_{tf} := \frac{\pi}{3} \cdot h_{tf} \cdot \left(R_o^2 - R_i^2 + R_o \cdot r_o - R_i \cdot r_i + r_o^2 - r_i^2\right)$$

V_{tf} = volume of funnel material

$W_{tf} := V_{tf} \cdot \rho_{304sst}$ — Wtf = weight of transition funnel material

$W_{tf} = 3.817\,lbf$

C1.3 Capsule Facility Body (Tube, 2-1/2-in. O.D., 0.120-in. wall, 304 SST, Dwg. 630430)

Tube with 0.120-inch wall section ("tube"):

$L_b := 149.68 \cdot in$ — L_b = length of entire capsule facility body

$L_{b1} := 77.68 \cdot in$ — L_{b1} = length of tube

$D_{bo} := 2.500 \cdot in$ — D_{bo} = outside diameter of capsule facility body

$t_{b1} := 0.120 \cdot in$ — t_{b1} = wall thickness of remaining tube

$D_{bi1} := D_{bo} - 2 \cdot t_{b1}$ — D_{bi1} = inside diameter of remaining tube

$D_{bi1} = 2.26\,in$

$A_{b1} := \frac{\pi}{4} \cdot \left(D_{bo}^2 - D_{bi1}^2\right)$ — A_{b1} = area of remaining tube cross-section

$A_{b1} = 0.897\,in^2$

$V_{b1} := A_{b1} \cdot L_{b1}$ — V_{b1} = volume of remaining tube

$V_{b1} = 69.698\,in^3$

In_core pressure tube section:

$L_{b2} := 72 \cdot in$ — L_{b2} = length of in-core pressure tube

$t_{b2} := 0.188 \cdot in$ — t_{b2} = thickness of in-core tube

$D_{bi2} := D_{bo} - 2 \cdot t_{b2}$ — D_{bi2} = inside diameter of in-core tube

$D_{bi2} = 2.124\,in$

$D_{grooves} := 0.126 \cdot in$ — $D_{grooves}$ = diameter of 13 inside wall grooves

$A_{b2} := \frac{\pi}{4} \cdot \left(D_{bo}^2 - D_{bi2}^2 - \frac{13}{2} \cdot D_{grooves}^2\right)$

$A_{b2} = 1.284\,in^2$ — A_{b2} = area of in-core tube cross-section

$V_{b2} := A_{b2} \cdot L_{b2}$ V_{b2} = volume of in-core tube

$V_{b2} = 92.481\,in^3$

$W_b := (V_{b1} + V_{b2}) \cdot \rho_{304sst}$ W_b = weight of entire capsule facility body

$W_b = 46.221\,lbf$

C1.4 Bottom Cap (Rod or Bar, 2-1/2-in. O.D., 304 SST, Dwg. 630428)

$R_{bc} := 1.250 \cdot in$ R_{bc} = radius of sphere

$V_{sp} := \frac{1}{2} \cdot \frac{4}{3} \cdot \pi \cdot R_{bc}^3$ V_{sp} = volume of solid half-sphere

$V_{sp} = 4.091\,in^3$

$V_{tr} := 0.125 \cdot in \cdot \frac{\pi}{4} \cdot (2.375 \cdot in)^2$ V_{tr} = volume of transition section

$V_{tr} = 0.554\,in^3$

$V_f := 0.125 \cdot in \cdot \frac{\pi}{4} \cdot (2.25 \cdot in)^2$ V_f = volume of straight section

$V_f = 0.497\,in^3$

$W_{bc} := (V_{sp} + V_{tr} + V_f) \cdot \rho_{304sst}$ W_{bc} = weight of bottom cap

$W_{bc} = 1.465\,lbf$

C1.5 Upper Line Cylinders (Dwg 630430, Bimba Online Data, SR-242-P-V)

$W_{ulc} := 2.0 \cdot lbf$

W_{ulc} = weight of each of the six upper line cylinders with a 2 inch stroke or 1.6 lbf rounded up to 2 lbs to account for any misc. mounting hardware

C1.6 Upper Cylinder Mounting Plates (1/4-inch plate, 304 SST, Dwg. 630428)

$D_{mpl} := 4.800 \cdot in$ D_{mpl} = plate diameter

$t_{mpl} := 0.250 \cdot in$ t_{mpl} = plate thickness

$D_1 := 1.040 \cdot in$ D_1 = diameter of three mounting holes

$D_2 := 0.625 \cdot in$ D_2 = diameter of three air line holes

$D_c := 0.755 \cdot in$ D_c = diameter of center hole

$$A_{mpl} := \frac{\pi}{4} \cdot \left(D_{mpl}^2 - 3 \cdot D_1^2 - 3 \cdot D_2^2 - D_c^2 \right)$$ A_{mpl} = area of plate minus holes

$W_{mpl} := A_{mpl} \cdot t_{mpl} \cdot \rho_{304sst}$ W_{mpl} = weight of each of 2 mounting plates

$$W_{mpl} = 1.01\, lbf$$

(The above is the weight of mounting plate #1. Mounting plate #2 is slightly lighter because of the three slots for push bars. However, using this weight for both plates will be acceptable.)

C1.7 Push Rod Alignment Plates (1/4-inch plates, 304 SST, Dwg. 630428)

<u>Alignment Plate #1:</u>

$D_{prap1} := D_{mpl}$ D_{prap1} = outer diameter of plate

$D_{cs} := 0.755 \cdot in$ D_{cs} = diameter of center hole

$D_{ph} := 0.375 \cdot in$ D_{ph} = diameter of six perimeter holes

$D_{slots} := 0.516 \cdot in$ D_{slots} = diameter of six slots

$$L_{slots} := \frac{(2.780 - 1.390) \cdot in}{2}$$ L_{slots} = length of slots minus end radii

$$A_{prap1} := \frac{\pi}{4} \cdot \left(D_{prap1}^2 - D_{cs}^2 - 6 \cdot D_{ph}^2 - 6 \cdot D_{slots}^2 \right) - 6 \cdot D_{slots} \cdot L_{slots}$$

A_{prap1} = area of alignment plate #1

$$A_{prap1} = 13.579\, in^2$$

$t_{prap} := 0.250 \cdot in$ t_{prap} = thickness of plate

$W_{prap1} := A_{prap1} \cdot t_{prap} \cdot \rho_{304sst}$ W_{prap1} = weight of alignment plate #1

$W_{prap1} = 0.967\,lbf$

Alignment Plate #2:

Plate #2 is identical to plate #1 except that three of the slots are simply circular push rod holes, and it has only three perimeter holes (which are smaller in diameter).

$D_{prh} := 0.565 \cdot in$ D_{prh} = diameter of three push rod holes

$D_{ph1} := 0.250 \cdot in$ D_{ph1} = diameter of three perimeter holes

$$A_{prap2} := \frac{\pi}{4} \cdot \left(D_{prap1}^2 - D_{cs}^2 - 3 \cdot D_{ph1}^2 - 3 \cdot D_{slots}^2 - 3 \cdot D_{prh}^2 \right) - 3 \cdot D_{slots} \cdot L_{slots}$$

A_{prap2} = area of alignment plate #2

$W_{prap2} := A_{prap2} \cdot t_{prap} \cdot \rho_{304sst}$ W_{prap2} = weight of alignment plate #2

$W_{prap2} = 1.072\,lbf$

Alignment Plate #3:

Plate #3 has only the center hole and six holes for the push rods.

$$A_{prap3} := \frac{\pi}{4} \cdot \left(D_{prap1}^2 - D_{cs}^2 - 6 \cdot D_{prh}^2 \right)$$ A_{prap3} = area of alignment plate #3

$W_{prap3} := A_{prap3} \cdot t_{prap} \cdot \rho_{304sst}$ W_{prap3} = weight of alignment plate #3

$W_{prap3} = 1.150\,lbf$

Alignment Plate #4:

Plate #4 has a center hole, six holes for the push rods, and six perimeter holes.

$D_{prap4} := 2.280 \cdot in$ D_{prap4} = outer diameter of plate #4

$D_{prh4} := 0.578 \cdot in$ D_{prh4} = diameter of six push rod holes in plate #4

$D_{ph4} := 0.189 \cdot in$ D_{ph4} = diameter of six perimeter holes in plate #4

$$A_{prap4} := \frac{\pi}{4} \cdot \left(D_{prap4}^2 - D_{cs}^2 - 6 \cdot D_{prh4}^2 - 6 \cdot D_{ph4}^2 \right)$$ A_{prap4} = area of alignment plate #4

$W_{prap4} := A_{prap4} \cdot t_{prap} \cdot \rho_{304sst}$ W_{prap4} = weight of alignment plate #4

$W_{prap4} = 0.135\,lbf$

Total weight of all four push rod alignment plates (W_{prap}):

$W_{prap} := W_{prap1} + W_{prap2} + W_{prap3} + W_{prap4}$ $W_{prap} = 3.325\,lbf$

C1.8 Push Bars (304 SST, Dwg. 630428)

$D_{pb} := 0.500 \cdot in$ — D_{pb} = push bar end diameter

$L_{pbr} := 0.695 \cdot in$ — L_{pbr} = length of rectangular portion of push bar cross-section

$L_{pb} := 16.706 \cdot in$ — L_{pb} = overall length of push bar

$$W_{pb} := \left(\frac{\pi}{4} \cdot D_{pb}^{2} + D_{pb} \cdot L_{pbr}\right) \cdot L_{pb} \cdot \rho_{304sst}$$

$W_{pb} = 2.589\,lbf$ — W_{pb} = approximate weight of each of six push bars (Note that the threaded holes were not removed while the larger radius at the upper end was not included. The resulting inaccuracy was considered acceptably small.)

C1.9 Upper Push Rods (304 SST, Dwg. 630428)

$D_{pr} := 0.563 \cdot in$ — D_{pr} = push rod major diameter

$D_{prm} := 0.472 \cdot in$ — D_{prm} = push rod minor diameter

$L_{lpr} := 77.261 \cdot in$ — L_{lpr} = length of long push rod

$L_{spr} := 65.483 \cdot in$ — L_{spr} = length of short push rod

$$W_{lpr} := \frac{\pi}{4} \cdot \left[D_{pr}^{2} \cdot \left(L_{lpr} - 0.38 \cdot in\right) + D_{prm}^{2} \cdot 0.38 \cdot in\right] \cdot \rho_{304sst}$$

$W_{lpr} = 5.474\,lbf$ — W_{lpr} = weight of each of 3 long push rods

$$W_{spr} := \frac{\pi}{4} \cdot \left[D_{pr}^{2} \cdot \left(L_{spr} - 0.38 \cdot in\right) + D_{prm}^{2} \cdot 0.38 \cdot in\right] \cdot \rho_{304sst}$$

$W_{spr} = 4.638\,lbf$ — W_{spr} = weight of each of 3 short push rods

C1.10 Upper Cylinder Load Cell Attachment Bolts (304 SST, Dwg. 630428)

$D_{lcab_s} := 0.5 \cdot in$ — D_{lcab_s} = diameter of small end of bolt

$D_{lcab_l} := 0.625 \cdot in$ — D_{lcab_l} = diameter of large end of bolt

$L_{lcab_l} := 1.690 \cdot in$ — L_{lcab_l} = length of large end of bolt

$L_{lcab_s} := 3.190 \cdot in - L_{lcab_l}$ — L_{lcab_s} = length of small end of bolt

$$W_{lcab} := \frac{\pi}{4} \cdot \left(D_{lcab_s}^{2} \cdot L_{lcab_s} + D_{lcab_l}^{2} \cdot L_{lcab_l}\right) \cdot \rho_{304sst}$$

$W_{lcab} = 0.232\,lbf$ — W_{lcab} = conservative weight of each load cell attachment bolt

(Actual load cells weigh less than 1/20 lbf and will be neglected herein.)

C1.11 Top Head Seal Plug (304 SST, Dwg. 630429)

Seal plug approximated as a bar with three sections of different diameters, with a center through hole with a threaded hole at one end.

$D_{sn1} := 5.87 \cdot in$ — D_{sn1} = diameter of first section

$D_{sn2} := 6.35 \cdot in$ — D_{sn2} = diameter of second section

$D_{sn3} := 4.75 \cdot in$ — D_{sn3} = diameter of third section

$L_{sn1} := 3.25 \cdot in$ — L_{sn1} = length of first section

$L_{sn2} := 2.75 \cdot in$ — L_{sn2} = length of second section

$L_{sn3} := 4.00 \cdot in$ — L_{sn3} = length of third section

$D_{snh1} := 2.50 \cdot in$ — D_{snh1} = diameter of threaded hole

$D_{snh2} := 1.39 \cdot in$ — D_{snh2} = diameter of though hole

$L_{snh1} := 2.00 \cdot in$ — L_{snh1} = length of threaded hole

$L_{snh2} := 8.00 \cdot in$ — L_{snh2} = length of through hole

$$V_{sn} := \frac{\pi}{4} \cdot \left[D_{sn1}^2 \cdot L_{sn1} + D_{sn2}^2 \cdot L_{sn2} + D_{sn3}^2 \cdot L_{sn3} - \left(D_{snh1}^2 \cdot L_{snh1} \right) - D_{snh2}^2 \cdot L_{snh2} \right]$$

$W_{sn} := V_{sn} \cdot \rho_{304sst}$ — V_{sn} = volume of seal plug material

$W_{sn} = 63.831\, lbf$ — W_{sn} = weight of seal plug

C1.12 Lower Spacer Tube (304 SST, Dwg. 630428)

$D_{lst1} := 2.230 \cdot in$ — D_{lst1} = outer diameter of lower spacer tube

$D_{lst2} := 2.010 \cdot in$ — D_{lst2} = inner diameter of tube

$L_{lst} := 7.375 \cdot in$ — L_{lst} = length of tube

$W_{lst} := \frac{\pi}{4} \cdot \left(D_{lst1}^2 - D_{lst2}^2 \right) \cdot L_{lst} \cdot \rho_{304sst}$ — W_{lst} = weight of lower spacer tube

$W_{lst} = 1.54\, lbf$

C1.13 Capsule Bottom Plate (304 SST, Dwg. 630428)

$D_{cbp1} := 2.149 \cdot in$ — D_{cbp1} = bottom plate outer diameter

$D_{cbp2} := 0.190 \cdot in$ — D_{cbp2} = diameter of 6 edge slots

$t_{cbp} := 0.750 \cdot in$ — t_{cpb} = thickness of main plate

$D_{cbp3} := 0.313 \cdot in$ — D_{cbp3} = diameter of 6 through holes

$W_{removed} := 0.1 \cdot lbf$ — $W_{removed}$ = assumed weight of removed metal in channels

$$V_{cbp} := \frac{\pi}{4} \cdot \left(D_{cbp1}^{2} - 6 \cdot \frac{D_{cbp2}^{2}}{2} - 6 \cdot D_{cbp3}^{2} \right) \cdot t_{cbp}$$

$V_{cbp} = 2.31\, in^3$ — V_{cbp} = volume plate

$W_{cbp} := V_{cbp} \cdot \rho_{304sst} - W_{removed}$ — W_{cbp} = weight of capsule bottom plate

$W_{cbp} = 0.558\, lbf$

C1.14 Lower Graphite Spacer (Graphite, POCO AXF-5Q, Dwg. 630427)

Weight will be approximated (minor details will be ignored).

$D_{lgs1} := 2.100 \cdot in$ — D_{lgs1} = outer diameter of spacer

$D_{lgs2} := 0.505 \cdot in$ — D_{lgs2} = diameter of 7 through holes

$L_{lgs} := 25.250 \cdot in$ — L_{lgs} = length of spacer

$$V_{lgs} := \frac{\pi}{4} \cdot \left(D_{lgs1}^{2} - 7 \cdot D_{lgs2}^{2} \right) \cdot L_{lgs}$$

$V_{lgs} = 52.054\, in^3$ — V_{lgs} = spacer volume

$\rho_{graphite} := 0.0641 \cdot \frac{lbf}{in^3}$ — $\rho_{graphite}$ = density of graphite (from Table 4 of report main body)

$W_{lgs} := V_{lgs} \cdot \rho_{graphite}$ — W_{lgs} = weight of lower graphite spacer

$W_{lgs} = 3.337\, lbf$

C1.15 Lower Graphite Specimen Holder (Graphite, POCO AXF-5Q, Dwg. 630427)

Weight will be approximated (minor details will be ignored).

$D_{lgsh1} := 2.073 \cdot in$ — D_{lgsh1} = maximum outer diameter of holder

$D_{lgsh2} := 1.939 \cdot in$ — D_{lgsh2} = minumum outer diameter of holder

$D_{lgsh_ave} := \frac{D_{lgsh1} + D_{lgsh2}}{2}$ — D_{lgsh_ave} = average diameter

$D_{lgsh_ave} = 2.006\,in$

$L_{lgsh} := 25.500 \cdot in$ — L_{lgsh} = length of holder

$D_{lgsh4} := 0.505 \cdot in$ — D_{lgsh4} = diameter of 6 perimeter through holes and center hole

(Ignore other features.)

$$V_{lgsh} := \frac{\pi}{4} \cdot \left(D_{lgsh_ave}^{2} - 7 \cdot D_{lgsh4}^{2}\right) \cdot L_{lgsh}$$

$V_{lgsh} = 44.839\,in^3$ — V_{lgsh} = lower graphite specimen holder volume

$W_{lgsh} := V_{lgsh} \cdot \rho_{graphite}$ — W_{lgsh} = weight of lower graphite specimen holder

$W_{lgsh} = 2.874\,lbf$

C1.16 Upper Graphite Specimen Holder (Graphite, POCO AXF-5Q, Dwg. 630427)

Weight will be approximated (minor details will be ignored).

$D_{ugsh1} := 2.073 \cdot in$ — D_{ugsh1} = maximum outer diameter of holder

$D_{ugsh2} := 1.643 \cdot in$ — D_{ugsh2} = minumum outer diameter of holder (approx.)

$D_{ugsh3} := \frac{D_{ugsh1} + D_{ugsh2}}{2}$ — D_{ugsh3} = average outer diameter of holder

$L_{ugsh} := 39.00 \cdot in$ — L_{ugsh} = overall length of holder

$D_{ugsh4} := 0.505 \cdot in$ — D_{ugsh3} = diameter of 6 perimeter through holes and center hole

(Ignore other features.)

$$V_{ugsh} := \frac{\pi}{4} \cdot \left(D_{ugsh3}^{2} - 7 \cdot D_{ugsh4}^{2}\right) \cdot L_{ugsh}$$

$V_{ugsh} = 51.061\,in^3$ V_{ugsh} = upper graphite specimen holder volume

$W_{ugsh} := V_{ugsh} \cdot \rho_{graphite}$ W_{ugsh} = weight of upper graphite specimen holder

$W_{ugsh} = 3.273\,lbf$

C1.17 Thermal Heat Shield (Haynes 230, Dwg. 630432)

This component weight will be estimated. The outer diameter is constant. The shield is made in five sections.

Top End Section:

$D_{hsod} := 2.110 \cdot in$ D_{hsod} = heat shield outer diameter

$t_{hs1} := 0.025 \cdot in$ t_{hs1} = top end section wall thickness

$D_{nubs} := 0.125 \cdot in$ D_{nubs} = 6 nubs on inside diameter

$L_{hs1} := 2.00 \cdot in$ L_{hs1} = length of top end section

$$V_{hs1} := \left(\pi \cdot D_{hsod} \cdot t_{hs1} + 3 \cdot \frac{\pi}{4} \cdot D_{nubs}^{2}\right) \cdot L_{hs1}$$

$V_{hs1} = 0.405\,in^3$ V_{hs1} = volume of top end section

Upper Section:

$t_{hs2a} := 0.010 \cdot in$ t_{hs2a} = end thickness of upper section

$t_{hs2b} := 0.005 \cdot in$ t_{hs2b} = middle thickness of upper section

$L_{hs2} := 16.0 \cdot in$ L_{hs2} = length of upper section

$$V_{hs2} := \pi \cdot D_{hsod} \cdot L_{hs2} \cdot \frac{t_{hs2a} + t_{hs2b}}{2}$$

$V_{hs2} = 0.795\,in^3$ V_{hs2} = volume of upper section

Middle Section:

$t_{hs3a} := 0.025 \cdot in$ t_{hs3a} = left end thickness of middle section

$t_{hs3b} := 0.010 \cdot in$ t_{hs3b} = right end thickness of middle section

$L_{hs3} := 16.02 \cdot in$ L_{hs3} = length of middle section

$$V_{hs3} := \pi \cdot D_{hsod} \cdot L_{hs2} \cdot \frac{t_{hs3a} + t_{hs3b}}{2}$$

$V_{hs3} = 1.856\, in^3$ V_{hs3} = volume of middle section

Lower Section: Same as middle section.

Bottom End Section:

$t_{hs4} := 0.025 \cdot in$ t_{hs4} = thickness of bottom end section

$L_{hs4} := 2.00 \cdot in$ L_{hs4} = length of bottom end section

$$V_{hs4} := \pi \cdot L_{hs4} \cdot D_{hsod} \cdot t_{hs4}$$

$V_{hs4} = 0.331\, in^3$ V_{hs4} = volume of bottom end section

Total Heat Shield Volume and Weight:

$$V_{hst} := V_{hs1} + V_{hs2} + 2 \cdot V_{hs3} + V_{hs4}$$

$V_{hst} = 5.244\, in^3$ V_{hst} = total volume of heat shield

$\rho_{H230} := 0.324 \cdot \frac{lbf}{in^3}$ ρ_{H230} = density of Haynes 230 (per manufacturer)

$W_{hs} := V_{hst} \cdot \rho_{H230}$ W_{hs} = estimated weight of heat shield

$W_{hs} = 1.699\, lbf$

C1.18 Typical Upper Compressed Specimen Stack (Graphite, Dwg. 630431 & 630427)

Upper Graphite Push Rod (simplified)

$D_{ugpr1} := 0.500 \cdot in$ — D_{ugpr1} = outer diameter of push rod

$D_{ugpr2} := 0.252 \cdot in$ — D_{ugpr2} = diameter of push rod hole

$L_{ugpr1} := 15.431 \cdot in$ — L_{ugpr1} = length of push rod

$L_{ugpr2} := 14.950 \cdot in$ — L_{ugpr2} = length of hole

$$W_{ugpr} := \frac{\pi}{4} \cdot \left(D_{ugpr1}^{2} \cdot L_{ugpr1} - D_{ugpr2}^{2} \cdot L_{ugpr2} \right) \cdot \rho_{graphite}$$

$W_{ugpr} = 0.146\,lbf$ — W_{ugpr} = weight of upper graphite push rod

Stressed Creep Specimens (15 total)

$D_{scs} := 0.501 \cdot in$ — D_{scs} = diameter of stressed creep specimen

$L_{scs} := 1.00 \cdot in$ — L_{scs} = length of specimen

$W_{scs} := \frac{\pi}{4} \cdot D_{scs}^{2} \cdot L_{scs} \cdot \rho_{graphite}$ — W_{scs} = weight of stressed creep specimen

$W_{scs} = 0.013\,lbf$ (each)

Specimen Spacer (16 total)

$D_{ss} := 0.475 \cdot in$ — D_{ss} = outer diameter of spacer (no nubs - considered negligible)

$L_{ss} := 0.25 \cdot in$ — L_{ss} = length of spacer

$W_{ss} := \frac{\pi}{4} \cdot D_{ss}^{2} \cdot L_{ss} \cdot \rho_{graphite}$ — W_{ss} = weight of specimen spacer

$W_{ss} = 0.003\,lbf$ (each)

Graphite Specimen Separator (Stop Block)

$D_{gss1} := 0.625 \cdot in$ — D_{gss1} = maximum outer diameter of separator

$L_{gss1} := 1.00 \cdot in$ — L_{gss1} = length of maximum outer diameter

$D_{gss2} := 0.472 \cdot in$ D_{gss2} = minimum outer diameter of separator

$L_{gss2} := 1.00 \cdot in$ L_{gss2} = length of minimum outer diameter

$$W_{gss} := \frac{\pi}{4} \cdot \left(D_{gss1}^{2} \cdot L_{gss1} + D_{gss2}^{2} \cdot L_{gss2} \right) \cdot \rho_{graphite}$$

$W_{gss} = 0.031\,lbf$ W_{gss} = weight of graphite specimen separator

Piggy Back Specimens (15 total)

$D_{pb1} := 0.249 \cdot in$ D_{pb1} = diameter of piggy back specimen

$L_{pb1} := 0.25 \cdot in$ $L._{pb1}$ = length of piggy back specimen

$W_{pb1} := \frac{\pi}{4} \cdot D_{pb1}^{2} \cdot L_{pb1} \cdot \rho_{graphite}$ W_{pb1} = weight of piggy back specimen

$W_{pb1} = 0.001\,lbf$

Total Weight of Upper Compressed Specimen Stack (W_{ucss})

$$W_{ucss} := W_{ugpr} + 15 \cdot \left(W_{scs} + W_{pb1} \right) + 16 \cdot W_{ss} + 6 \cdot W_{gss}$$

$W_{ucss} = 0.578\,lbf$

(Note that the weight of the alignment pins was not calculated. However, their weight was included in the total weight W_{ucss} because the pin holes in the matching components were not deducted from their individual weights.)

C1.19 Typical Lower Uncompressed Specimen Stack (Graphite, Dwg. 630431 & 630427)

Unstressed Control Specimens (14 total)

$D_{ucs} := 0.501 \cdot in$ — D_{ucs} = diameter of unstressed control specimen

$L_{ucs} := 1.00 \cdot in$ — L_{ucs} = length of specimen

$W_{ucs} := \frac{\pi}{4} \cdot D_{ucs}^{2} \cdot L_{ucs} \cdot \rho_{graphite}$ — W_{ucs} = weight of unstressed control specimen

$W_{ucs} = 0.013\,lbf$ (each)

Specimen Spacer (25 total)

$D_{ss9} := 0.475 \cdot in$ — D_{ss9} = outer diameter of spacer (no nubs)

$L_{ss9} := 0.25 \cdot in$ — L_{ss9} = length of spacer

$W_{ss9} := \frac{\pi}{4} \cdot D_{ss}^{2} \cdot L_{ss} \cdot \rho_{graphite}$ — W_{ss9} = weight of specimen spacer

$W_{ss9} = 0.003\,lbf$ (each)

Unstressed Piggy Back Specimens (10 total)

$D_{upb} := 0.501 \cdot in$ — D_{upb} = diameter of piggy back specimen

$L_{upb} := 0.25 \cdot in$ — L_{upb} = length of piggy back specimen

$W_{upb} := \frac{\pi}{4} \cdot D_{upb}^{2} \cdot L_{upb} \cdot \rho_{graphite}$ — W_{upb} = weight of piggy back specimen

$W_{upb} = 0.003\,lbf$ (each)

Lower Graphite Push Rod

$D_{lcpr} := 0.457 \cdot in$ — D_{lcpr} = outer diameter of lower push rod

$L_{lcpr} := 27.262 \cdot in$ — L_{lcpr} = length of lower push rod

$W_{lcpr} := \frac{\pi}{4} \cdot \left(D_{lcpr}^{2} \cdot L_{lcpr}\right) \cdot \rho_{graphite}$

$W_{lcpr} = 0.287\,lbf$ — W_{lcpr} = weight of lower cylinder push rod (no holes accounded for)

Total Weight of Lower Uncompressed Specimen Stack (W_{luss})

$$W_{luss} := 14 \cdot W_{ucs} + 25 \cdot W_{ss9} + 10 \cdot W_{upb} + W_{lcpr}$$

$$W_{luss} = 0.566\,lbf$$

(Note that the weight of the alignment pins was not calculated. However, their weight was included in the total weight W_{luss} because the pin holes in the matching components were not deducted from their individual weights.)

C1.20 Perimeter Channel Stack (Upper Compressed plus Lower Uncompressed Stacks)

$W_{pcs} := W_{ucss} + W_{luss}$ W_{pcs} = weigth of perimeter channel stack

$$W_{pcs} = 1.145\,lbf$$

C1.21 Center Channel Uncompressed Specimen Stack (Graphite, Dwg. 630431 & 630427)

This center channel consists of a upper center spacer, an uncompressed stack of piggy back specimens and spacers, and the lower center spacer. It may be looked at as a continuous stack of graphite 0.500-inches in diameter.

$D_{cc} := 0.500 \cdot in$ D_{cc} = outer diameter of stack

$L_{cc} := 20.75 \cdot in + 48.00 \cdot in + 27.030 \cdot in$ L_{cc} = stack total length

$$L_{cc} = 95.78\,in$$

$W_{cc} := \frac{\pi}{4} \cdot D_{cc}^{2} \cdot L_{cc} \cdot \rho_{graphite}$ W_{cc} = weight of center channel stack

$$W_{cc} = 1.205\,lbf$$

C1.22 Lower Line Cylinders (Dwg 630430, Bimba Online Data, SR-022-P-V)

$W_{llc} := 0.5 \cdot lbf$ W_{llc} = 0.16 lbf weight of each of the 6 lower line cylinders with a 2 inch stroke, rounded up to 0.5 lbf to account for any mounting hardware

C1.23 Channel Through Tubes (304L SST, Dwg. 630430)

$D_{ctt} := 0.188 \cdot in$ D_{ctt} = tube outer diameter

$t_{ctt} := 0.065 \cdot in$ t_{ctt} = tube wall thickness

$L_{ctt} := 86 \cdot in$ L_{ctt} = tube length

$W_{ctt} := \pi \cdot D_{ctt} \cdot t_{ctt} \cdot L_{ctt} \cdot \rho_{304sst}$ W_{ctt} = weight of each of the 6 channel through tubes

$W_{ctt} = 0.941\, lbf$

C1.24 Gas Lines (304L SST, Dwg. 630430)

These gas lines are 1/16-inch O.D. with 0.010-inch thick walls. Their weight is negligible.

C1.25 Thermocouple Lines and Other Wires (Dwg. 630430)

These lines and wires are also of negligible weight.

C1.26 Hanger Rod Assembly (out-of-reactor, Dwg. 630429)

Top Head Seal Nut (304 SST, ASME SA-240) - Simplified

$D_{thsn1} := 2.50 \cdot in$ D_{thsn1} = thread diameter

$D_{thsn2} := 1.385 \cdot in$ D_{thsn2} = through hole diameter

$L_{thsn} := 2.50 \cdot in$ L_{thsn} = nut length

$$W_{thsn} := \frac{\pi}{4} \cdot \left(D_{thsn1}^{2} - D_{thsn2}^{2}\right) \cdot L_{thsn} \cdot \rho_{304sst}$$

$W_{thsn} = 2.424\, lbf$ W_{thsn} = weight of top head seal nut

Outer Tube (304 SST, ASME SA-213)

$D_{ot} := 2.375 \cdot in$ D_{ot} = tube outer diameter

$t_{ot} := 0.125 \cdot in$ t_{ot} = tube thickness

$L_{ot} := 26 \cdot in$ L_{ot} = length of tube

$$W_{ot} := \frac{\pi}{4} \cdot \left[D_{ot}^{2} - \left(D_{ot} - 2 \cdot t_{ot} \right)^{2} \right] \cdot L_{ot} \cdot \rho_{304sst}$$

$W_{ot} = 6.547\,lbf$ W_{ot} = weight of outer tube

Bayonet (304 SST, ASME SA-240) - Simplified

$D_{b1} := 1.75 \cdot in$ D_{b1} = assumed equivalent outer diameter for simplified bayonet

$D_{b2} := 1.25 \cdot in$ D_{b2} = inner diameter of through hole

$L_{b9} := 3.0 \cdot in$ L_{b9} = length

$$W_{b9} := \frac{\pi}{4} \cdot \left(D_{b1}^{2} - D_{b2}^{2} \right) \cdot L_{b9} \cdot \rho_{304sst}$$ W_{b9} = weight of bayonet

$W_{b9} = 1.007\,lbf$

Other Components Inside the Outer Tube

Insufficient data is available to calculate the weight of the other components that are within the outer tube. Therefore, it will be assumed that those components are 5 lbf or less.

$W_{other} := 5.0 \cdot lbf$ W_{other} = assumed weight of interior components

$$W_{hanger_rod} := W_{other} + W_{b9} + W_{ot} + W_{thsn}$$

$W_{hanger_rod} = 14.979\,lbf$ W_{hanger_rod} = total out of reactor component weight

C1.27 Total Capsule Facility Weight

$W_{boundary_in} := W_{hr} + W_{tf} + W_b + W_{bc}$

$W_{boundary_in} = 173.1\,lbf$

[hanger rod + transition funnel + capsule facility body + bottom cap]

$W_{upper_in} := 6 \cdot W_{ulc} + 2 \cdot W_{mpl} + W_{prap} + 6 \cdot W_{pb} + 3 \cdot (W_{lpr} + W_{spr}) + 6 \cdot W_{lcab}$

$W_{upper_in} = 64.6\,lbf$

[6 upper line cylinders + 2 upper mounting plates + 4 push rod alignment plates + 6 push bars + 3 long and 3 short push rods + 6 attachment bolts]

$W_{lower_in} := W_{lst} + W_{cbp} + W_{lgs} + W_{lgsh} + W_{ugsh} + W_{hs} + 6 \cdot W_{pcs} + W_{cc} + 6 \cdot (W_{llc} + W_{ctt})$

$W_{lower_in} = 30\,lbf$

[lower spacer tube + capsule bottom plate + lower graphite spacer + lower graphite specimen holder + upper graphite specimen holder + heat shield + 6 perimeter channel stacks + center channel stack + 6 lower line cylinders + 6 channel through tubes]

$W_{total_in} := W_{boundary_in} + W_{upper_in} + W_{lower_in}$

$W_{total_in} = 267.7\,lbf$

W_{total_in} = total weight inside of reactor

$W_{total_out} := W_{hanger_rod} + W_{sn}$

W_{total_out} = out-of-vessel hanger rod and seal plug

$W_{total_out} = 78.8\,lbf$

$W_{total} := W_{total_in} + W_{total_out}$

W_{total} = total weight of facility

$W_{total} = 347\,lbf$

The weight of the displaced in-reactor water is calculated as follows:

$\rho_{water} := 62.4 \cdot \frac{lbf}{ft^3}$

$W_{water} := \rho_{water} \cdot \left[\frac{\pi}{4} \cdot \left(D_o^{\,2} \cdot L_{hr} + D_{bo}^{\,2} \cdot L_b \right) + \frac{\pi}{3} \cdot h_{tf} \cdot \left(R_o^{\,2} + R_o \cdot r_o + r_o^{\,2} \right) + V_{sp} \right]$

$W_{water} = 135\,lbf$

Therefore, the total capsule facility weight in water is:

$W_{net} := W_{total} - W_{water}$

$W_{net} = 211\,lbf$

C2. Hydrodynamic Mass

The hanger rod extension and transition tubes, the transition funnel, and the capsule facility body are inside the ATR vessel. The mass of these components, for the purposes of calculating system natural frequencies and responses due to seismic loadings, will include a "hydrodynamic mass" to account for the effects of the reactor coolant. The calculation of the hydrodynamic mass will follow that given in Reference C1, consistent with the analysis of previous ATR experiment evaluations (Ref.'s C2 & C3). Above the locater tie that secures the top the chopped dummy inpile tube that is located within the South flux trap, into which the AGC-1 experiment will be inserted, the hanger rod extension and transition tubes, the transition funnel, and the capsule facility body look like "components in a large pool of water."

C2.1 Above the Locater Tie

Hanger Rod Extension and Transition Tubes, and Funnel Transition Tube

$\rho_{water} = 0.036 \frac{lbf}{in^3}$ — ρ_{water} = weight of water per volume

$D_{o_hrt} := 5.000 \cdot in$ — D_{o_hrt} = outside diameter of hanger rod tubes

$M_{h_hrt} := \rho_{water} \cdot \pi \cdot \left(\frac{D_{o_hrt}}{2}\right)^2$ — M_{h_hrt} = additional hydrodynamic mass (in terms of weight) per 1 foot of hanger rod tube length

$M_{h_hrt} = 8.508 \frac{lbf}{ft}$

Transition Funnel

$D_{o_f_average} := \frac{5 \cdot in + 2.5 \cdot in}{2}$ — $D_{o_f_average}$ = average diameter of funnel

$D_{o_f_average} = 3.75\, in$

$h_f := 5.375 \cdot in$ — h_f = funnel length

$M_{h_funnel} := \rho_{water} \cdot \pi \cdot \left(\frac{D_{o_f_average}}{2}\right)^2 \cdot h_f$ — M_{h_funnel} = additional hydrodynamic mass (in terms of weight) of the funnel

$M_{h_funnel} = 2.144\, lbf$ (total additional weight on funnel)

Capsule Facility Body

$D_{o_cfb} := 2.500 \cdot in$

D_{o_cfb} = outer diameter of capsule facility body tube

$$M_{h_cfb} := \rho_{water} \cdot \pi \cdot \left(\frac{D_{o_cfb}}{2}\right)^2$$

$$M_{h_cfb} = 2.127 \frac{lbf}{ft}$$

M_{h_cfb} = additional hydrodynamic mass (in terms of weight) per 1 foot of capsule faciltiy body tube length

C2.2 Below the Locater Tie

Below the locater tie the capsule facility body is within the chopped dummy in-pile tube, with transverse restraint provided by that tube. The chopped dummy in-pile tube is transversly supported by the locater tie and as it passes through the core South flux trap. No mass to account for hydrodynamic effects is necessary in this region.

C3. Piping Model Weights

The piping model requires a weight per foot to be entered for each section/component as part of the model input. This will be calculated next.

C3.1 Hanger Rod Extension Tube

The weight per foot of hanger rod extension tube for the piping model will include the self weight of the tube and the hydrodynamic weight. (Other components in the extension tube such as gas lines, thermocouple leads, etc., are all very lightweight components and will be ignored throughout these piping weight calculations.)

$L_{HRET} = 108.15\,in$

L_{HRET} = length of hanger rod extension tube

$$W_{HRET} := \frac{W_{hr}}{L_{hr}} + M_{h_hrt}$$

W_{HRET} = model weight per foot for hanger rod extension tube length

$$W_{HRET} = 18.228\,\frac{lbf}{ft}$$

C3.2 Hanger Rod Transition Tubes & Funnel Transition Tube

The weight per foot of the three hanger rod transition tubes (each 12 inches long) and the funnel transition tube (6 inches long) will be averaged over the total length (42 inches). The total weight will include the weight of the tubes, two upper cylinder mounting plates, three push rod alignment plates, six upper line cylinders, six push bars, six load cell attachment bolts, and the portion of the push rods in those tubes (14 inches long for three long rods, 2 inches long for three short rods), and the hydrodynamic weight.

$$W_{prap_tt} := W_{prap1} + W_{prap2} + W_{prap3}$$

W_{prap_tt} = alignment plates in these tubes

$$W_{prap_tt} = 3.19\,lbf$$

$$W_{hrtt_d} := \frac{W_{hr}}{L_{hr}} \cdot 42in + 2 \cdot W_{mpl} + W_{prap_tt} + 6 \cdot \left(W_{ulc} + W_{pb} + W_{lcab}\right) + \frac{W_{lpr}}{L_{lpr}} \cdot 3 \cdot (14 \cdot in + 2 \cdot in)$$

$$W_{hrtt_d} = 71.557\,lbf$$

W_{hrtt_d} = total dry weight of components

$$W_{HRTT} := \frac{W_{hrtt_d}}{42 \cdot in} + M_{h_hrt}$$

W_{HRTT} = model weight per foot of these transition tubes

$$W_{HRTT} = 28.953\,\frac{lbf}{ft}$$

Initial runs in the PipeStress piping program showed that some internal checks within the program did not allow such a large weight per foot for this pipe size. Therefore, the workaround was to use the Hanger Rod Extension Tube weight per foot value with an additional weight placed at each cylinder mounting plate and push rod alignment plate in these tubes.

$$W_{upper_c} := \frac{(W_{HRTT} - W_{HRET}) \cdot 42 \cdot in}{5}$$

W_{upper_c} = concentrated weight at each cylinder mounting and alignment plate

$W_{upper_c} = 7.507\,lbf$ applied at each of the five plates

C3.3 Transition Funnel

The weight per foot of the transition funnel (which is 5.375 inches long) will include the self weight, the weight of six push rods passing through it, and the hydrodynamic weight.

$L_{TF} := h_{tf}$ $\quad L_{TF} = 5.375\,in$

L_{TF} = length of transition funnel

$$W_{TF} := \frac{W_{tf} + 3 \cdot h_{tf} \cdot \left(\frac{W_{lpr}}{L_{lpr}} + \frac{W_{spr}}{L_{spr}}\right) + M_{h_funnel}}{h_{tf}}$$

$W_{TF} = 18.408\,\frac{lbf}{ft}$

W_{TF} = model weight per foot for transition funnel

C3.4 Capsule Facility Body

The weight per foot of the capsule facility body will include the weight of the tube, the weight of all internal components including the push rods, one push rod stabilizing plate, the graphite specimen holders and specimens, the lower graphite spacer, the heat shield, the capsule bottom plate, lower spacer tube, the channel through tubes, the bottom cap, and the hydrodynamic weight addition above the locater tie.

Above the Locater Tie (about 12 inches of length)

$L_{alt} := 12 \cdot in$

L_{alt} = length above locater tie

$$W_{CFB_1} := \frac{W_b}{L_b} + 3 \cdot \left(\frac{W_{spr}}{L_{spr}} + \frac{W_{lpr}}{L_{lpr}}\right) + M_{h_cfb}$$

W_{CFB_1} = model weight per foot of capsule facility body above locater tie

$W_{CFB_1} = 10.933\,\frac{lbf}{ft}$

From Locater Tie to Top of the Upper Graphite Specimen Holder (40.125 inches of length, top of holder is 14.875 inches above top of core)

$L_{blt} := 40.125 \cdot in$

L_{blt} = length from locater tie to top of upper specimen holder

$$W_{CFB_2} := \frac{W_b}{L_b} + 3 \cdot \left(\frac{W_{spr}}{L_{spr}} + \frac{W_{lpr}}{L_{lpr}}\right) + \frac{W_{prap4}}{L_{blt}}$$

W_{CFB_2} = model weight per foot of capsule facility body between locater tie and top of upper specimen holder

$W_{CFB_2} = 8.846\,\frac{lbf}{ft}$

From Top of Upper Graphite Specimen Holder to Bottom Cap (97.385 inches).
[In this region the weight will be evenly distributed over the length. This simplification is considered acceptable since the transverse motion is restrained by the chopped dummy inpile tube held by the reactor core. The only motion would be in the vertical direction, which will be unaffected by the simplified even distribution of weight.]

$L_8 := 8 \cdot in$

L_8 = 8-inch length of upper push rods in the top of the upper specimen holder

$L_{remaining} := 94.385 \cdot in$

$L_{remaining}$ = length from top of upper specimen holder to bottom cap

$$W_{CFB_3} := \frac{W_b}{L_b} + \frac{W_{bc} + W_{lower_in} + 3 \cdot \left(\frac{W_{lpr}}{L_{lpr}} + \frac{W_{spr}}{L_{spr}} \right) \cdot L_8}{L_{remaining}}$$

$W_{CFB_3} = 8.138 \frac{lbf}{ft}$

W_{CFB_3} = model weight per foot of capsule body between top of upper specimen holder to bottom cap, evenly distributed

Check to see that all weight was accounted for:

$W_{check1} := W_{HRET} L_{HRET} + 5 \cdot W_{upper_c} + W_{HRET} \cdot 42 \cdot in$

$W_{check1} = 265.6\, lbf$

$W_{check2} := W_{TF} \cdot L_{TF} + W_{CFB_1} \cdot L_{alt} + W_{CFB_2} \cdot L_{blt} + W_{CFB_3} \cdot L_{remaining}$

$W_{check2} = 112.8\, lbf$

$W_{check_total} := W_{check1} + W_{check2}$

W_{check_total} = total model weight

$W_{check_total} = 378.4\, lbf$

The total model weight (W_{check_total}) should equal the total in-vessel dry weight (W_{total_in}) plus the hydrodynamic weights of the in-vessel hanger rod tubes, transition funnel, and capsule facility body above the locater tie:

$W_{verify} := W_{total_in} + M_{h_hrt} \cdot L_{hr} + M_{h_funnel} + M_{h_cfb} \cdot L_{alt}$

$W_{verify} = 378.5\, lbf$

W_{verify} = weight for verifying against W_{check_total}

:The model weight (W_{check_total}) is considered an acceptable match to the verified weight (W_{verify}).

C4. References

C1. R. J. Fritz, *The Effects of Liquids on the Dynamic Motions of Immersed Solids*, Transactions of the ASME Journal of Engineering for Industry, February 1972.

C2. S. D. Snow, *Structural Evaluation of the ATR Irradiation Capsule Experiment (ICE) Test and Facility*, EDF ATR-TRA-1275, Rev. 0, November 1997.

C3. R. K. Blandford, *Structural Evaluation of the ATR Multiple Irradiation Capsule Experiment (MICE) Test Train, Facility and Equipment*, EDF ATR-TRA-1512, Rev. 0, September 1999.

Appendix D

ASME Code - Computer Calculations

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The Class 3 in-vessel portion of the AGC-1 experiment consists of the hanger rod extension and transition tubes, a funnel transition tube, a transition funnel, the capsule facility body (tube also), and a bottom cap. Appendix B evaluated these components using the design by rule (specifically, for minimum thickness requirements) equations for design and Service Levels A through C conditions. Loadings considered included internal and external pressure, flow drag, and flow vibration at the condition temperature. Other Code design requirements, including Service Level D (seismic) conditions will be evaluated in this appendix using computer-based analysis methods.

This AGC-1 experiment resembles a piping system more than a traditional vessel design. The ASME Code for Class 3 components (Ref. 3 of the report main body references), Subsection ND-3600 defines the requirements for piping systems. This typically requires the evaluation of design conditions (sustained mechanical loads: ND-3652, Equation 8), Service Level A and B conditions (occasional mechanical loads: ND-3653.1, Equation 9) including thermal expansion (ND-3653.2, Equation 10), Service Level C conditions (ND-3654.2 → ND-3653.1, Equation 9), and Service Level D conditions (ND-3655 → ND-3653.1, Equation 9), each with specified allowable stress limits. In these equations, pressure stresses (where applicable) are added to the stresses produced by moments in the pipe due to sustained and occasional loadings (e.g., gravity, seismic).

However, because this experiment is a straight, vertically oriented assembly (see Figure D1), there are no moments produced in the pipe due to gravity and no moments due to thermal expansion (experiment is unrestrained longitudinally). Therefore, the minimum thicknesses calculations performed in Appendix B satisfy the design and Service Level A through C conditions and the associated required calculations. Only the Service Level D seismic conditions produce moments in the AGC-1 experiment.

Therefore, this appendix will only address the analysis of the in-vessel portion of the AGC-1 experiment under the Service Level D conditions. The following analysis employed the PipeStress computer program, run on computer MIRA, which has been validated (see Appendix A) for application to piping systems being analyzed to the requirements of the ASME Code for Class 3 piping.

The report main body defined the seismic loading which consisted of two enveloping acceleration response spectra (at 5% critical damping). The experiment was modeled consistent with the design drawings, using the piping model weights calculated in Appendix C. The ASME Code requires that Subsection ND-3653.1 Equation (9) be satisfied. That equation is as follows:

$B_1 * P_{max} * D_o / 2 * t_n + B_2 * (M_A + M_B) / Z \leq 3 * S_h$ or $2 * S_y$

where:

B_1, B_2 = primary stress indices for the specific product under investigation
P_{max} = peak pressure (use 390 psig, even though this is external design/operating pressure)
D_o = outside diameter of the component
t_n = nominal thickness of the component
M_A = moment on the pipe due to sustained loads (0 in this case)
M_B = moment on the component due to seismic loads (to be calculated by PipeStress)
S_h = allowable stress at temperature (240 F, @20 ksi for 304 – see Table 2 in report)
S_y = yield strength at temperature (240 F, @ 23.9 ksi for 304)

Figure D1 shows the model of the AGC-1 experiment.

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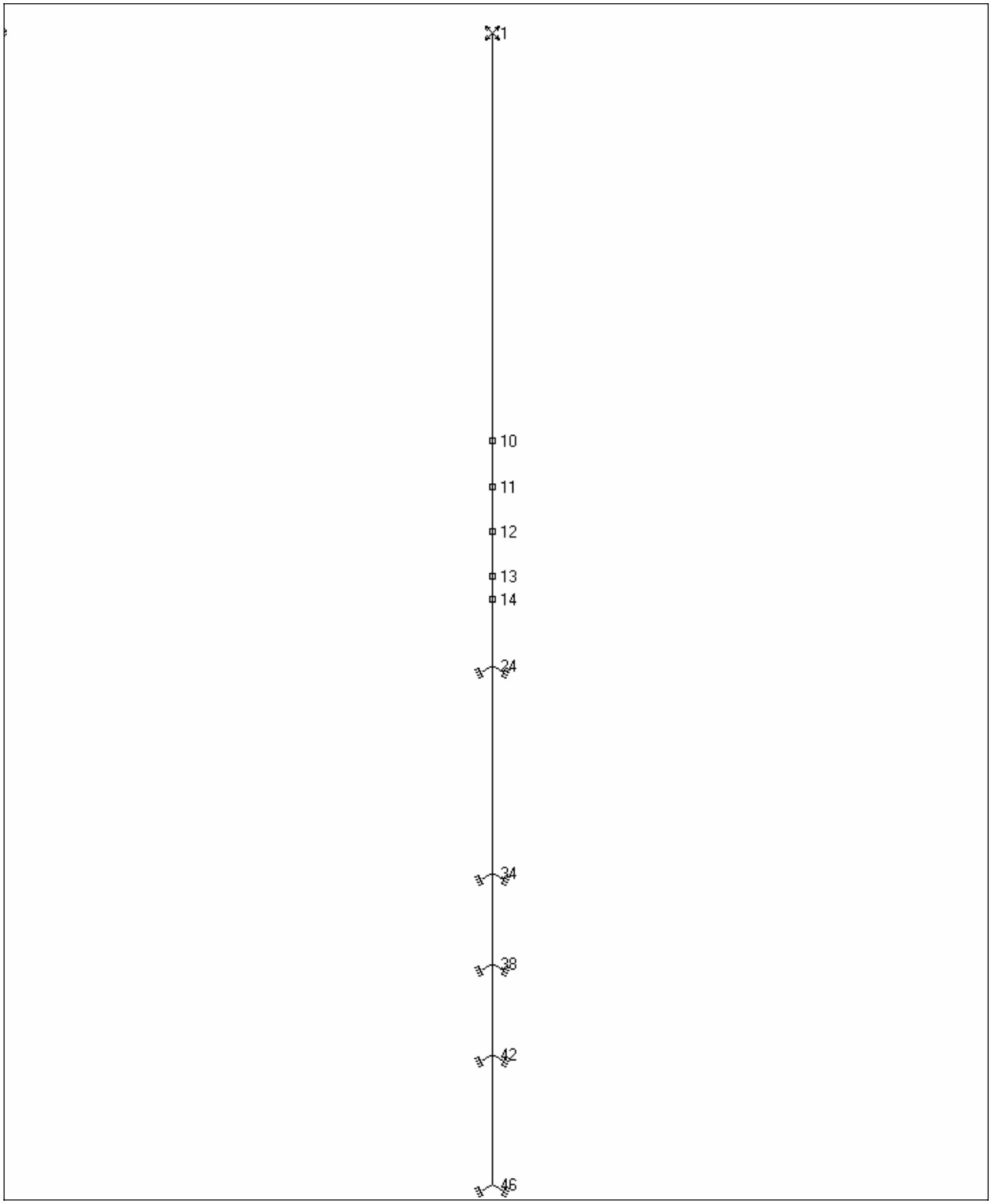

Figure D1. PipeStress model of AGC-1 experiment. (+Y up, +X & +Z Horizontal)

On the PipeStress model (shown in Figure D1), the following represents:

- Point 1 represents the seal plug which is anchored (6-direction restraint),
- Points 1 through 10 represent the hanger rod extension tube,
- Points 10 through 14 represent the hanger rod and funnel transition tubes,
- Points 14 to 20 represent the transition funnel,
- Points 20 through 46 represent the capsule facility body,
- Point 24 represents the locater tie (horizontal restraints),
- Point 34 represents the top of the core (horizontal restraints),
- Point 38 represents the core centerline (horizontal restraints),
- Point 42 represents the core bottom (horizontal restraints),
- Point 46 represents the bottom cap (horizontal restraints).

The capsule facility body enters the chopped dummy in-pile tube at 2-inches above the locater tie and is contained within that tube through the bottom cap. The chopped dummy in-pile tube essentially restrains the capsule facility body from horizontal motion, though above and below the reactor core some small motion of the in-pile tube is possible. Therefore, the capsule facility body was only restrained horizontally at the locater tie, the top, middle, and bottom of the core, and at the bottom cap. This was considered conservative since it would allow for some horizontal motion between those support points.

First, the natural frequencies of the system were calculated as follows:

Mode	Frequency (Hz.)
1 and 2	20.1
3 and 4	56.7
5 and 6	81.2

Each mode occurred twice, once in the model +X horizontal direction and once in the model +Z horizontal direction (because of symmetry). There were no modes below 100 Hz. whose motion was in the vertical (model Y) direction.

Next, the acceleration response spectra were applied to the model. Again, it is noted that the external design/operating pressure of 390 psig with a 0 psig internal pressure were employed in this PipeStress model. The Equation (9) resulting stresses in the model components were as follows:

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```
CALCULATION NUMBER  100         CODE SECTION III CLASS 3  ASME-2001 REV A02  SDSnow              2006/05/04  09:55:04  [129]
AGC-1 Class 3 Analysis

LOADING CASE NO.  20     COMB.STRESS ANALYSIS - DW + Press + Seismic          PR CASE   1   CASES MA=   1 MB=  11 MC=   0
                                                                              METH ABSADD   FACT      1.0     1.0

EQUATION 9    OCCASIONAL LOAD - LEVEL D
                                                                              ========== STRESSES IN PSI ==========
```

	POINT NO.	-------- MOMENT STRESSES -------- SUST	OCCAS	THERM	B2	MOMENT STRESS	B1 LOCAL	L PRES STRESS	TOTAL STRESS	STRESS RATIO
ANCHOR	1									
			* ALLOWABLE STRESS MIN(3.0SH,2.0SY) =				47800. *			
TANGENT	1	0.	1204.		1.000	1204.	0.500	2593.	3797.	0.079
	2	0.	869.		1.000	869.	0.500	2593.	3463.	0.072
TANGENT	2	0.	869.		1.000	869.	0.500	2593.	3462.	0.072
	3	0.	540.		1.000	540.	0.500	2593.	3133.	0.066
TANGENT	3	0.	540.		1.000	540.	0.500	2593.	3133.	0.066
	4	0.	223.		1.000	223.	0.500	2593.	2816.	0.059
TANGENT	4	0.	223.		1.000	223.	0.500	2593.	2816.	0.059
	5	0.	82.		1.000	82.	0.500	2593.	2675.	0.056
TANGENT	5	0.	82.		1.000	82.	0.500	2593.	2675.	0.056
	6	0.	337.		1.000	337.	0.500	2593.	2930.	0.061
TANGENT	6	0.	337.		1.000	337.	0.500	2593.	2931.	0.061
	7	0.	551.		1.000	551.	0.500	2593.	3144.	0.066
TANGENT	7	0.	551.		1.000	551.	0.500	2593.	3144.	0.066
	8	0.	708.		1.000	708.	0.500	2593.	3301.	0.069
TANGENT	8	0.	708.		1.000	708.	0.500	2593.	3301.	0.069
	9	0.	802.		1.000	802.	0.500	2593.	3395.	0.071
TANGENT	9	0.	802.		1.000	802.	0.500	2593.	3395.	0.071
1 Trans Begins	10	0.	828.		1.000	828.	0.500	2593.	3421.	0.072
TANGENT	10	0.	828.		1.000	828.	0.500	2593.	3421.	0.072
2 Trans Begins	11	0.	761.		1.000	761.	0.500	2593.	3354.	0.070
TANGENT	11	0.	761.		1.000	761.	0.500	2593.	3354.	0.070
3 Trans Begins	12	0.	609.		1.000	609.	0.500	2593.	3202.	0.067
TANGENT	12	0.	609.		1.000	609.	0.500	2593.	3202.	0.067
4 Trans Begins	13	0.	389.		1.000	389.	0.500	2593.	2982.	0.062
TANGENT	13	0.	388.		1.000	388.	0.500	2593.	2981.	0.062
Funnel Begins	14	0.	257.		1.000	257.	0.500	2593.	2850.	0.060
REDUCER	14	0.	220.		1.000f	220.	1.000f	4333.	4553.	0.095
	20	0.	830.		1.000f	830.	1.000f	4062.	4892.	0.102
TANGENT	20	0.	830.		1.000	830.	0.500	2031.	2861.	0.060
	22	0.	142.		1.000	142.	0.500	2031.	2173.	0.045
TANGENT	22	0.	142.		1.000	142.	0.500	2031.	2173.	0.045
	24	0.	1119.		1.000	1119.	0.500	2031.	3150.	0.066
TANGENT	24	0.	1119.		1.000	1119.	0.500	2031.	3150.	0.066
	26	0.	907.		1.000	907.	0.500	2031.	2939.	0.061
TANGENT	26	0.	907.		1.000	907.	0.500	2031.	2939.	0.061
4 Alignment Pl	28	0.	691.		1.000	691.	0.500	2031.	2722.	0.057
TANGENT	28	0.	691.		1.000	691.	0.500	2031.	2722.	0.057
	30	0.	394.		1.000	394.	0.500	2031.	2425.	0.051
TANGENT	30	0.	394.		1.000	394.	0.500	2031.	2425.	0.051
Holder Top	32	0.	62.		1.000	62.	0.500	2031.	2094.	0.044
TANGENT	32	0.	65.		1.000	65.	0.500	2120.	2184.	0.046
Top of Core	34	0.	458.		1.000	458.	0.500	2120.	2578.	0.054
TANGENT	34	0.	458.		1.000	458.	0.500	2120.	2578.	0.054
	36	0.	178.		1.000	178.	0.500	2120.	2297.	0.048
TANGENT	36	0.	178.		1.000	178.	0.500	2120.	2297.	0.048
Core Center	38	0.	108.		1.000	108.	0.500	2120.	2228.	0.047
TANGENT	38	0.	108.		1.000	108.	0.500	2120.	2228.	0.047
	40	0.	46.		1.000	46.	0.500	2120.	2165.	0.045
TANGENT	40	0.	46.		1.000	46.	0.500	2120.	2165.	0.045
Bottom of Core	42	0.	43.		1.000	43.	0.500	2120.	2163.	0.045
TANGENT	42	0.	43.		1.000	43.	0.500	2120.	2163.	0.045
	44	0.	53.		1.000	53.	0.500	2120.	2172.	0.045
TANGENT	44	0.	53.		1.000	53.	0.500	2120.	2172.	0.045
Bottom Cap	46	0.	0.		1.000	0.	0.500	2120.	2120.	0.044

The above shows the sustained stress at zero (as expected due to no moments caused by gravity), the pressure stress due to the 390 psig external design/operating pressure, and the stresses due to the occasional (seismic) loads. The largest total Eqn. (9) stress of 4,892 psi occurred in the transition funnel at Point 20. This is very low, especially when compared to the allowable stress of 40,800 psi (shown above).

:AGC-1 Experiment design satisfies the ASME Code for Class 3 components under the specified seismic loading.

PipeStress Input Model

```
*AGC-1 Experiment
*Spencer Snow
*File Created:  June 2, 2005
*File Last Saved:  May 4, 2006
*-------------Identification and Title cards
IDEN JB=100 CD=3 VA=0 GR=-Y IU=2 OU=2 PL=/AGC-1 Experiment/ EN=/SDSnow/
* JB = 100
* CD = ASME Section III Class 3
* VA = terminate execution if errors occur
* GR = Gravity in -Y direction
* IU & OU = Input and Output Units = In/Lbf
TITL BL=8 GC=1 GL=0 SU=1 IP=0 CV=18 PR=1 HS=1 TI=/AGC-1 Class 3 Analysis/
* BL = Uniform mass for static, lumped mass for dynamic
* GC = report left-out-forces
* GL = forces and moments in global coordinates
* SU = print summary report for supports
* IP = No pressure elongation
* CV = Code version 2001 + 02 Addenda
* PR = Use PDo/2t
* MD = Use hot (oper. temperature) modulus
* HS = Report highest stress points
* TI = report title
*-------------Frequency Analysis card
FREQ LO=1 RP=0 FR=100 MP=100 MX=6 TI=/AGC-1 Frequency Calcs/
* LO = Left-out-forces report
* RP = report mode shape for all modes
* FR = maximum frequency
* MP = auto mass modeling to frequency
* MX = Calculate first 6 modes
*-------------Load Case cards
LCAS CA=1 RF=1 PR=1 TY=3 EC=0 EQ=2 TI=/Weight + Design Pressure Case/
* CA = Case number
* RF = base case
* PR = include pipe loads at restraint locations report
* TY = Type of analysis = weight
* EC = Use modulus of elasticity at operating temperature
* EQ = output based on type of analysis (TY)
*-------------Dynamic Analysis Card
RCAS CA=11 EV=1 PR=1 TY=2 EQ=5 SU=1 MX=0 FX=1.0 FY=1.0 FZ=1.0 LO=9
     TI=/Spectra Envelope, 5% Damping/
* CA = Case number
* EV = Event number
* PR = Include selected supports in the report
* TY = Safe shutdown
* EQ = Level D event
* SU = SRSS addition, 10% grouping, SRSS
* MX = Response case is based on the number of requested modes
* LO = left out forces (missing mass) included by SRSS
CSTR CA=20 RF=1 PR=1 OP=0 ME=1 EQ=5 MA=1 MB=11
     TI=/DW + Press + Seismic/
* CA = Case Number
* RF = Reference operating case number
* PR = Pipe loads at restraints reported
* ME = Add cases using absolute values
* OP = write out all output
```

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```
* EQ = ASME Equation 9
* MA = Case number for sustained load
* MB = Case number for occasional load
SPEC FS=ENV EV=1 RA=0 FP=0 ME=1 BT=5 TI=/Spectra Envelope/
     LV=1
     DI=XZ
      0.00/0.000  0.001/0.013  1.00/0.354    2.50/0.751
      9.00/0.626  13.50/0.512  33.0/0.303    50.0/0.240
     100.0/0.240
     DI=Y
      0.00/0.000  0.001/0.009   1.00/0.236   2.50/0.501
      7.63/0.435  20.00/0.435   33.0/0.274   50.0/0.180
     100.0/0.180
* FS = Spectrum name
* EV = Event number
* RA = Spectral acceleration not to exceed 10g
* FP = Spectrum is Freq. vs. Accel
* ME = Linear Freq vs. linear Accel
* BT = Percent critical damping = 5%
*-------------Define Materials
*--304L Stainless Steel for Transition Funnel
MATH CD=304 EX=0 TY=4 TX=240.0 TA=70.0 AL=/304 SST/
* 304 Stainless steel
* EX = linear thermal expansion (in/100 ft)
* TY = Austennitic Stainless
* TX = Maximum temperature of 240 deg. F
* TA = Ambient temperature of 70 deg. F
MATD TE=70.0 EH=28.3 EX=0.0  SH=20.0 SY=30.0 SM=20.0
MATD TE=100. EH=28.3 EX=0.3  SH=20.0 SY=30.0 SM=20.0
MATD TE=180. EH=27.7 EX=1.16 SH=20.0 SY=25.7 SM=20.0
MATD TE=200. EH=27.6 EX=1.40 SH=20.0 SY=25.0 SM=20.0
MATD TE=240. EH=27.4 EX=1.88 SH=20.0 SY=23.9 SM=20.0
*-------------Define OPERATING & Design Conditions
DESN PR=390.0 TE=240.0
OPER CA=1 TE=240.0 PR=390.0
*-------------Define Piping
MATL CD=304 AL=/304 SST/
CROS CD=1 OD=5.000 WT=0.188 MA=18.228 SO=0.0 AL=/Extension Tube/
COOR PT=1 AX=0.0 AY=0.0 AZ=0.0
ANCH PT=1 EW=2 AL=/Seal Plug/
TANG PT=2 DY=-12.0
TANG PT=3 DY=-12.0
TANG PT=4 DY=-12.0
TANG PT=5 DY=-12.0
TANG PT=6 DY=-12.0
TANG PT=7 DY=-12.0
TANG PT=8 DY=-12.0
TANG PT=9 DY=-12.0
TANG PT=10 DY=-12.15 EW=1 AL=/1 Trans Begins/
LUMP PT=10 MA=7.526 AL=/1 Mounting Plt/
TANG PT=11 DY=-12.0 EW=1 AL=/2 Trans Begins/
LUMP PT=11 MA=7.526 AL=/2 Mounting Plt/
TANG PT=12 DY=-12.0 EW=1 AL=/3 Trans Begins/
LUMP PT=12 MA=7.526 AL=/1 Alignment Plt/
TANG PT=13 DY=-12.0 EW=1 AL=/4 Trans Begins/
LUMP PT=13 MA=7.526 AL=/2 Alignment Plt/
TANG PT=14 DY=-6.0 EW=1 AL=/Funnel Begins/
```

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```
LUMP PT=14 MA=7.526 AL=/3 Alignment Plt/
CROS CD=2  OD=5.000 WT=0.225 MA=18.408 SO=0.0 AL=/Funnel/
CRED PT=20 EW=1 DY=-5.375
CROS CD=3 OD=2.500 WT=0.120 MA=10.933 SO=0.0 AL=/CFB Begins/
TANG PT=22 DY=-6.0
TANG PT=24 DY=-6.17
RSTN PT=24 PR=1 LO=0 DX=1.0 SP=1.0E6 AL=/Locater Tie/
RSTN PT=24 PR=1 LO=0 DZ=1.0 SP=1.0E6
CROS CD=4 OD=2.500 WT=0.120 MA=8.846 SO=0.0
TANG PT=26 DY=-9.00
TANG PT=28 DY=-8.83 EW=1 AL=/4 Alignment Plt/
TANG PT=30 DY=-11.0
TANG PT=32 DY=-11.295 AL=/Holder Top/
CROS CD=5 OD=2.500 WT=0.115 MA=8.138 SO=0.0
TANG PT=34 DY=-14.875 AL=/Top of Core/
RSTN PT=34 PR=1 LO=0 DX=1.0 SP=1.0E6
RSTN PT=34 PR=1 LO=0 DZ=1.0 SP=1.0E6
TANG PT=36 DY=-12.0
TANG PT=38 DY=-12.0 AL=/Core Center/
RSTN PT=38 PR=1 LO=0 DX=1.0 SP=1.0E6
RSTN PT=38 PR=1 LO=0 DZ=1.0 SP=1.0E6
TANG PT=40 DY=-12.0
TANG PT=42 DY=-12.0 AL=/Bottom of Core/
RSTN PT=42 PR=1 LO=0 DX=1.0 SP=1.0E6
RSTN PT=42 PR=1 LO=0 DZ=1.0 SP=1.0E6
TANG PT=44 DY=-17.255
TANG PT=46 DY=-17.255 EW=4 AL=/Bottom Cap/
RSTN PT=46 PR=1 LO=0 DX=1.0 SP=1.0E6
RSTN PT=46 PR=1 LO=0 DZ=1.0 SP=1.0E6
*-------------End Analysis
```

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Appendix E

Other Computer Calculations

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This appendix contain the computer model that was referenced in Appendix B.

Upper Cylinder Mounting Plate Model

```
**   ==============================================================
**
**     ADVANCED GRAPHITE CREEP EXPERIMENT AGC-1
**     ANALYSIS OF UPPER CYLINDER MOUNTING PLATE (WITH 3 SLOTS)
**
**     MODEL TO RUN IN ABAQUS/STANDARD
**
**          IDEAS MODEL FILE: M:\u1\sds\ideas\MS10\AGC-1_upper_cyl_
                                mounting_plt_final.mf1
**          ABAQUS INPUT FILE: AGC-1_upper_cyl_mounting_plt_final.inp
**          LAST SAVE DATE:    10-Aug-2005
**
**               UNITS: IN-Inch (pound f)
**                      LENGTH : inch
**                      TIME   : sec
**                      MASS   : lbf-sec**2/in
**                      FORCE  : pound (lbf)
**
**         FILE ORGANIZATION:
**          SECTION 1.  NODE DEFINITIONS
**          SECTION 2.  ELEMENT DEFINITIONS
**          SECTION 3.  ADDITIONAL NODE AND ELEMENT SETS
**          SECTION 4.  MATERIAL AND PHYSICAL PROPERTY DEFINITIONS
**          SECTION 5.  CONTACT DEFINITIONS
**          SECTION 6.  SOLUTION STEP DATA
**
**
*HEADING
AGC-1 UPPER CYLINDER MOUNTING PLATE (3 * 600-lbf LOADING)
**
*****************************************************************
**  SECTION 1.  NODE DEFINITIONS
*****************************************************************
**
*NODE, NSET=ALLNODES, SYSTEM=R
         1, 2.4000000E+00, 0.0000000E+00, 2.5000000E-01

(nodes removed for brevity)
**
*****************************************************************
**  SECTION 2.  ELEMENT DEFINITIONS
*****************************************************************
**
*ELEMENT, TYPE=C3D8R, ELSET=PLATE
    708,    536,    533,      1,     21,   2982,   2970,    842,    922

(elements removed for brevity)
**
*****************************************************************
**  SECTION 3.  ADDITIONAL NODE AND ELEMENT SETS
*****************************************************************
**
```

```
*NSET,NSET=BS000001
842,843,844,922,923,924,926,927,928,930,931,932,934,935,936,938
939,940,942,943,944,946,947,948,950,951,952,954,955,956,958,959
960,962,963,964,966,967,968,970,971,972,974,975,976,978,979,980
982,983,984,986,987,988,990,991,992,994,995,996,998,999,1000,1002
1003,1004,1006,1007,1008,1010,1011,1012,1014,1015,1016,1018,1019,1020,1022
1023,1024,1026,1027,1028,1030,1031,1032,1034,1035,1036,1038,1039,1040,1042
1043,1044,1046,1047,1048,1050,1051,1052,1054,1055,1056,1058,1059,1060,1062
1063,1064,1066,1067,1068,1070,1071,1072,1074,1075,1076,1078,1079,1080,1082
1083,1084,1086,1087,1088,1090,1091,1092,1094,1095,1096,1098,1099,1100,1102
1103,1104,1106,1107,1108,1110,1111,1112,1114,1115,1116,1118,1119,1120,1122
1123,1124,1126,1127,1128,1130,1131,1132,1134,1135,1136,1138,1139,1140,1142
1143,1144,1146,1147,1148,1150,1151,1152,1154,1155,1156,1158,1159,1160,1162
1163,1164,1166,1167,1168,1170,1171,1172,1174,1175,1176,1178,1179,1180,1182
1183,1184,1186,1187,1188,1190,1191,1192,1194,1195,1196,1198,1199,1200,1202
1203,1204,1206,1207,1208,1210,1211,1212,1214,1215,1216,1218,1219,1220,1222
1223,1224,1226,1227,1228,1230,1231,1232,1234,1235,1236,1238,1239,1240,1242
1243,1244,1246,1247,1248,1250,1251,1252,1254,1255,1256,1258,1259,1260,1262
1263,1264,1266,1267,1268,1270,1271,1272,1274,1275,1276,1278,1279,1280,1282
1283,1284,1286,1287,1288,1290,1291,1292,1294,1295,1296,1298,1299,1300,1302
1303,1304,1306,1307,1308,1310,1311,1312,1314,1315,1316,1318,1319,1320,1322
1323,1324
*NSET,NSET=BS000002
8,14,20,166,167,168,169,170,171,172,173,174,175,176,177,178
179,180,181,182,183,184,185,186,216,217,218,219,220,221,222,223
224,225,226,227,228,229,230,231,232,233,234,235,236,266,267,268
269,270,271,272,273,274,275,276,277,278,279,280,281,282,283,284
285,286
**
*****************************************************************
**  SECTION 4.  MATERIAL AND PHYSICAL PROPERTY DEFINITIONS
*****************************************************************
**
*SOLID SECTION,ELSET=PLATE,MATERIAL=SSTEEL
**
*MATERIAL,NAME=SSTEEL
*ELASTIC,TYPE=ISOTROPIC
 3.00E+07,  0.29
*DENSITY
7.32E-04,
*PLASTIC
30000.,0.
100000.,1.0
**
**
*****************************************************************
**  SECTION 5.  CONTACT DEFINITION
*****************************************************************
**
**NO CONTACT IN MODEL
**
*****************************************************************
**  SECTION 6.  SOLUTION STEP DATA
*****************************************************************
**
*STEP,AMPLITUDE=RAMP,INC=100
*STATIC
```

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```
0.1,1.0,1.0E-06,
**
*BOUNDARY,OP=NEW
BS000001,    1,3,       0.00000E+00
**
** APPLY 600 LB LOAD AT 3 PLACES
*CLOAD,OP=NEW
BS000002,    3, 2.7273E+01
**
*OUTPUT,FIELD,VARIABLE=PRESELECT
*OUTPUT,HISTORY,VARIABLE=PRESELECT
**
*END STEP
*************************************************************
```

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Appendix F

Thermal Stress Analysis of the Capsule Reactor Core Components

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1. Background

The AGC-1 experiment will have high temperature gradients during operation (see Fig. 3). It is necessary to evaluate the effect of the thermal stresses caused by these gradients in the experiment. Areas of concern are the outer pressure boundary, the graphite holder and the heat shield.

2. Thermal Stress Model

The thermal stresses in the AGC-1 experiment will be evaluated using finite elements and analyzed using ABAQUS/Standard. The various components of in the finite element model are shown in Figures 1 and 2.

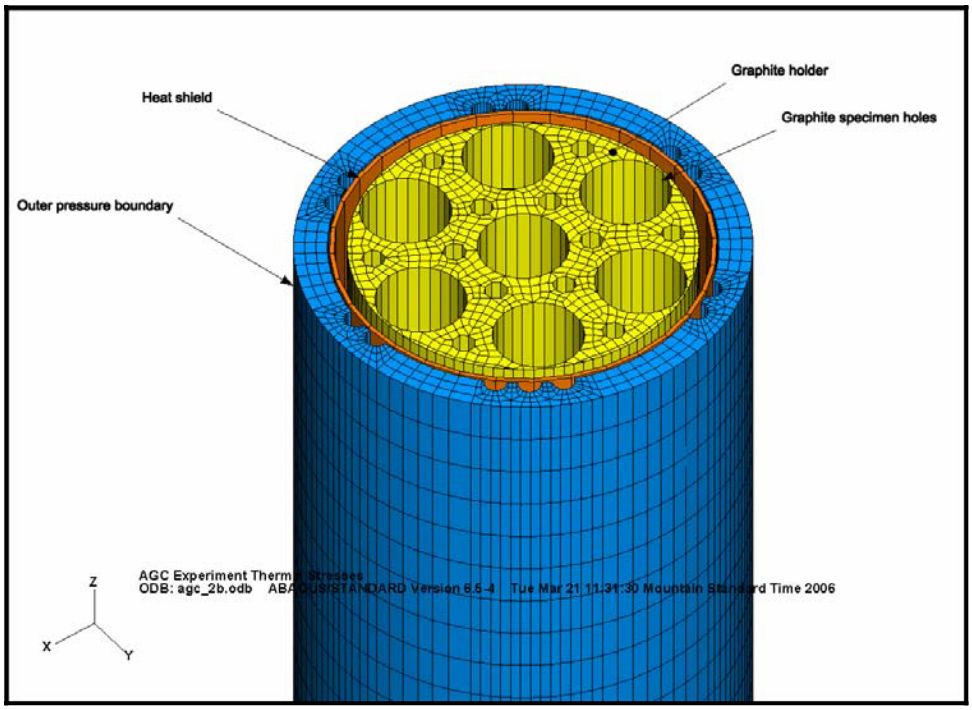

Figure 1. Finite element model of the AGC-1 experiment.

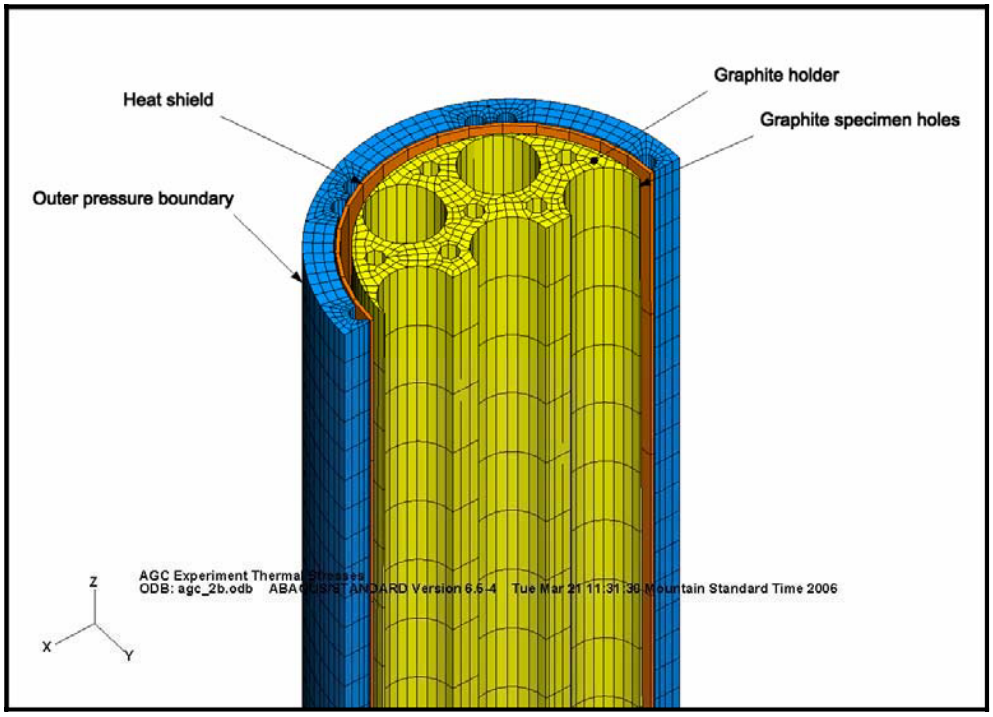

Figure 2. Cutaway view showing the inside of the experiment.

2.1 Components

2.1.1 Outer Pressure Boundary

The outer pressure boundary is 72 inches long with an outside diameter of 2.500 inches (Ref. 1). It has an inside diameter of 2.144 inches with a wall thickness of 0.178 inches. Small semi-circular grooves with a radius of 0.063 inches, parallel to the axis of the cylinder, are spaced around the inside of the tube in pairs, except for one location where three grooves are located (see Fig. 1). This outer pressure boundary is fabricated from type 304 stainless steel.

2.1.2 Heat Shield

The heat shield is also cylindrical. It is 52 inches long with an outer diameter of 2.110 inches (Ref. 2). The inner surface of the cylinder tapers so that at core centerline, the wall thickness is 0.005 inches. It increases in thickness upward until it is 0.025 inches at 24 inches above the core centerline at the top of the core and maintains this thickness for 2.00 more inches to the top. It tapers the same way below the core centerline. The high nickel alloy heat shield is fabricated from Haynes 230 (see Ref. 2).

2.1.3 Graphite Holder

The graphite holder is also cylindrical (Ref. 3). The outside has a gradual taper from 2.074-in diameter at the core centerline to about 1.913-in diameter at the top of the core. It has 6 specimen holes with a diameter of 0.635 inches on a circular pattern with a diameter of 1.390 inches. The center hole is also has a diameter of 0.635 in. There are multiple holes with a diameter of 0.132 inches interspersed among the specimen holes for gas tubes and thermocouples. The graphite holder is machined from AXF-5Q1 graphite.

2.2 Materials

Material properties for the components used in this analysis are listed in Section 7 of the main body of this EDF. They are also listed in the abbreviated input file in Section 7 of this appendix.

2.3 Modeling Details

Temperatures calculated for this experiment are considered symmetrical about the reactor core centerline. Therefore, only the portion of the experiment from the core centerline to the top of the core was modeled. The temperatures decrease rapidly above the core and will not result in thermal stresses that are higher than those calculated for the in-core section.

The graphite specimens are not included in the thermal stress model since they are smaller than the holes. They are not predicted to swell in size and cause contact stresses in the graphite specimen holder.

The loads applied by the push rods are not applied to the finite element model because the calculations show that they do not cause high stresses in the graphite holder (see section B4.1.6 in the main EDF). Also, the graphite becomes stronger with increased temperature and irradiation. The loads will be applied to the graphite specimens which in turn transfer the load to the graphite holder just above the core centerline. This load, applied to a short section of the graphite holder, will result in negligible additional stresses.

2.4 ABAQUS Finite Element Model

The finite element model was created using I-DEAS (Ref. 4) and then translated to an ABAQUS/Standard (Ref. 5) input file.

The outer pressure boundary was modeled using brick elements to account for the grooves on the inside surface. The heat shield was modeled using continuum shell elements since the thickness varies along its length. These elements are modeled the same as brick elements, but they pick up their thickness from the node spacing in the thickness direction. The graphite specimen holder was modeled with brick elements. It was originally modeled with a straight outer surface. The outer node coordinates were then modified with a C program to move the nodes inward and give the holder the correct taper.

Contact was modeled using contact pairs since general contact is not available in ABAQUS/Standard. A generic coefficient of friction of 0.4 was used between all surfaces.

Each node was given an initial temperature of 70°F in the model.

3. Temperatures

Temperatures for this thermal stress model were calculated in an ABAQUS/Standard thermal model and then imported into the stress model (Ref. 6). Temperatures were imported component by component basis. The temperature assigned to the node in the stress model was imported from the closest node in the thermal model for that component. Figures 3 and 4 show the temperature distribution (°F) used for this analysis.

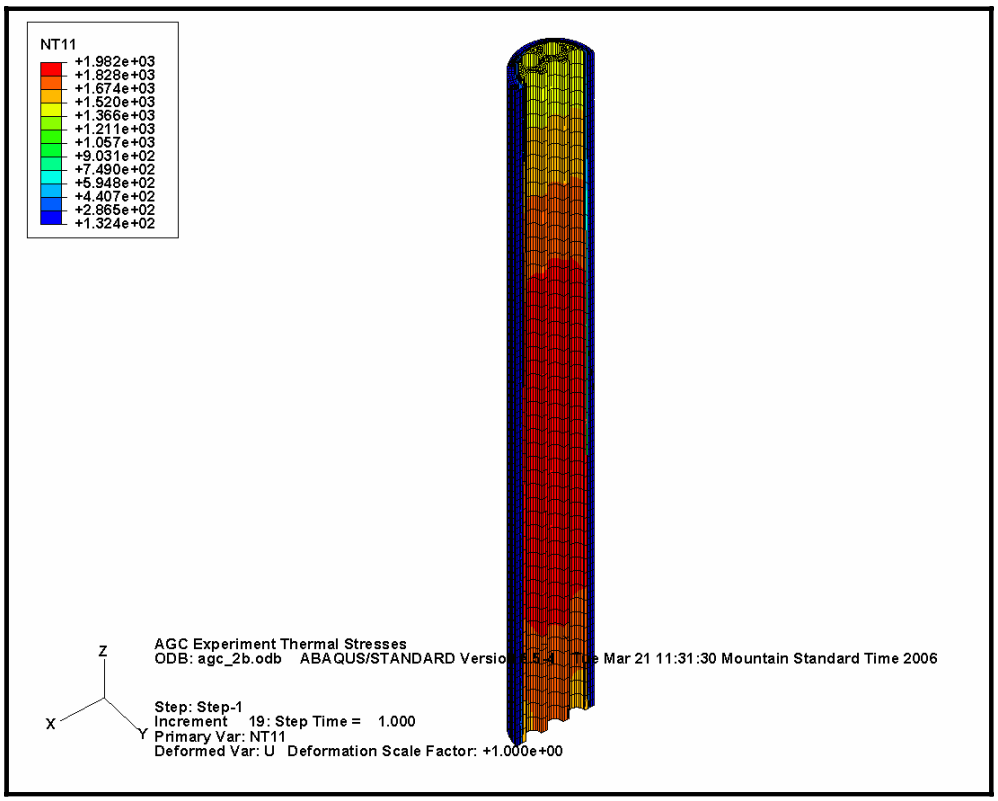

Figure 3. Temperatures (°F) imported from the thermal model into the stress model.

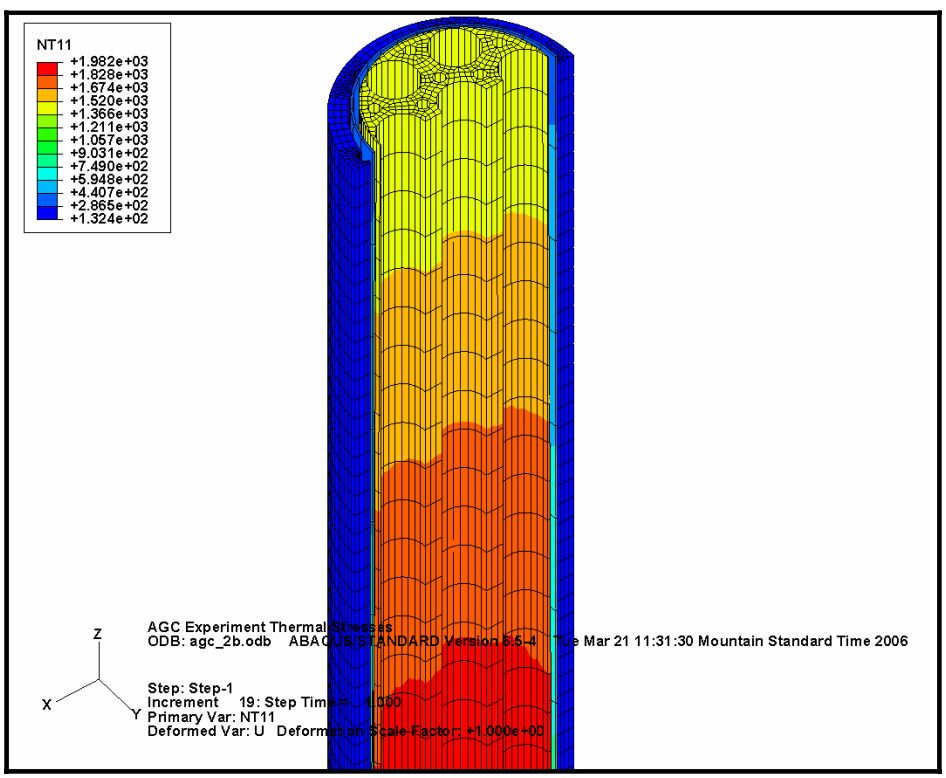

Figure 4. Close-up view of the temperature distribution.

4. Results

Plastic strains, due to thermal expansion of the components, occur in the lower portion of the outer pressure boundary (Fig. 5). These strains are located at the bottom of the grooves on the inside of the outer pressure boundary and are shown in more detail in Figure 6. The maximum calculated plastic strain is less than 0.5%.

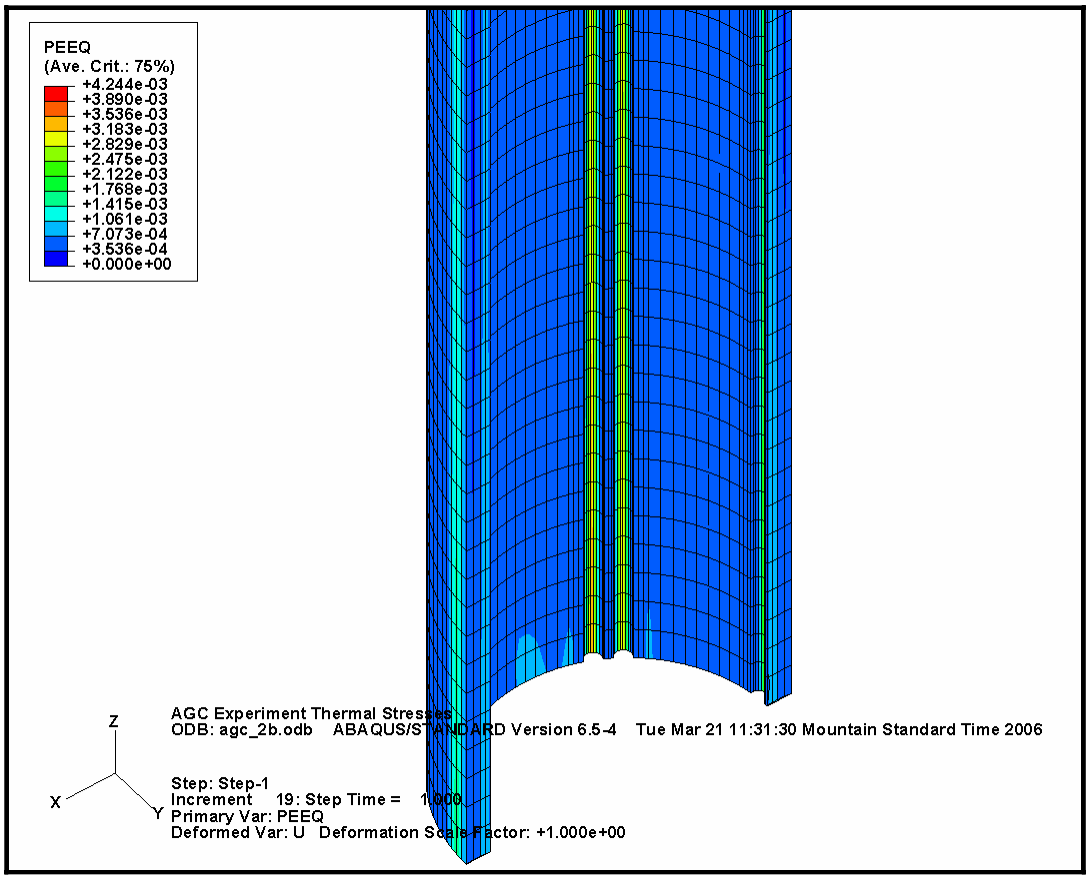

Figure 5. Plastic strains in the bottom portion of the outer pressure boundary.

These calculated temperatures are based on a reactor design temperature of 240°F for normal operating temperatures (Ref. 6).

These strains are produced by thermal or secondary stresses. The first time the experiment heats up to temperature the material will strain plastically (less than 0.5%) and relieve the stresses. After this material plastically strains, the stresses will be at or below yield. On subsequent startup cycles the stresses will always be at or below yield and additional plastic straining will not occur. Thermal stresses will not cause failure of the outer pressure boundary.

Therefore, after the initial startup, subsequent thermal cycles will only produce an elastic response in this outer pressure boundary.

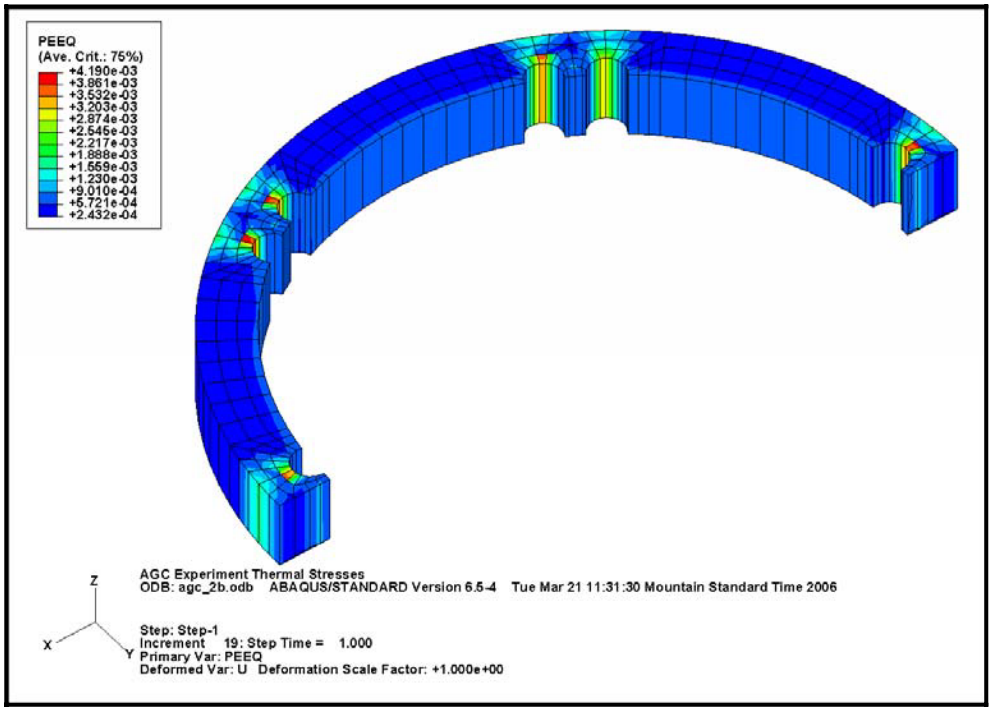

Figure 6. Plastic strain in the outer pressure boundary just above the core centerline.

The thermal stresses in the heat shield are less than 10 ksi (Fig. 7). These low stresses indicate that there is no plastic strain in the heat shield. The maximum temperature of the heat shield is about 1142°F (Fig. 8). The yield strength of the Haynes 230 at this temperature is about 22.2 ksi.

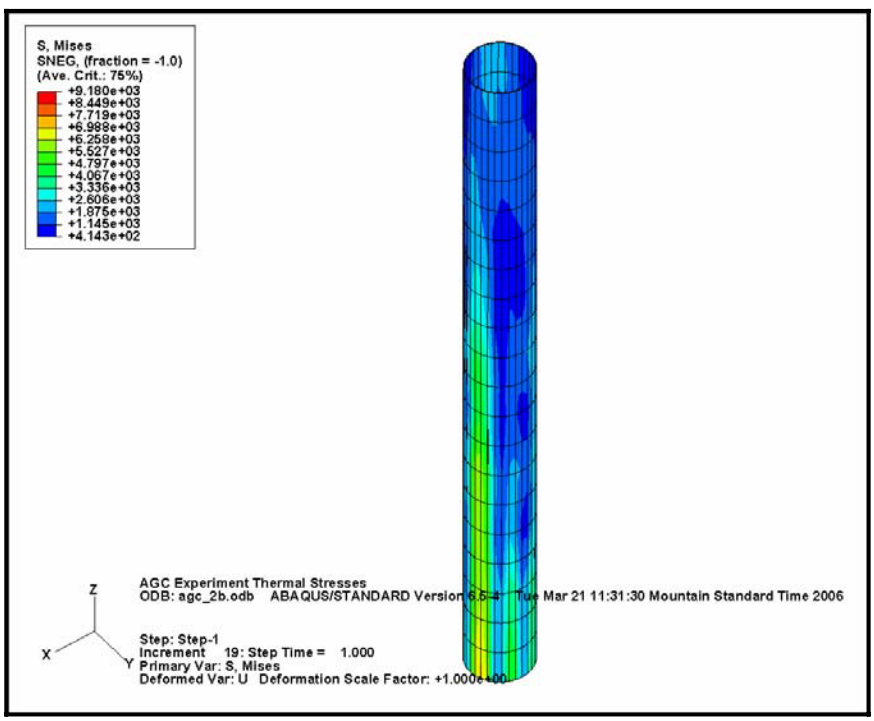

Figure 7. Stresses in the thermal heat shield.

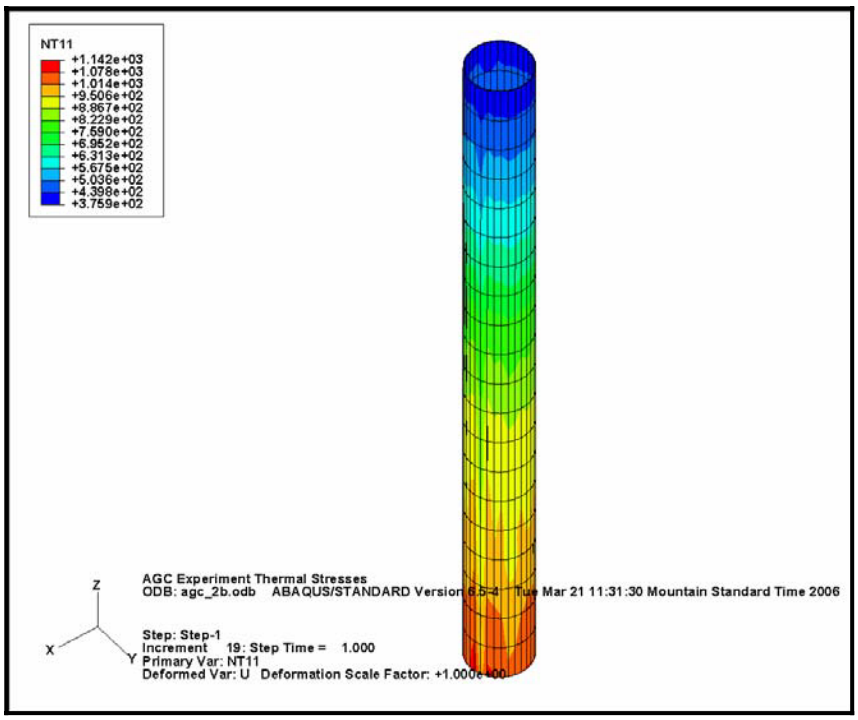

Figure 8. Temperature distribution in the heat shield.

Figure 9 shows the stresses in the graphite specimen holder. The maximum calculated stress is 621 psi. The yield strength at the maximum temperatureof 1985°F (Fig. 10) is 2321 psi. The thermal stresses in the graphite are not high enough to cause cracking.

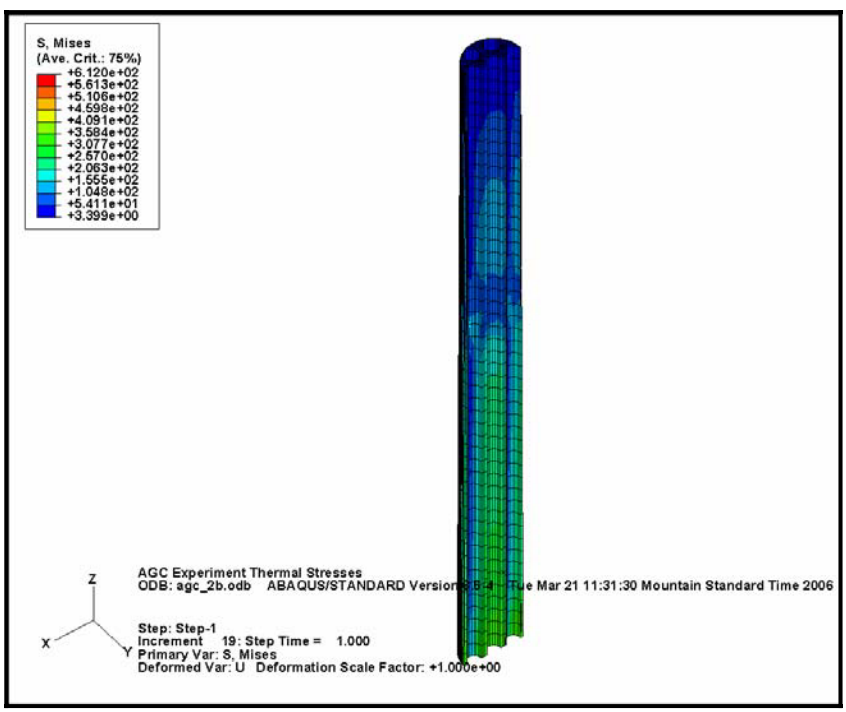

Figure 9. Cutaway view of the graphite specimen holder showing the Von Mises stress.

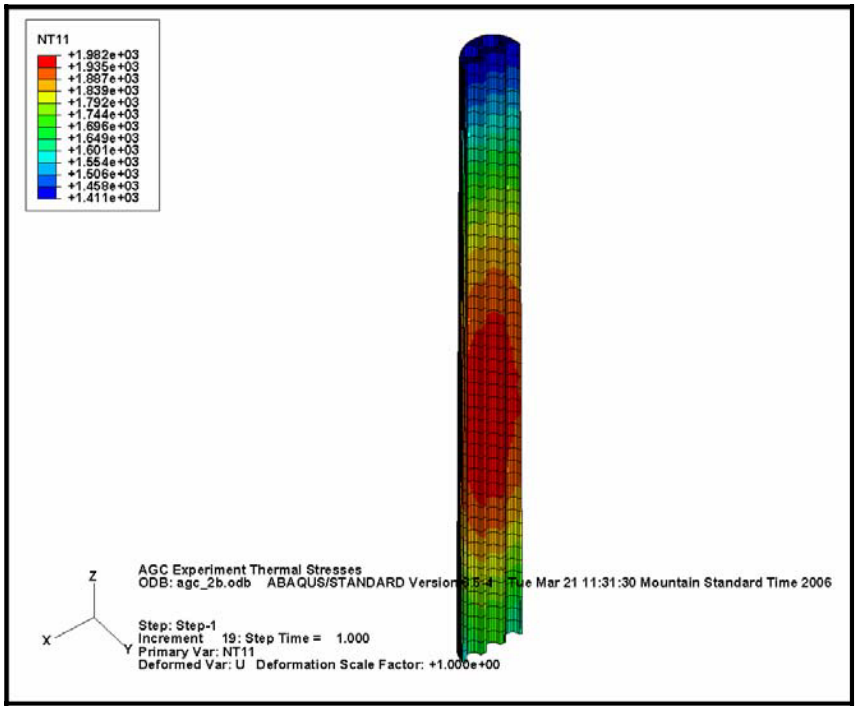

Figure 10. Temperature in the graphite specimen holder.

5. Conclusions

The calculated thermal stresses in the AGC-1 experiment cause some slight (0.5%) plastic strain in the outer pressure boundary at the root of the grooves on the inner surface. These plastic strains, caused by the thermal stresses or secondary stresses will not cause failure of the outer pressure boundary. The heat shield and the graphite specimen holder have stresses well below the yield strength at their maximum temperature. These components meet the code requirements for this experiment.

6. References

1. INL Drawing 630434, Rev. Draft
2. INL Drawing 630432, Rev. Draft
3. INL Drawing 630427, Rev. Draft
4. I-Deas 11 NX, 2005
5. ABAQUS/Standard Version 6.5-4, 2005
6. RGA EDF
7. ASME Boiler and Pressure Vessel Code, 2001 with 2002 addenda

7. Abbreviated ABAQUS Input File

```
** file = agc_2b.inp
** b version uses a node based surface for the contact with outer pressure boundary
** standard experiment with grooved outer boundary
** Second major iteration of the AGC experiment
** This file contains the experiment from the core centerline
```

```
**   to the top of the core (24 inches)
** experiment centerline = Z axis (core cl @ z=0)
** temperatures are from rga ABAQUS run
**%   ============================================================
**%          MODEL FILE: D:\bdh\MS11\AGC_thermal-2.mf1
**%          INPUT FILE: AGC_2.inp
**%            EXPORTED: AT 14:10:25 ON 21-Feb-06
**%
**%               UNITS: IN-Inch (pound f)
**%                     ... LENGTH : inch
**%                     ... TIME   : sec
**%                     ... MASS   : lbf-sec**2/in
**%                     ... FORCE  : pound (lbf)
**%                     ... TEMPERATURE : deg Fahrenheit
**%
**%   ============================================================
**%
*HEADING
AGC Experiment Thermal Stresses
**%==========================================
**%          MODAL DATA
**%==========================================
*NODE, NSET=ALLNODES, SYSTEM=R
*** heat shield nodes
         1,   8.7304309E-01,   5.8334875E-01,   0.0000000E+00
.....
      1344,  -9.7470470E-01,  -4.0370251E-01,   4.1670118E-06
*** Lower graphite holder nodes
     12001,  -1.0830128E-08,   8.8600000E-01,   0.0000000E+00
.....
     34077,   6.0121757E-01,   3.0952046E-01,   1.4000000E+01
***Upper graphite holder nodes
     35001,  -1.0830128E-08,   8.8600000E-01,   1.4000000E+01
.....
     50804,   6.0121757E-01,   3.0952046E-01,   2.4000000E+01
*** Nodes for grooved outer pressure boundary
      60001, 1.2158696E+00, 2.9010552E-01, 0.0000000E+00
.....
     127222, 8.0266181E-01, 6.9997126E-01, 2.4000000E+01
*ELEMENT, TYPE=SC8R    , ELSET=heat_shield_el
      1,      1,      2,     23,     22,    358,    359,    695,    694
.....
    640,    690,    691,    337,    338,   1343,   1344,   1009,   1010
*ELEMENT, TYPE=C3D8R, ELSET=LOWER_HOLDER_EL
  12001,  12846,  13378,  14106,  13154,  12847,  13379,  14107,  13155
.....
  28752,  31620,  30808,  33316,  32564,  31621,  30809,  33317,  32565
*ELEMENT, TYPE=C3D8R, ELSET=UPPER_HOLDER_EL
  35001,  35014,  35048,  35011,  35001,  36017,  36697,  35957,  35206
.....
  46616,  50683,  50663,  50623,  50603,  50684,  50664,  50624,  50604
*ELEMENT, TYPE=C3D8R, ELSET=OUTER_TUBE_EL
  60001,  60757,  61141,  61237,  60853,  60758,  61142,  61238,  60854
.....
 109344, 124725, 125877, 125685, 123477, 124726, 125878, 125686, 123478
******************************
*** Sections
******************************
*shell section, elset=heat_shield_el, stack direction=3, material=inconel230
 0.1
*SOLID SECTION, ELSET=lower_holder_el, MATERIAL=GRAPHITE
*SOLID SECTION, ELSET=upper_holder_el, MATERIAL=GRAPHITE
*SOLID SECTION, ELSET=outer_tube_el, MATERIAL=ss304_tube
```

```
******************************
*** Material Definitions
******************************
***************************************
*** Properties are for 304 seamless pipe from Sect. II Part D
***************************************
*MATERIAL,NAME=SS304_TUBE
***************************************
*** Table TM-1, pg. 671, Group G
***************************************
*ELASTIC,TYPE=ISOTROPIC
 28.3E+7,  0.29, 70.0
 27.6E+7,  0.29, 200.0
 27.0E+7,  0.29, 300.0
 26.5E+7,  0.29, 400.0
 25.8E+7,  0.29, 500.0
 25.3E+7,  0.29, 600.0
 24.8E+7,  0.29, 700.0
 24.1E+7,  0.29, 800.0
 23.5E+7,  0.29, 900.0
 22.8E+7,  0.29, 1000.0
 22.1E+7,  0.29, 1100.0
 21.2E+7,  0.29, 1200.0
 20.2E+7,  0.29, 1300.0
 19.2E+7,  0.29, 1400.0
 18.1E+7,  0.29, 1500.0
*DENSITY
 7.4793E-04,
****************************
*** From Sect. II, Part D, pg 651, Table TE-1, Group 3 column B
****************************
*EXPANSION,TYPE=ISO,ZERO=70.0
 8.5E-6,  70.0
 8.6E-6, 100.0
 8.8E-6, 150.0
 8.9E-6, 200.0
 9.1E-6, 250.0
 9.2E-6, 300.0
 9.3E-6, 350.0
 9.5E-6, 400.0
 9.6E-6, 450.0
 9.7E-6, 500.0
 9.8E-6, 550.0
 9.8E-6, 600.0
 9.9E-6, 650.0
 10.0E-6, 700.0
 10.0E-6, 750.0
 10.1E-6, 800.0
 10.1E-6, 850.0
 10.2E-6, 900.0
 10.3E-6, 950.0
 10.3E-6, 1000.0
 10.4E-6, 1050.0
 10.5E-6, 1100.0
 10.5E-6, 1150.0
 10.6E-6, 1200.0
 10.6E-6, 1250.0
 10.7E-6, 1300.0
 10.7E-6, 1350.0
 10.8E-6, 1400.0
 10.8E-6, 1450.0
 10.8E-6, 1500.0
*PLASTIC
```

```
** yield strength from Sect. II, Part D, 2001, pg.556 line 10
 30.0E+3, 0.0, 100.0
 26.7E+3, 0.0, 150.0
 25.0E+3, 0.0, 200.0
 23.6E+3, 0.0, 250.0
 22.4E+3, 0.0, 300.0
 20.7E+3, 0.0, 400.0
 19.4E+3, 0.0, 500.0
 18.4E+3, 0.0, 600.0
 18.0E+3, 0.0, 650.0
 17.6E+3, 0.0, 700.0
 17.2E+3, 0.0, 750.0
 16.9E+3, 0.0, 800.0
 16.5E+3, 0.0, 850.0
 16.2E+3, 0.0, 900.0
 15.9E+3, 0.0, 950.0
 15.5E+3, 0.0, 1000.0
**********************************
*** Graphite = POCO AXF-5Q
*** Information is from "Isotropic Space Power Materials Handbook"
**********************************
*MATERIAL,NAME=GRAPHITE
*ELASTIC,TYPE=ISOTROPIC
 1.692E+6, 0.15, 68.0
 2.110E+6, 0.15, 1985.0
 2.578E+6, 0.15, 3002.0
*PLASTIC
 2.031E+3, 0.0, 68.0
 3.270E+3, 6.557E-5, 68.0
 4.582E+3, 2.874E-4, 68.0
 5.825E+3, 5.497E-4, 68.0
 6.851E+3, 9.388E-4, 68.0
 7.733E+3, 1.412E-3, 68.0
 8.471E+3, 1.969E-3, 68.0
 2.321E+3, 0.0, 1985.0
 4.069E+3, 6.915E-5, 1985.0
 5.673E+3, 3.062E-4, 1985.0
 7.135E+3, 6.098E-4, 1985.0
 8.381E+3, 1.015E-3, 1985.0
 9.411E+3, 1.521E-3, 1985.0
 1.015E+4, 2.164E-3, 1985.0
 2.321E+3, 0.0, 3002.0
 2.541E+3, 1.414E-5, 3002.0
 4.796E+3, 1.380E-4, 3002.0
 6.837E+3, 3.438E-4, 3002.0
 8.446E+3, 7.165E-4, 3002.0
 9.912E+3, 1.143E-3, 3002.0
 1.094E+4, 1.738E-3, 3002.0
 1.183E+4, 2.387E-3, 3002.0
*DENSITY
 1.758E-04,
*EXPANSION,TYPE=ISO,ZERO=70.00
*** data used is from POCO on-line data
 4.0E-6, 70.0
 4.44E-6, 1832.0
** 4.050E-6, 752.0
** 4.126E-6, 1112.0
** 4.230E-6, 1472.0
** 4.330E-6, 1832.0
** 4.422E-6, 2192.0
** 4.517E-6, 2552.0
** 4.612E-6, 2912.0
** 4.704E-6, 3272.0
```

```
** 4.797E-6, 3632.0
** 4.886E-6, 3992.0
** 4.973E-6, 4352.0
**********************************
*** Inconel alloy 230 (UNS N06230)
*** www.specialmetals.com
**********************************
*MATERIAL, NAME=INCONEL230
**********************************
*** Material is N06230 with 57% Ni
*** Properties.  Elastic modulus from Section II, Part D,
*** Poisson's ratio is from Vendor data
**********************************
*ELASTIC, TYPE=ISOTROPIC
 30.6E+6, 0.34, 100.0
 29.9E+6, 0.33, 200.0
 29.5E+6, 0.33, 300.0
 29.0E+6, 0.34, 400.0
 28.6E+6, 0.34, 500.0
 28.2E+6, 0.35, 600.0
 27.7E+6, 0.34, 700.0
 27.2E+6, 0.34, 800.0
 26.7E+6, 0.32, 900.0
 26.1E+6, 0.32, 1000.0
 25.5E+6, 0.33, 1100.0
 24.9E+6, 0.34, 1200.0
 24.2E+6, 0.33, 1300.0
 23.6E+6, 0.31, 1400.0
*PLASTIC
**********************************
*** Yield strength is from Sect. II, Part D, pg. 618 (2005 Ed.)
*** Ultamate strength is from Sect. II, Part D, pg. 482 (2005 Ed.)
*** True stress and true strain calculated in Mathcad file
**********************************
 45.0E+3, 0.0, 100.0
 160.6E+3, 0.378, 100.0
 42.3E+3, 0.0, 200.0
 160.6E+3, 0.378, 200.0
 39.6E+3, 0.0, 300.0
 158.4E+3, 0.365, 300.0
 37.0E+3, 0.0, 400.0
 154.0E+3, 0.358, 400.0
 34.7E+3, 0.0, 500.0
 150.9E+3, 0.365, 500.0
 32.9E+3, 0.0, 600.0
 149.2E+3, 0.372, 600.0
 31.9E+3, 0.0, 700.0
 148.3E+3, 0.375, 700.0
 31.4E+3, 0.0, 800.0
 147.9E+3, 0.378, 800.0
 31.3E+3, 0.0, 900.0
 143.0E+3, 0.351, 900.0
 31.3E+3, 0.0, 1000.0
 139.7E+3, 0.336, 1000.0
 23.2E+3, 0.0, 1100.0
 138.3E+3, 0.368, 1100.0
 22.2E+3, 0.0, 1200.0
 140.9E+3, 0.419, 1200.0
 22.2E+3, 0.0, 1300.0
 125.9E+3, 0.482, 1300.0
 21.2E+3, 0.0, 1400.0
 106.2E+3, 0.560, 1400.0
*EXPANSION, ZERO=70.0
```

```
**********************************
*** CTE data is from Section II, Part D, pg. 676 (2005 Ed.)
**********************************
 6.9E-6, 100.0
 7.0E-6, 200.0
 7.1E-6, 300.0
 7.2E-6, 400.0
 7.3E-6, 500.0
 7.4E-6, 600.0
 7.5E-6, 700.0
 7.6E-6, 800.0
 7.7E-6, 900.0
 7.9E-6, 1000.0
 8.0E-6, 1100.0
 8.1E-6, 1200.0
 8.2E-6, 1300.0
 8.3E-6, 1400.0
*DENSITY
 8.385E-04,
******************************
*** Node Sets
******************************
*NSET,NSET=HEAT_SHIELD_ND, GENERATE
         1,     1344,        1
*NSET,NSET=LOWER_HOLDER_ND, GENERATE
     12001,    34077,        1
*NSET,NSET=UPPER_HOLDER_ND, GENERATE
     35001,    50804,        1
*NSET,NSET=LOW_HOLDER_TOP_ND, GENERATE
     12674,    12821,      147
     12849,    22005,       28
     22081,    29137,       28
     29189,    32493,       28
     32593,    34077,       28
*NSET,NSET=UPPER_HOLDER_CEN_ND
   35007,   35008,   35037,   35075,   35101,   35138,   35139,   35168,   35235,
35272,   35273
   35302,   35366,   35403,   35404,   35433,   35500,   35537,   35538,   35567,
35629,   35667
   35696,   35760
*NSET,NSET=SHELL_IN1_ND, GENERATE
     60004,    60020,        4
.....
    127031,   127222,        1
*NSET,NSET=SHELL_IN2_ND, GENERATE
     60092,    60094,        1
.....
     98231,    98518,        1
*NSET,NSET=SHELL_IN3_ND, GENERATE
     60213,    60215,        1
.....
    105623,   105910,        1
*NSET,NSET=SHELL_IN4_ND, GENERATE
     60334,    60336,        1
.....
    113015,   113302,        1
*NSET,NSET=SHELL_IN5_ND, GENERATE
     60455,    60457,        1
.....
    120407,   120694,        1
*NSET,NSET=SHELL_IN6_ND, GENERATE
     60560,    60577,       17
.....
```

```
    122807,   123094,        1
******************************
*** Element Sets
******************************
*ELSET,ELSET=HEAT_SHIELD_EL, GENERATE
         1,      640,        1
*ELSET,ELSET=LOWER_HOLDER_EL, GENERATE
     12001,    28752,        1
*ELSET,ELSET=UPPER_HOLDER_EL, GENERATE
     35001,    46616,        1
*ELSET,ELSET=LOW_HOLDER_OUT_EL, GENERATE
     12001,    12026,        1
.....
     28293,    28320,        1
*ELSET,ELSET=LOW_HOLDER_TOP_EL, GENERATE
     12027,    12083,       28
.....
     27340,    28656,       28
*ELSET,ELSET=UP_HOLDER_OUT_EL, GENERATE
     35061,    35100,        1
.....
     45977,    46116,        1
*ELSET,ELSET=UP_HOLDER_BOT_EL, GENERATE
     35001,    37881,       20
.....
     42797,    46597,       20
*ELSET,ELSET=HS_1_EL, GENERATE
         1,       80,        1
       321,      380,        1
*ELSET,ELSET=HS_2_EL, GENERATE
       361,      480,        1
*ELSET,ELSET=HS_3_EL, GENERATE
       461,      600,        1
*ELSET,ELSET=HS_4_EL, GENERATE
       261,      320,        1
       561,      640,        1
*ELSET,ELSET=HS_5_EL, GENERATE
       161,      280,        1
*ELSET,ELSET=HS_6_EL, GENERATE
        61,      180,        1
******************************
*** Surface Definitions
******************************
*surface, name=out_shell_surf1, type=node
 shell_in1_nd,
*surface, name=out_shell_surf2, type=node
 shell_in2_nd,
*surface, name=out_shell_surf3, type=node
 shell_in3_nd,
*surface, name=out_shell_surf4, type=node
 shell_in4_nd,
*surface, name=out_shell_surf5, type=node
 shell_in5_nd,
*surface, name=out_shell_surf6, type=node
 shell_in6_nd,
*surface, name=hs_out1_surf, type=element
 hs_1_el, s2
*surface, name=hs_out2_surf, type=element
 hs_2_el, s2
*surface, name=hs_out3_surf, type=element
 hs_3_el, s2
*surface, name=hs_out4_surf, type=element
 hs_4_el, s2
```

```
*surface, name=hs_out5_surf, type=element
 hs_5_el, s2
*surface, name=hs_out6_surf, type=element
 hs_6_el, s2
*surface, name=hs_in_surf, type=element
 heat_shield_el, s1
*surface, name=low_holder_out_surf, type=element
 low_holder_out_el,
*surface, name=low_holder_top_surf, type=element
 LOW_HOLDER_TOP_EL,
*surface, name=up_holder_out_surf, type=element
 up_holder_out_el,
*surface, name=up_holder_bot_surf, type=node
 UPPER_HOLDER_CEN_ND
****************************
*** Define Contact Pairs
*****************************
*surface interaction, name=fric
*friction
 0.3
*contact pair, interaction=fric
 out_shell_surf1, hs_out1_surf
*contact pair, interaction=fric
 out_shell_surf2, hs_out2_surf
*contact pair, interaction=fric
 out_shell_surf3, hs_out3_surf
*contact pair, interaction=fric
 out_shell_surf4, hs_out4_surf
*contact pair, interaction=fric
 out_shell_surf5, hs_out5_surf
*contact pair, interaction=fric
 out_shell_surf6, hs_out6_surf
*contact pair, interaction=fric
 hs_in_surf, low_holder_out_surf
*contact pair, interaction=fric
 hs_in_surf, up_holder_out_surf
****************************
*** Tie Definition
*****************************
*tie, name=holders_tied
 up_holder_bot_surf, low_holder_top_surf
****************************
*** Initial Conditions
*****************************
*initial conditions, type=temperature
 allnodes, 70.0
**%
**%=========================================
**%          HISTORY DATA
**%=========================================
**%
**% ====== STEP NUMBER   1 ======
**%
*STEP,INC=100
*STATIC
  0.1, 1.0, 1.0e-8, 0.5
**%  BOUNDARY CONDITION SET 1
**%  CL_FIXED
*BOUNDARY,OP=NEW
BS000001,    2, 3,     0.00000E+00
BS000002,    3,,       0.00000E+00
BS000003,    1,,       0.00000E+00
BS000003,    3,,       0.00000E+00
```

```
BS000004,    2, 3,      0.00000E+00
*NSET,NSET=BS000001
60024,60028,60057,60058,60061,60349,60350,60359,60362,60425
*NSET, NSET=BS000002, GENERATE
         1,       43,       21
.....
     60741,    60742,        1
*NSET,NSET=BS000003
232,481,904,1134,12003,12402,60141,60142,60143,60144,60513,60514,60515
60516,
*NSET,NSET=BS000004
64,649,736,1302,12135,12537
*TEMPERATURE, INPUT=rga_temperatures.inp
*OUTPUT, FIELD
*NODE OUTPUT
 U, NT
*ELEMENT OUTPUT
 S, PEEQ
*END STEP
```

Appendix J

The Design Review Chairman's Report on the AGC-1 Preliminary Design Review

INTEROFFICE MEMORANDUM

Idaho National Laboratory

Date: July 27, 2006

To: Distribution

From: K. R. Estes MS 7101 533-4136

Subject: REPORT OF THE PRELIMINARY DESIGN REVIEW OF THE ADVANCED TEST REACTOR ADVANCED GRAPHITE CAPSULE GRAPHITE CREEP CAPSULE EXPERIMENT

The preliminary design review for the Advanced Test Reactor Advanced Graphite Capsule AGC-1 experiment has been completed. The preliminary design review was held at the AmeriTel Inn located at 2501 South 25th East in Idaho Falls on May 31, 2006. The following members submitted comments and/or attended the review.

Attendees:

Name	Function	Discipline/Organization
R. G. Ambrosek	Presenter	Analyst
S. Bader	Observer	Project Manager
S. L. Barrie	Reviewer	ATR Engineering
R. L. Bratton	Presenter	Project Manager
M. J. Chaffin	Reviewer	ATR Quality Engineering
D. E. Clark	Presenter	Welding/Materials
K. R. Estes	Chairman	ATR Engineering
J. A. Galbraith	Observer	BEA Staff
B. L. Grant	Reviewer	ATR Radiological Support
L. Harrison	Reviewer	ATR Engineering
B. D. Hawkes	Presenter	BEA Applied Mechanics
G. O. Hayner	Observer	NGNP Materials Manager
M. M. Heberling	Reviewer	ATR Operations
R. C. Howard	Reviewer	ATR Engineering
S. C. Johnson	Reviewer	Nuclear Maintenance Planning Manager
E. D. King	Reviewer	BEA Nuclear Operations Environmental
K. K. Clayton	Reviewer	ATR Engineering
F. M. Marshall	Observer	ATR New Business Department Manager
G. A. Marts	Reviewer	ATR Engineering
J. R. Parry	Presenter	Irradiation Test Programs
S. D. Snow	Presenter	BEA Applied Mechanics
T. M. Stumpf	Reviewer	ATR Engineering
T. A. Tomberlin	Reviewer	ATR Nuclear Safety
K. D. Weaver	Observer	NGNP Technical Manager
L. M. Whitehead	Observer	Design & Drafting

The meeting was called to order and it was determined by the design review chairman that those present consisted of an acceptable design review committee. Written comments were received by the Chairman after the review from K. K. Clayton (attached). The project design team presented the capsule, structural analysis, reactor physics, and thermal analysis aspects of the design. Unresolved committee comments were recorded during the meeting (attached). At the conclusion of this preliminary design review, as a result of insufficient information, a determination could not be made as to whether the design meets requirements.

Thank you for your participation in the review.

kre

Attachments

Distribution
R. G. Ambrosek, MS 3885
S. Bader, MS 3790
S. L. Barrie, MS 7101
R. L. Bratton, MS 3710
M. J. Chaffin, MS 7102
D. E. Clark, MS 2210
J. A. Galbraith, MS 3605
B. L. Grant, MS 7110
L. Harrison, MS 7101
B. D. Hawkes, MS 3760
G. O. Hayner, MS 3750
M. M. Heberling, MS 7106
R. C. Howard, MS 7101
S. C. Johnson, MS 7119
E. D. King, MS 7137
K. K. Clayton, MS 7101
F. M. Marshall, MS 7101
G. A. Marts, MS 7101
J. R. Parry, MS 3870
S. D. Snow, MS 3760
T. M. Stumpf, MS 7101
T. A. Tomberlin, MS 7136
K. D. Weaver, MS 3850
L. M. Whitehead, MS 3770

cc: J. E. Dwight, MS 7117 (w/o Att.)
D. J. Schoonen, MS 7101
K. R. Estes Letter File (KRE-01-06)
AGC-1 Project File

Uniform File Code: 0450
Disposition Authority: N1-434-95-5-1-f-1
Retention Schedule: Cutoff at completion of project. Destroy 10 years after cutoff.

NOTE: Original disposition authority, retention schedule, and Uniform Filing Code applied by the sender may not be appropriate for all recipients. Make adjustments as needed.

Technical Point of Contact:	Phone No.:	Return Comments To:	MS:	E-Mail:	Comments Due By:	Reviewer's Name/Discipline:	Phone No.:
R. L. Bratton	526-1579	K. R. Estes	7101	KE7	5/31/06	Preliminary Design Review Committee	

Comments resolved by:	Date:	Signature of reviewer accepting comment resolutions:	Date:

All comments, submitted within the scope of the review, must be resolved between submitter and document owner. If an acceptable resolution cannot be negotiated, the comment will be escalated to management for resolution.

Document ID:		Document Title:	Revision ID:	DAR No.:
Item No.	Page No./ Section/Zone	Review Comment	Comment Resolution	
1	Structural Analysis	Nuclear Safety (T. Tomberlin) brought into question flow induced vibration. It was suggested that "stand-offs" be added to the capsule exterior to center the capsule in the core location. S. D. Snow (Applied Mechanics) will review the potential for flow induced vibration and the need for "stands-offs."		
2	ASME Code	Quality (M. Chaffin) questioned what year of the ASME code is used for the design. Is it the 1989 edition? R. C. Howard (ATR Engineering) will answer this question.		
3	Reactor Programmatic Impact	ATR Engineering (K. Estes) asked what Project Management plans to do if unacceptability high temperatures are reached during the high power PALM run. Will the reactor be shut down to remove the experiment? Will the reactor continue operation? R. Bratton (AGC Project Management) will answer this question.		
4	Reactor Programmatic Impact	ATR Engineering (K. Estes) and ATR Operations (M. Heberling) asked if analysis had been performed to show that the experiment does not negatively affect core delta-pressure for emergency coolant pump, 2 primary coolant pump, and 3 primary coolant pump operating conditions. The requirement for core delta pressure from emergency pump coolant flow will be found in Section 7.6.7 of the ATR SAR to be updated during the 137B outage. The primary coolant pump flow core delta-pressure requirements are currently found in TSR Section 3.3.1.4. R. Ambrosek will answer this question.		

Document ID:		Document Title:	Revision ID:	DAR No.:
Item No.	Page No./ Section/Zone	Review Comment	Comment Resolution	
5	Code Boundary	Nuclear Safety (T. Tomberlin) stated that the ATR reactor vessel top head closure for the experiment must be maintained as a ASME Section 3 Class 1 boundary. For the area of the experiment top head closure where the gas lines and thermocouples pass through, verify the opening area (not ASME Section 3 Class 1) will not exceed the "area" assumed for a Condition 2 LOCA event. R. Bratton (AGC Project Management) will answer this question.		
6	Accident Condition	Nuclear Safety (T. Tomberlin) stated that the experiment design needs to consider the affects of an accidental start up of an additional (4th) primary coolant pump. R. Bratton (AGC Project Management) will answer this question.		
7	Personnel Safety	Nuclear Safety (T. Tomberlin) stated that during reactor operation and during reactor outages when the reactor Transfer Shield Plate is removed it must be shown that radiation streaming out of the top of the experiment is acceptable. R. Ambrosek will answer this question.		
8	Experiment Fabrication	Assembly space for the experiment has been identified in the NR warehouse next to the large machining area where ITV was assembled and as necessary the ATR machine shop for final assembly.		

Technical Point of Contact:	Phone No.:	Return Comments To:	MS:	E-Mail:	Comments Due By:	Reviewer's Name/Discipline:	Phone No.:
R. L. Bratton	6-1579	K. R. Estes	7101		?	Kevin Clayton	3-4109

Comments resolved by:	Date:	Signature of reviewer accepting comment resolutions:	Date:

All comments, submitted within the scope of the review, must be resolved between submitter and document owner. If an acceptable resolution cannot be negotiated, the comment will be escalated to management for resolution.

Document ID:		Document Title:	Revision ID:	DAR No.:
Item No.	Page No./ Section/Zone	Review Comment	Comment Resolution	
1	General	It looks like the He-Ar mixture is going to fill up the leadout tube and be exhausted near the top closure. The volume of the leadout will be approx. 3,200 cubic inches less the space taken up by the Bimba cylinders, etc. If you are flowing typical instrumented lead gas values of 30 cc/min at 15 psig, have you looked at rather the gas will stagnate and possibly stratify in the leadout tube area? If it does, you might end up building a head of argon gas above the graphite. Will this affect your test?		
2	General	Are the gas passages through the graphite such that none of the gas channels will be starved? Or does is matter if some of the gas passages are short circuited?		
3	General	The Bimba cylinders have a small vent hole that exhausts into the lead-out tube. If the seal(s) in the Bimba cylinder(s) develop leak(s), they will also exhaust into the lead-out tube and could pressurize the lead-out. If the lead-out tube pressure rises above the Ar-He system supply pressure, the Ar-He system will not flow, resulting in loss of temperature control.		
		I am including comments on the drawings with the realization that this is only a Title I review and the drawings are still working and have not gone through check.		

Document ID:		Document Title:	Revision ID:	DAR No.:
Item No.	Page No./ Section/Zone	Review Comment	Comment Resolution	
4	630430	The part numbers on the material list do not match the item numbers on the drawings.		
5	630430	The items numbers in the notes do not coincide with the numbers in the material list.		
6	630431	The description for item 76 is incorrect. The view of this part needs to be redrawn showing them as Items 630427-5 and 630427-10		
7	630431	Item 75 should reference 630427-7		
8	630431	The max OD of 630431-16 through 31 is 0.250", the min ID of 630427-5 is 0.250". Pretty tight fit.		
9	630427	Should the fit between items 9/12 and Item 7 be a slip or interference? As shown it could be either.		
10	630431	Should the fit between items 73 and Items 32 through 37 be a slip or interference? As shown it could be both.		
11	630431	A stack of 8 Items 54 through 61 can be 2" long. The SiC Temp Monitors can be only 1.748" long. Might not catch all eight specimens.		
12	630431	If the referenced overall lengths of Arrangements 1 through 13 are important, this callout will need to be changed as you can miss this number from the component stackups.		
13	630434	Have you found someone who can cut the .063 radius slots in the tube ID?		
14	630430	This drawing (or somewhere) needs to show how the items from drawing 630427 are assembled. Specifically, Items -1, -2, -3, -4 and -8.		
15	630430	This drawing (or somewhere) needs to show where the heat shied (635765-1) go and their orientation.		
16	630427	Where does the -12 pin go?		

Document ID:		Document Title:	Revision ID:	DAR No.:
Item No.	Page No./ Section/Zone	Review Comment	Comment Resolution	
17	630427	Is the tolerance on the thickness of item -7 +/- .010 (ie, .240 to .260)?		
18	630430	The parts do not coincide with the proper fabrication drawings and item numbers.		
19	630427	Can you slide specimen stackup arrangements (630431-1 through 13) into the bores of the graphite components (630427-1 through -3)? Some of these parts might have zero clearance depending upon the machining tolerances. Look at .504 IDs on dwg 630427 and .504 OD of item 630427-7. The other components might have only a .002 clearance.		
20	General	The graphite specimen arrangements have anywhere from 32 to 192 components in the stack. Even with the tight run out and parallel tolerances, it is going to be a challenge to get this together. Is the radial expansion/shrinkage quantified well enough that you will be able to slide the stacks back out after irradiation? Especially the center stack that does not get periodically move by a pneumatic ram. Are you going to irradiate the graphite samples past turn-around?		