ORNL/LTR-2018/1039

Experimental Plan for NBG-18 Graphite Biaxial Strength Testing in the Second and Third Stress Quadrants

Timothy D. Burchell
Donald L. Erdman III

April 2019

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Materials Science and Technology Division

EXPERIMENTAL PLAN FOR NBG-18 GRAPHITE BIAXIAL STRENGTH TESTING IN THE SECOND AND THIRD STRESS QUADRANTS

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Date Published: April 2019

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283
managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

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ACKNOWLEDGMENTS

This work was supported by the US Department of Energy Office of Nuclear Energy, Advanced Research and Technology-Materials Program.

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ABBREVIATIONS AND ACRONYMS

ASME	American Society of Mechanical Engineers
ASTM	ASTM International (formerly the American Society for Testing and Materials)
ORNL	Oak Ridge National Laboratory
Q2/Q3	quadrant 2/quadrant 3

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ABSTRACT

The plan for the biaxial test system's shake-down and eventual (funding permitting) bi-axial testing of grade NBG-18 graphite in the second and third stress quadrant are reported. Testing in the first and fourth stress quadrants was previously reported.[1,2] Details of the specimen and test system design are given, along with the anticipated stress ratios to be tested, including specimen numbers. The estimated control pressures needed to attain the planned stress ratios are also reported.

1. INTRODUCTION

This experimental plan discusses the testing of biaxial strength in the second and third stress quadrants (Q2/Q3) (i.e., external pressure and axial tension or compression) (Figure 1). Details of the test rig, biaxial test specimen and specimen numbers, stress ratios, and uniaxial core specimen testing are given.

The anticipated schedule for this work is discussed briefly. Previously the biaxial strength of NBG-18 graphite was determined in the first and fourth stress quadrants.[1,2] Currently the American Society of Mechanical Engineers (ASME) Code for high-temperature reactor graphite core components III, 5, and Non-Metallic (Graphite) high-temperature reactor Core Design and Construction Code[3] assumes that stresses can be combined using the maximum deformation energy theory. This allows for an arbitrary stress state at a point to be converted to an equivalent stress. The current work seeks to confirm this assumption for NBG-18–grade graphite.

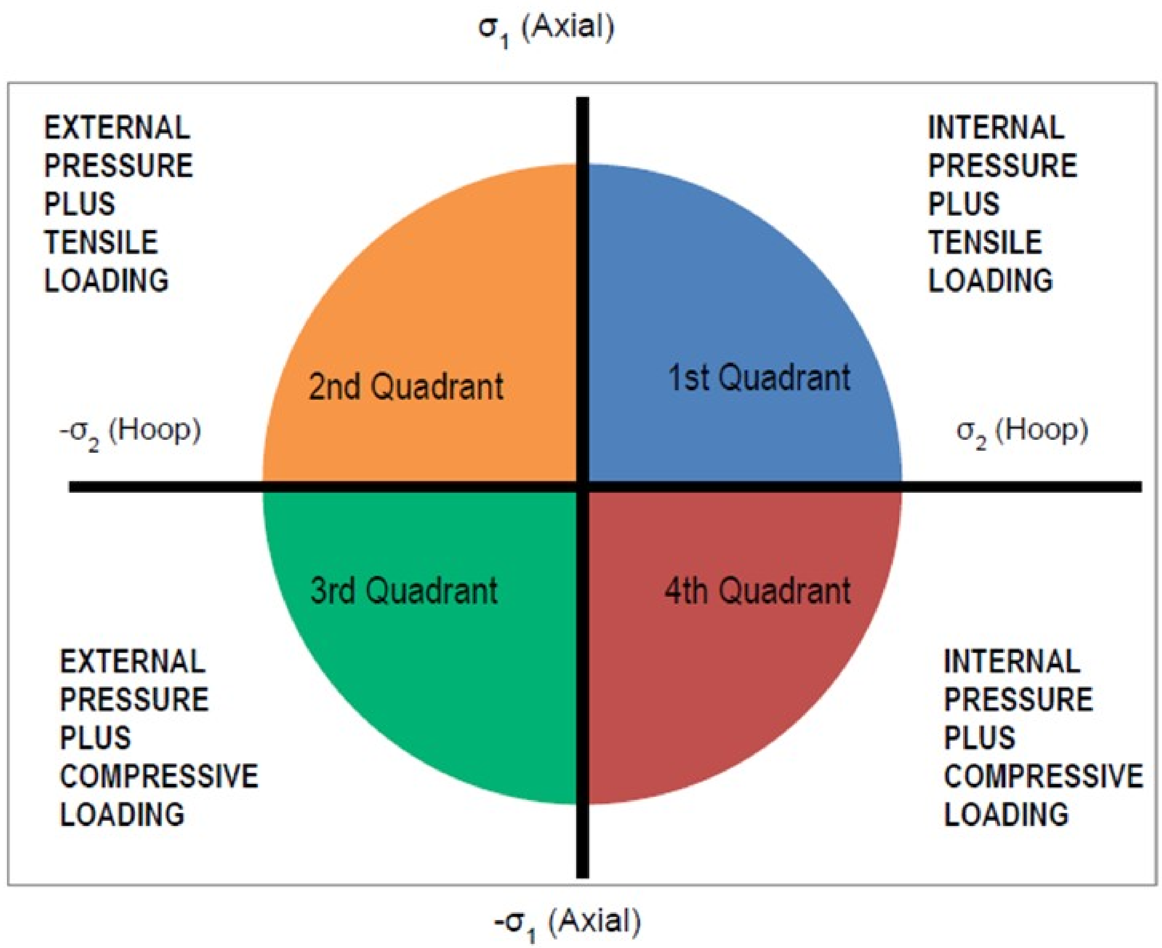


Figure 1. Stress circle quadrants.

2. TEST RIG

The test system comprises a 20,000 psi (137.9 MPa) rated vessel and piston, as shown schematically in Figure 2. The test system (Figure 3) supplies compressed gas to both sides of the piston. The desired stress state is achieved by altering the ratio of pressures P1 and P2.

An aluminum plug (**Figure 4**) is bonded into each end of the graphite specimen and is held to the piston and vessel end by means of a stainless-steel stud (Figure 5). The graphite specimen will be in the form of a hollow cylinder. The specimen will require sealing to prevent diffusion of the pressurizing gas (air) through the specimen wall. This will most likely be achieved with an elastic sealant coating on the specimen's exterior gauge section.

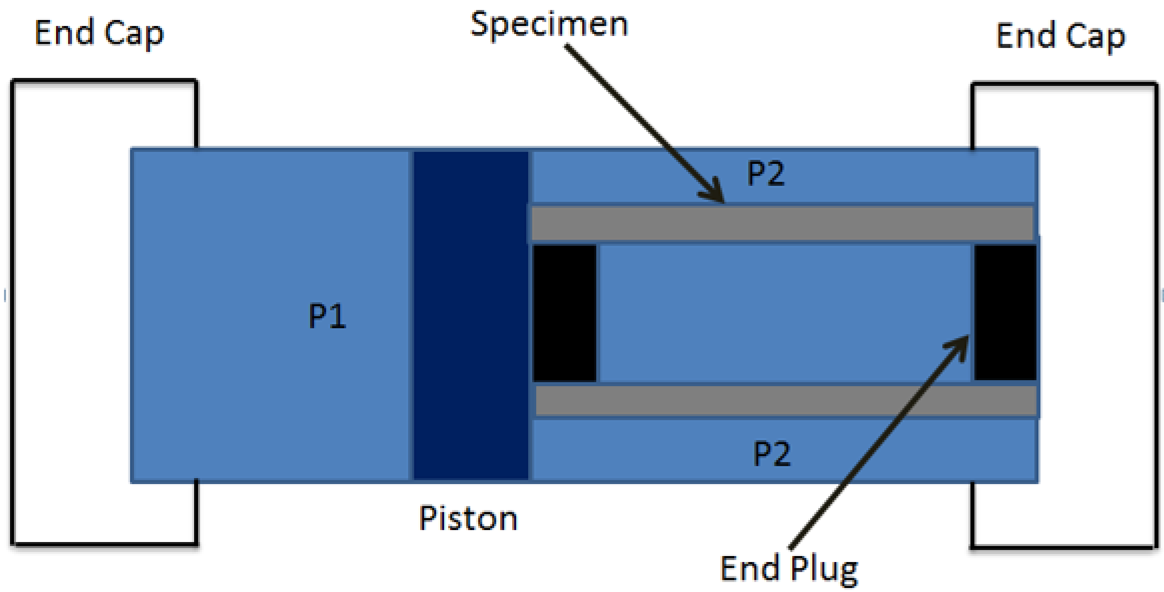


Figure 2. Piston and test vessel schematic.

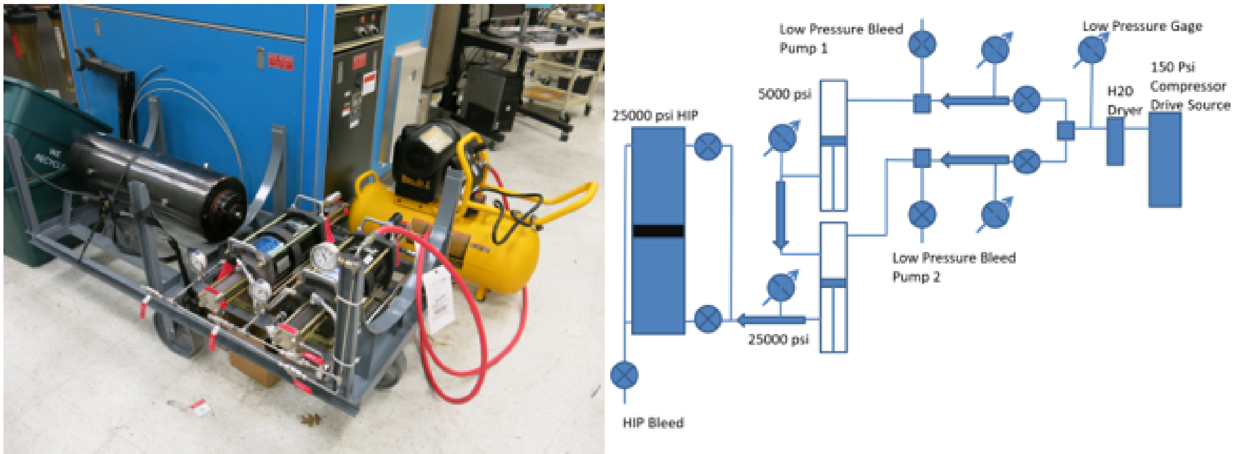


Figure 3. Q2/Q3 biaxial strength test system.

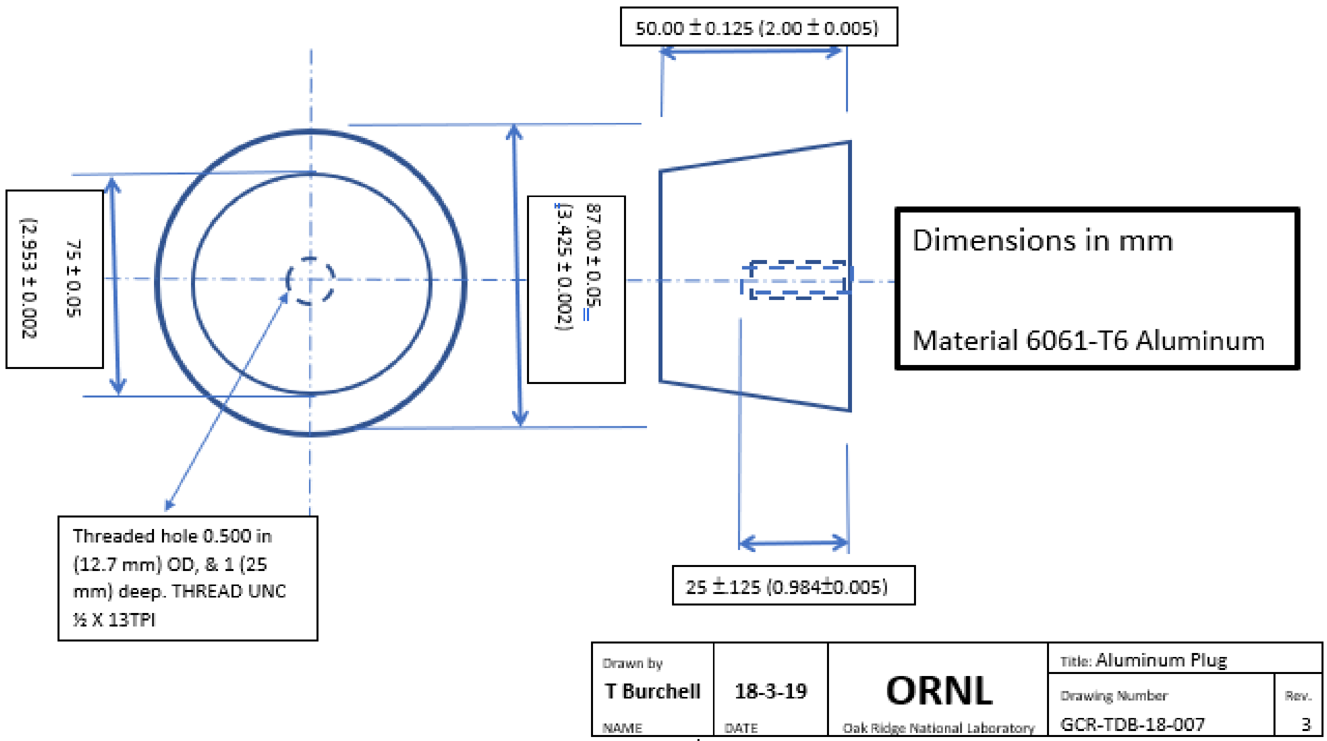


Figure 4. Aluminum plug.

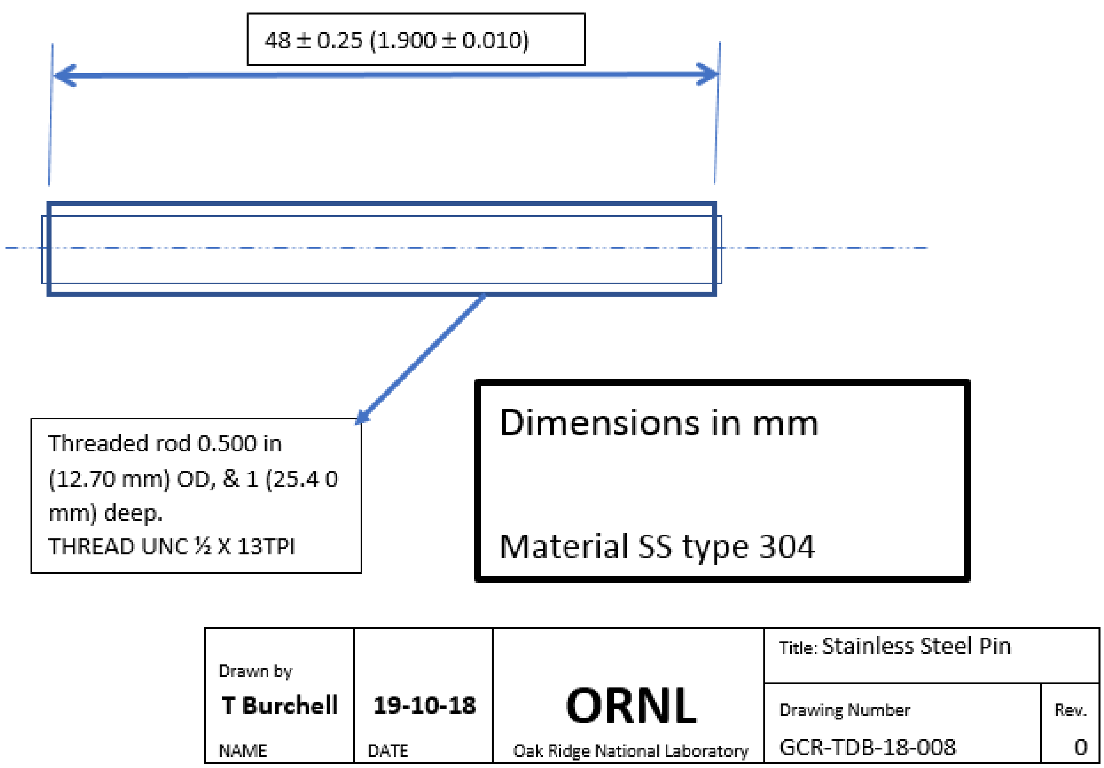


Figure 5. Stainless-steel stud.

3. BILLET CUT PLAN AND SPECIMEN DETAILS

The biaxial graphite specimen (Figure 6) will be machined from company-supplied graphite material. For shakedown testing, the specimens will be prepared from seven existing blanks (Figure 7). For Q2/Q3 stress testing, we will acquire an additional half-billet of NBG-18 from Idaho National Laboratory. The cut plans for this billet are shown in Figure 8, Figure 9, and Figure 10. Per Figure 6, 48 specimens will be produced (including 192 tensile specimens per Figure 11).

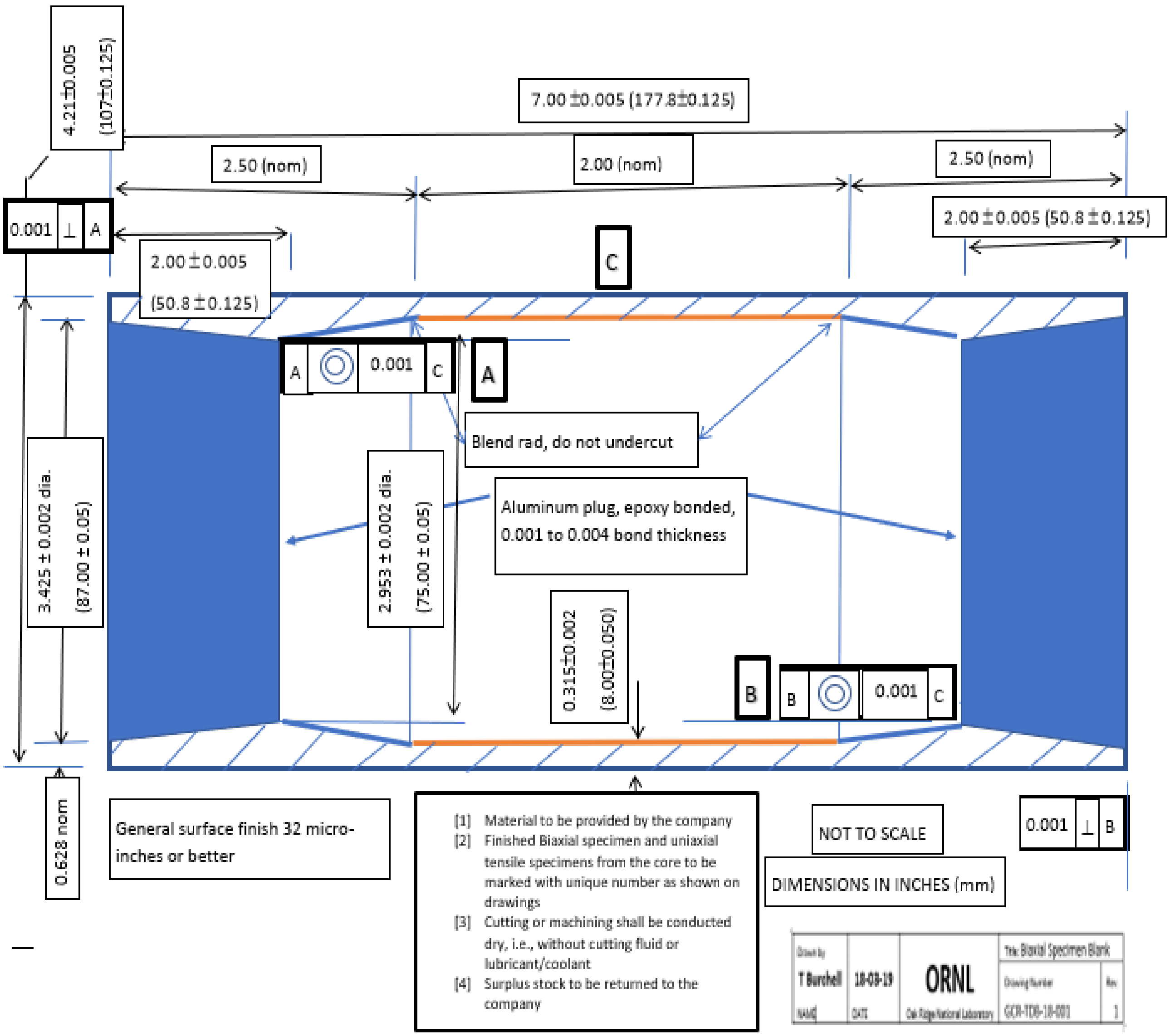


Figure 6. Biaxial graphite specimen for Q2/Q3 stress testing (for reference only see drawing for details)

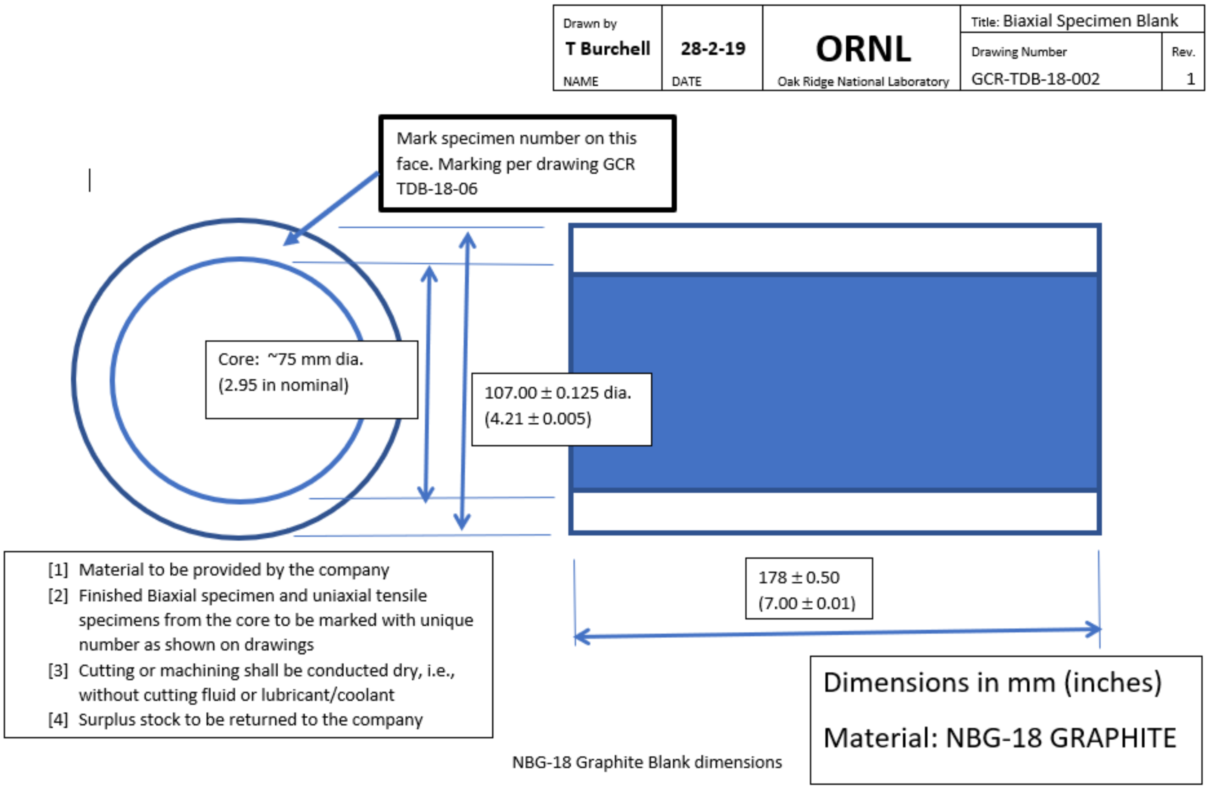


Figure 7. Graphite blank to be used here for biaxial system shakedown testing.

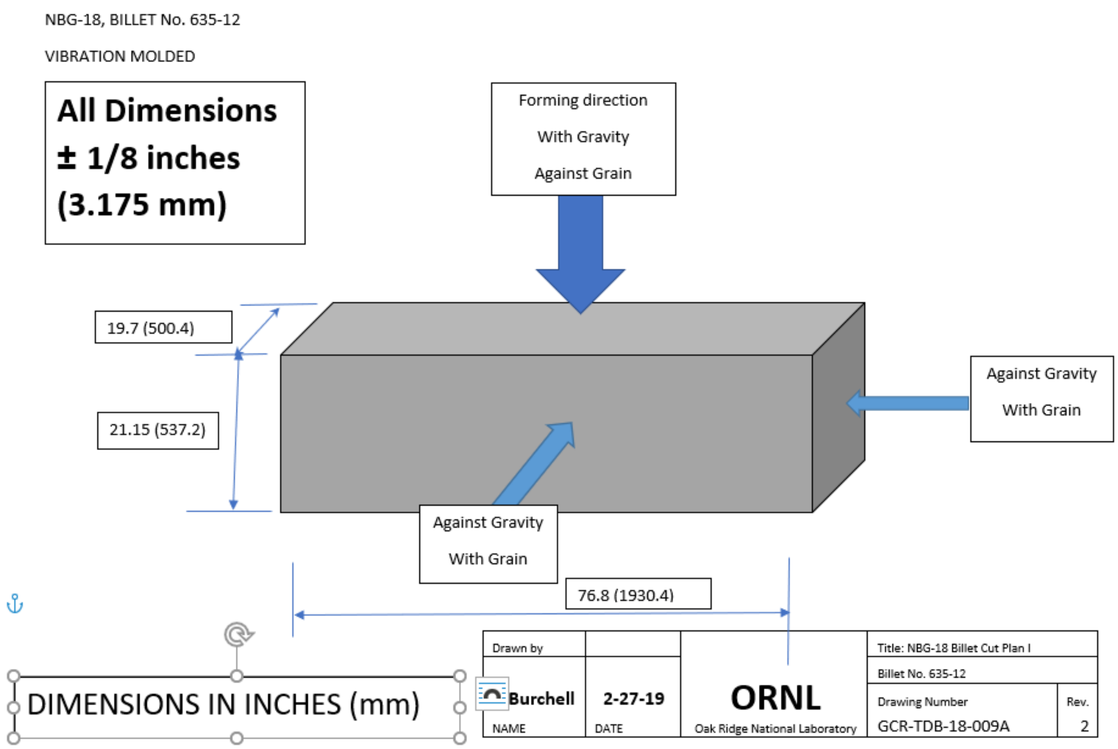


Figure 8. NBG-18 billet no. 635-12 cut plan (drawing A).

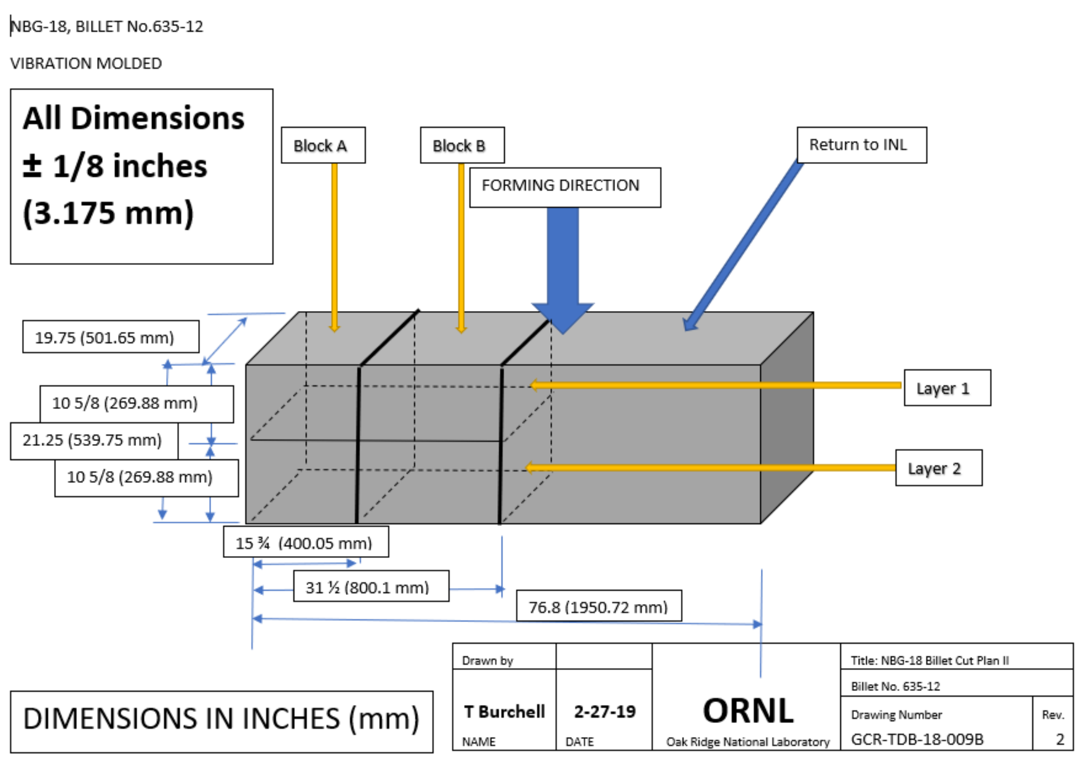


Figure 9. NBG-18 billet no. 635-12 cut plan (drawing B).

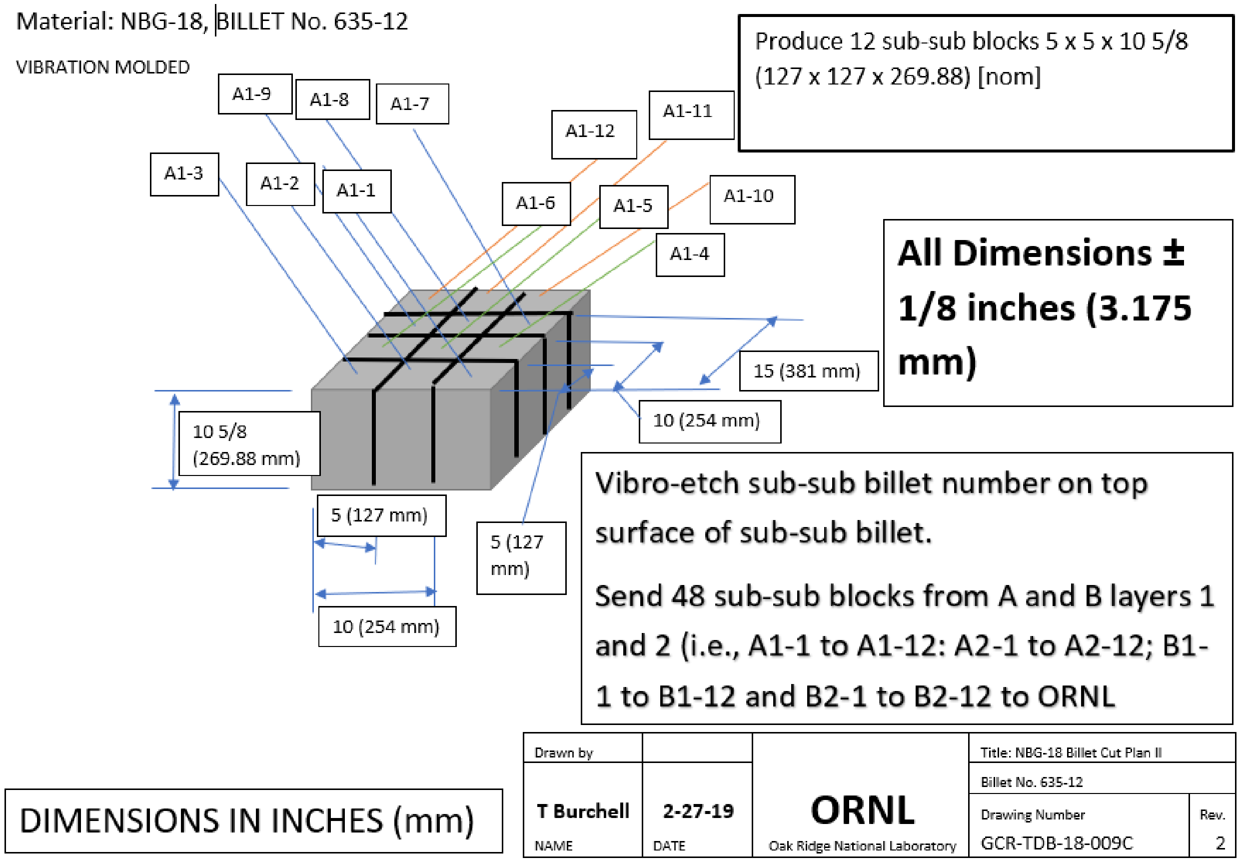
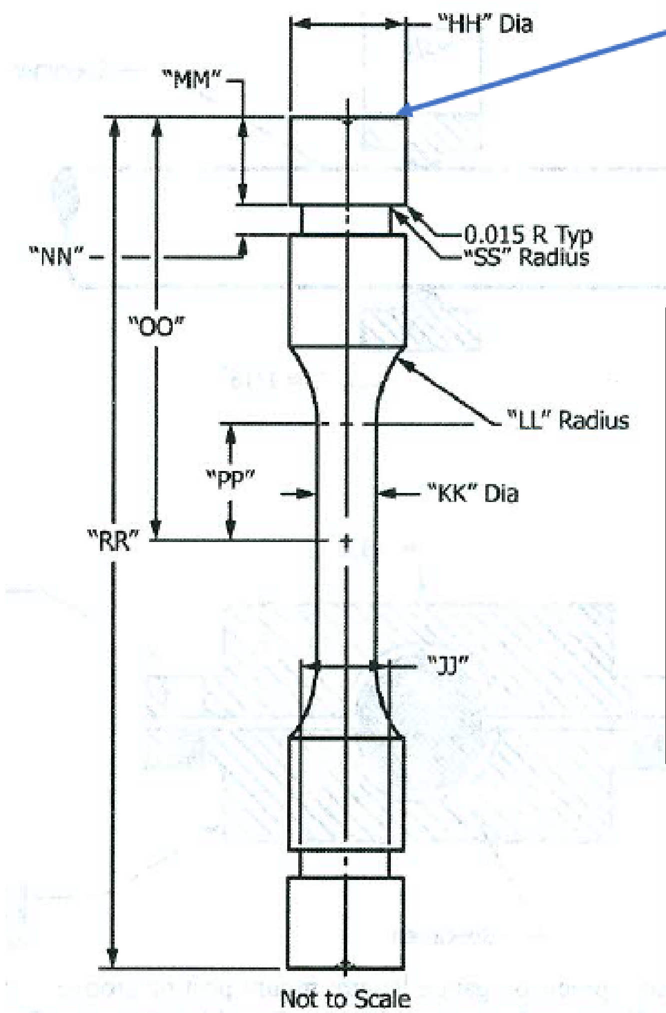


Figure 10. NBG-18 billet no. 635-12 cut plan (drawing C).

Each specimen will yield a core that is further divided into four blanks (Figure 12) and each yields a type-113 ASTM International (ASTM) C749[4] tensile specimens (Figure 11**Error! Reference source not found.**). Thus, a population of tensile test data can be generated and additional assurance of the integrity of each biaxial specimen attained. The graphite tensile type-113 (Figure 11) and biaxial specimens (Figure 6) shall be marked in accordance with drawing GCR-TDB-18-006 (Figure 13).



Mark specimen number on this face. Acceptable methods are laser engraving, vibro-engraving or CNC machining per drawing GCR TDB-18-06

Dimensions, in. (mm)	113
HH	0.760 + 0.000 – 0.002 (19.30 + 0.00 – 0.05)
JJ	0.640 (16.26)
KK	0.375 ± 0.002 (9.52 ± 0.05)
LL	1 (25.4)
MM	0.635 (16.13)
NN	0.125 (31.75)
OO	2⅜ (60.32)
PP	⅞ (22.22)
RR	4¾ (120.65)
SS	0.030 + 0.000 – 0.005 (0.76 + 0.00 – 0.13)

Drawn by			Title: Tensile Specimen	
T Burchell	28-2-19	ORNL	Drawing Number	Rev.
NAME	DATE	Oak Ridge National Laboratory	GCR-TDB-18-005	1

Figure 11. ASTM C749 type-113 graphite tensile specimen.

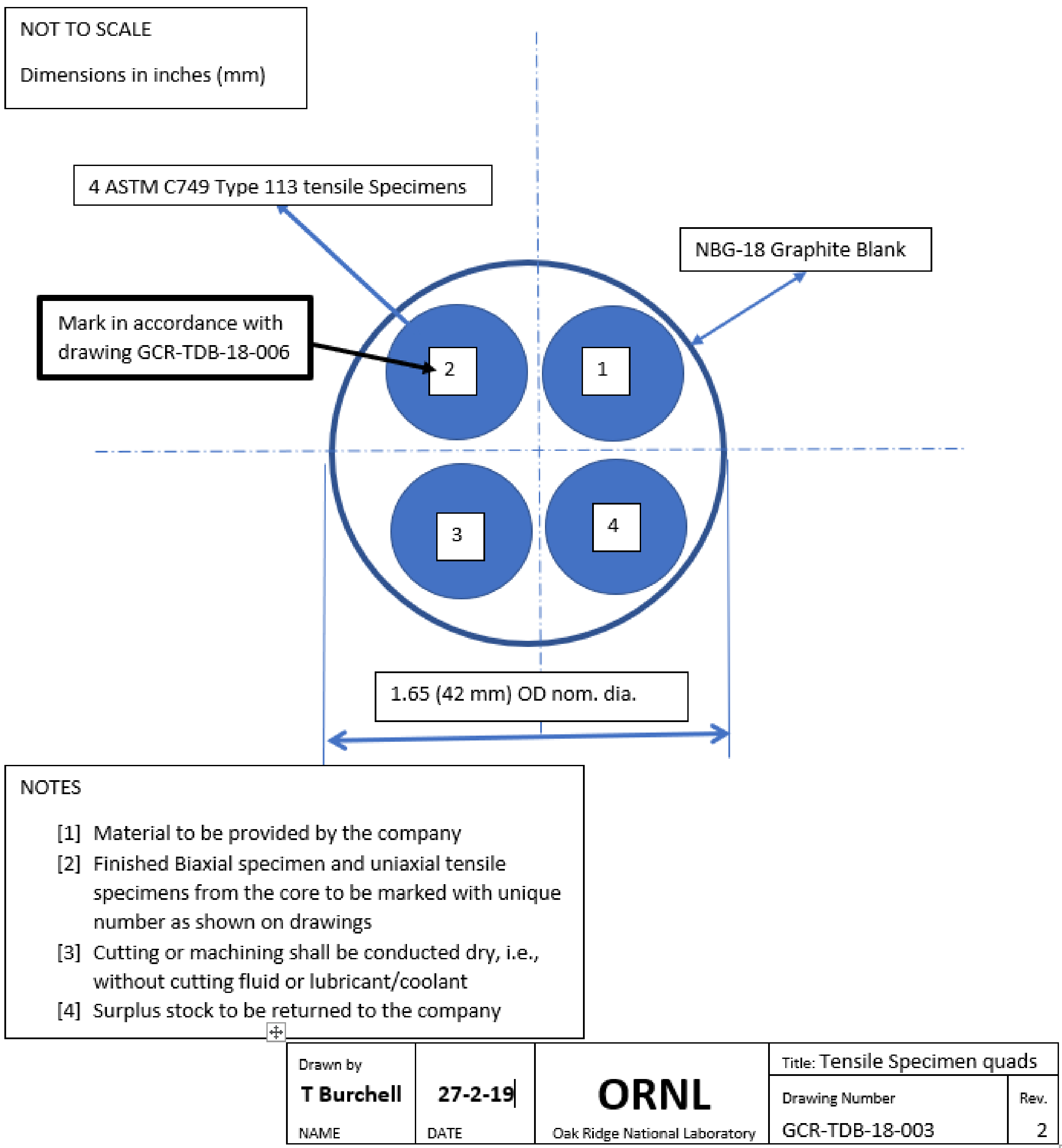
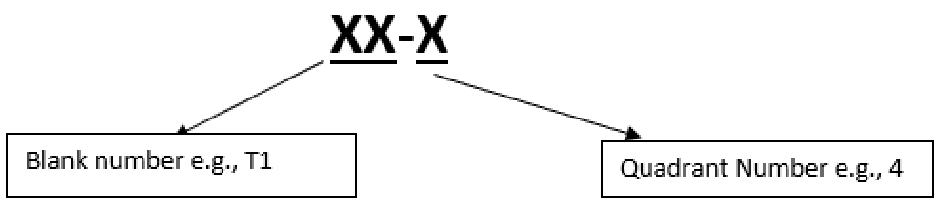
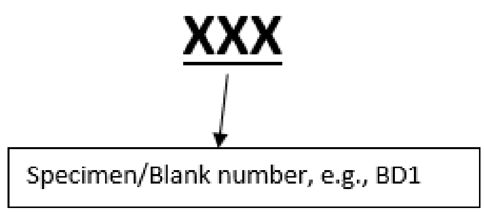


Figure 12. Biaxial specimen core used here for the uniaxial specimens.

UNIAXIAL TENSILE SPECIMEN MARKING



BIAXIAL SPECIMEN MARKING



1. Markings to be at least 0.25 in (8.89 mm) high
2. All markings to be legible
3. Acceptable methods of marking are LASER engraving, Vibro-Etching or CNC machining

Drawn by			Title: Marking Details	
T Burchell	**28-2-19**	**ORNL**	Drawing Number	Rev.
NAME	DATE	Oak Ridge National Laboratory	GCR-TDB-18-006	1

Figure 13. Specimen marking requirements.

4. SYSTEM SHAKEDOWN

Before graphite testing of the 7 shake-down samples, the test system must be operated, and its utility demonstrated. The following have been identified as potential issues and needed system upgrades:

- Sensitive inlet control valves for controlling P1 and P2 (note P1 and P2 will probably be in psi).
- Gas pressure accumulators and high-pressure regulators (P1 and P2).
- Real-time read out for axial and hoop stress.
- Data-logging system to record P1, P2, stress, and time.
- Select elastomeric sealant for specimen outside diameter.

5. STRESS RATIOS AND ASSOCIATED CONTROL PRESSURES (Q2 AND Q3)

5.1 STRESS RATIOS

The stress ratios desired to define Q2 and Q3 stresses (Figure 1) are shown in Figure 14, where the stress ratio is plotted as the axial stress divided by the hoop stress.

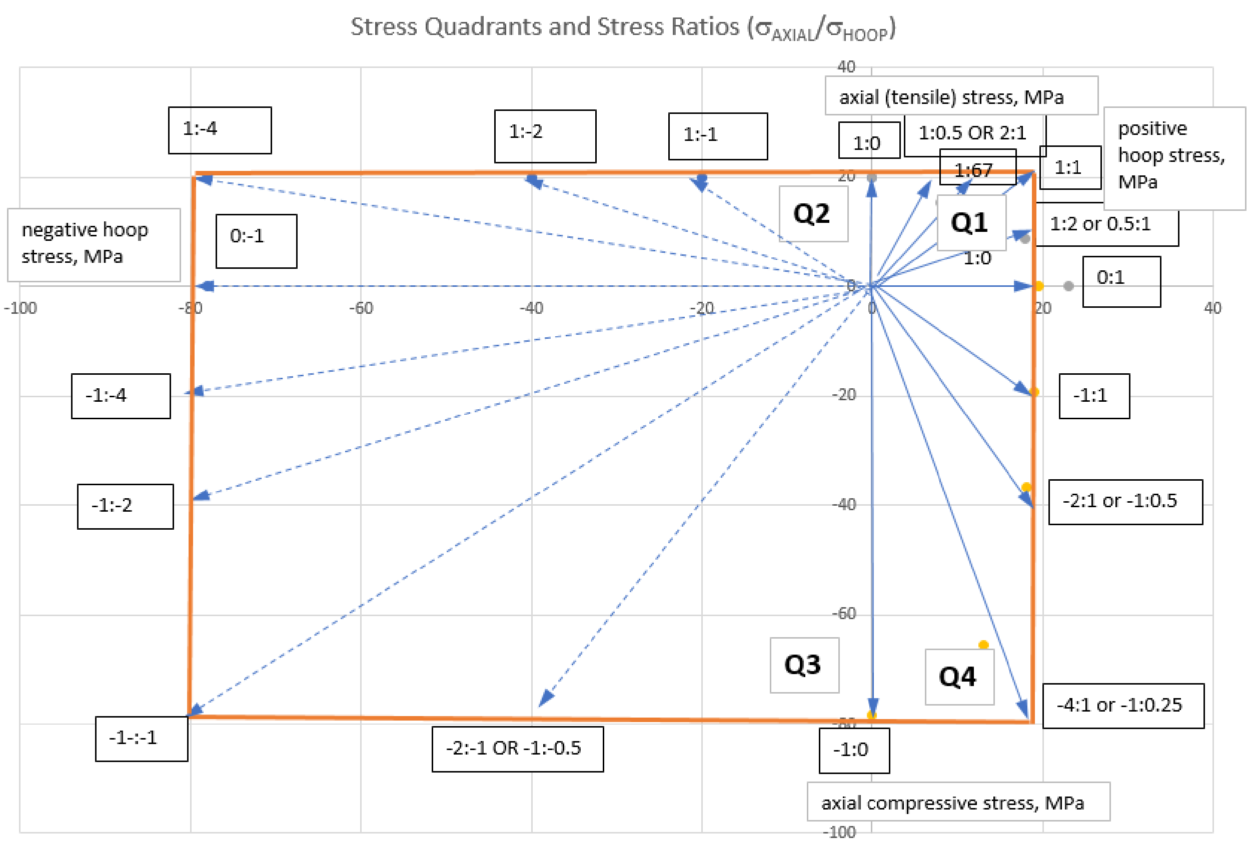


Figure 14. Stress ratios to be achieved (dotted lines) and already achieved (solid lines).

5.2 CALCULATION OF THE REQUIRED OPERATING PRESSURES

The operating (control) pressures needed to attain the stresses indicated in Figure 14 are achieved by balancing pressure P_1 and P2 (Figure 2). To estimate the required operating pressures, the following assumptions are made, and thus the following equations applied:

The specimen is assumed to be a ‘thin” cylinder such that the circumferential or “hoop” stress is given by

$$\sigma_h = \frac{P2 \times d}{2 \times t},$$

where σ_h (σ_2) is the hoop stress, Pa,
P2 is the specimen external (control) pressure, N/m^2 (Figure 2),
d is the specimen inside diameter (75 mm),
t is the specimen thickness (8 mm).

Rearranging and assuming the compressive hoop strength is 78 MPa for NBG-18 (same as compressive strength),

$$P2 = \frac{\sigma_h \times 2 \times t}{d}.$$

Applying pressure, P2 to the specimen exterior will induce a pressure difference and thus a specimen wall hoop stress provided there is no leakage (diffusion) through the specimen wall. This will be achieved by coating the specimen exterior with a sealant or by placing a rubber sheet around the specimen. Pressure P_2 will also displace the piston (Figure 2) laterally away from the specimen, thus inducing a tensile stress in the specimen. This force is given by

$$F1 = P2 \times (A_1 - A_2),$$

where P2 is the applied (control) gas pressure,
A_1 is the piston area,
A_2 is the specimen solid area.

Force F1 acts over the specimen cross-sectional area to produce an axial stress (σ_{t1}) in the specimen

$$\sigma_{t1} = F1/A_3,$$

where F1 is the force acting on,
A_3 is the specimen cross-sectional area.

The tensile stress produced by P2 usually exceeds the tensile strength of the graphite specimen (assumed here to be 20 MPa); thus, it is necessary to use an opposing force F_{c1} produce from P1 (Figure 2) such that

$$F_{c1} = P1 \times A_1,$$

where P1 is the applied (control) gas pressure,
A_1 is the piston area.

Then σ_{c1} can be obtained from

$$\sigma_{c1} = F_{c1}/A_3\ .$$

The net stress (tensile or compressive) is a function of P1 and P2 and can be calculated from

$$\sigma 1 \text{ (AXIAL TOTAL)} = \sigma_{t1} + \sigma_{c1} \; .$$

By assuming the stress Q2 and Q3 hoop failure strength is equal to the compressive strength of ~78 MPa and the tensile strength is ~20 MPa, the operating pressure P1 and P2 required to give the desired stress ratios can be estimated.

5.3 SECOND STRESS QUADRANT

The desired Q2 stress ratios are shown in Figure 14. Development of the induced circumferential (hoop) stress and axial stress as a function of the applied pressures P1 and P2 is shown in Figure 15 through Figure 19.

To achieve the pure tensile stress with no hoop stress case (Figure 15), stress ratio 1:0, we plan to use a standard specimen with small (2 mm diameter) holes (two per end) drilled through the wall adjacent to the aluminum plug. Thus, P2 does not cause a pressure differential between the inside and outside of the specimen and the hoop stress is zero. The axial stress (Pa) is given by

$$\sigma_{Axial} = P2^{*} \, (A_1 - A_2 + A_4)/A_3,$$

where P2 is the applied (control) pressure, N/mm^2,
A_1 is the piston area, m^2,
A_2 is the specimen (external) area, mm^2,
A_3 is the specimen cross-sectional area, mm^2,
A_4 is the plug area, mm^2.

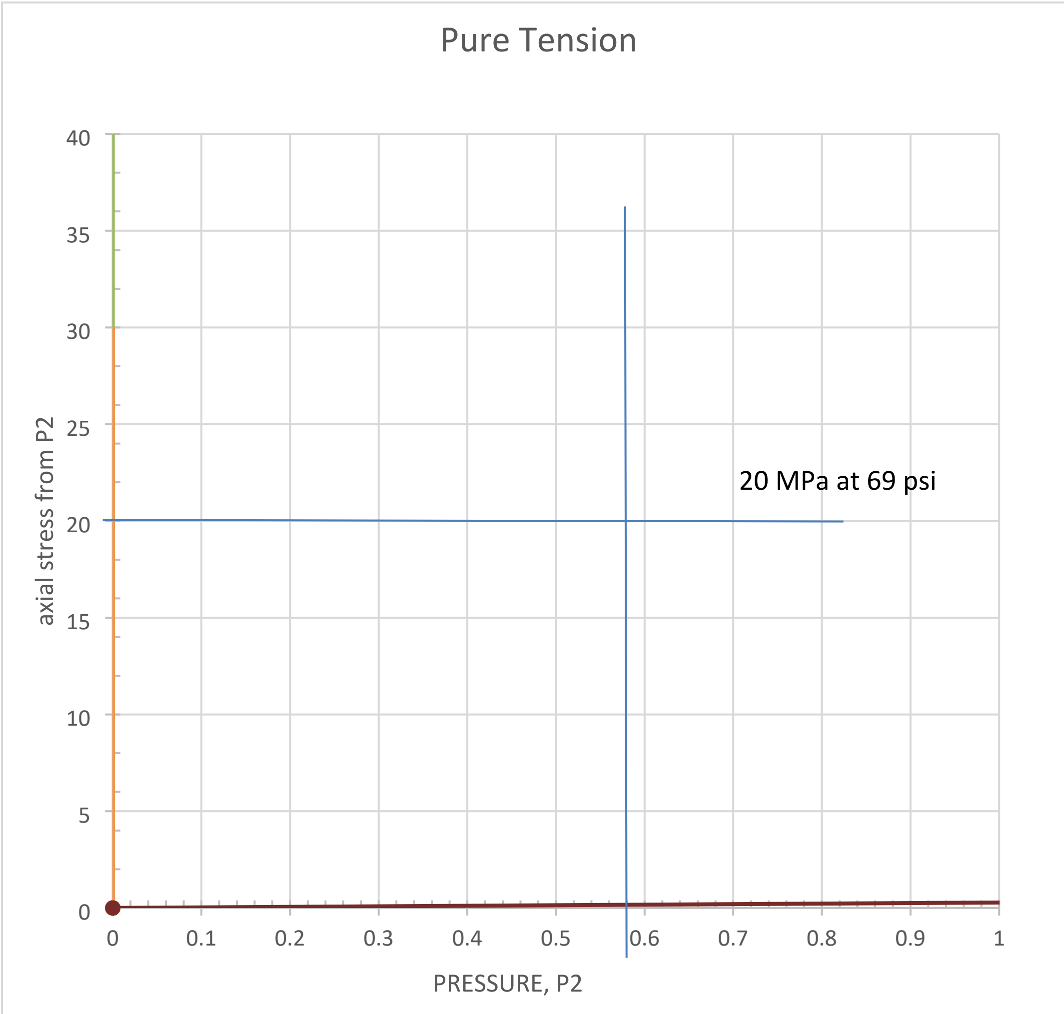


Figure 15. Induced axial stress arising from P2 for the pure tension case.

The second desired stress ratio (Figure 14) is 1:-1, and Figure 16 shows the buildup of stresses with applied gas pressure P1 and P2. The application of P2 at 3.03 MPa (440 psi) will induce a hoop stress of 20 MPa but will additionally cause an axial stress of 57 MPa. This must be opposed by an axial compressive stress induced by P1 of 37 MPa at P1 = 83 psi (0.572 MPa) to produce a net axial tensile stress of 20 MPa.

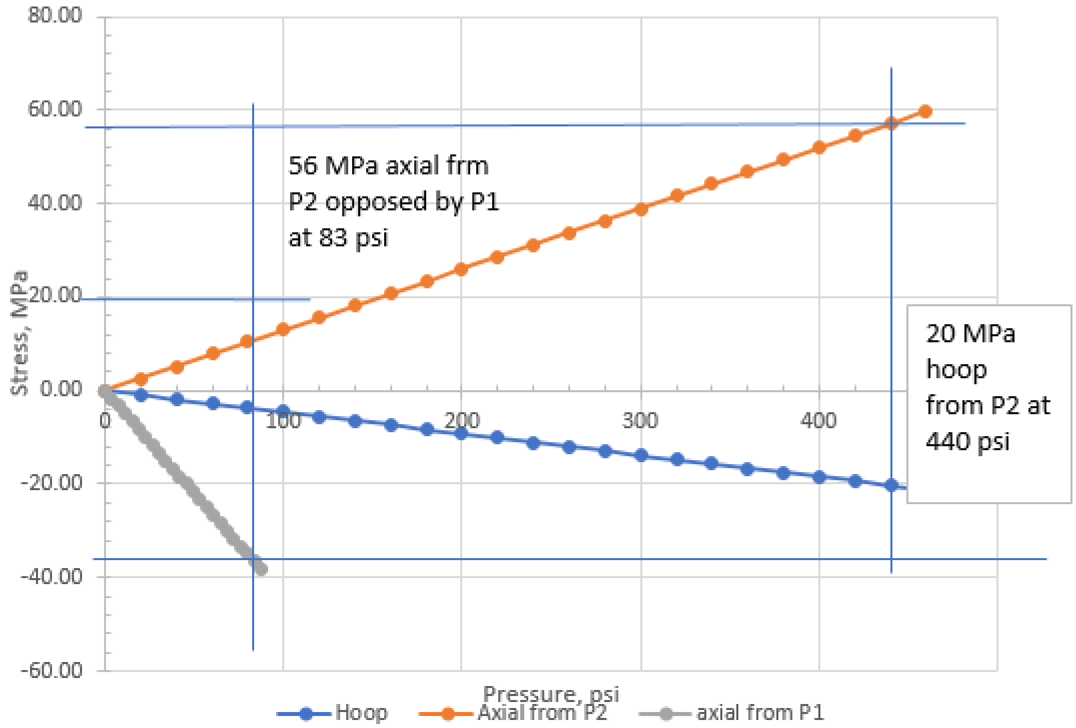


Figure 16. Induced axial and hoop stress arising from both P1 and P2 for the 1:-1 stress ratio case.

However, the net stress should not exceed 20 MPa and cause tensile failure until a P2 pressure of` 440 psi has been applied. Thus, it is essential that both P1 and P2 be applied simultaneously.

The next desired stress ratio is 1:-2, or ~20 MPa tension and -40 MPa hoop stress (Figure 14). This ratio is attained at the pressures indicated in Figure 17. The desired hoop stress is attained at P2 = ~880 psi (6.068 MPa). This also causes an axial tension of ~114 MPa, which must be opposed by an axial compression of ~94 MPa, causing a net stress of ~20 MPa at P1 = ~215 psi (1.482 MPa).

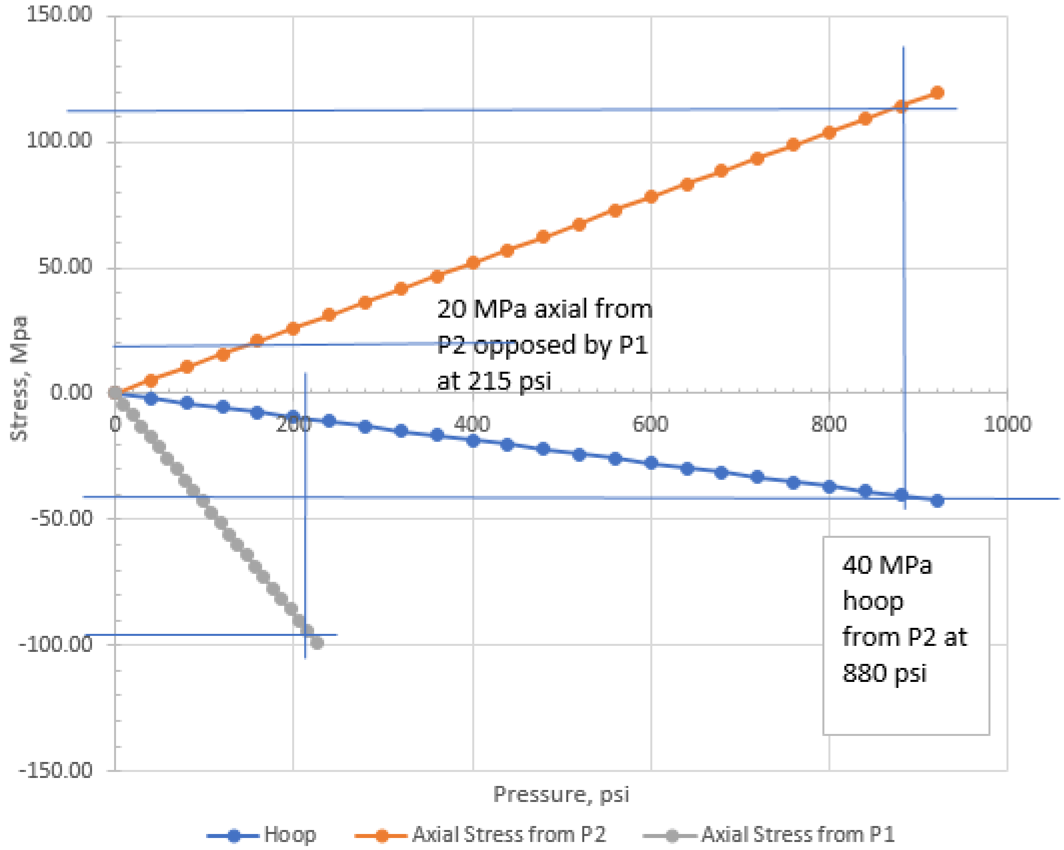


Figure 17. Induced axial and hoop stress arising from both P1 and P2 for the 1:-2 stress ratio case.

The third ratio in this stress quadrant is 1:-4 (Figure 14), and the stresses and pressures are shown in Figure 18.

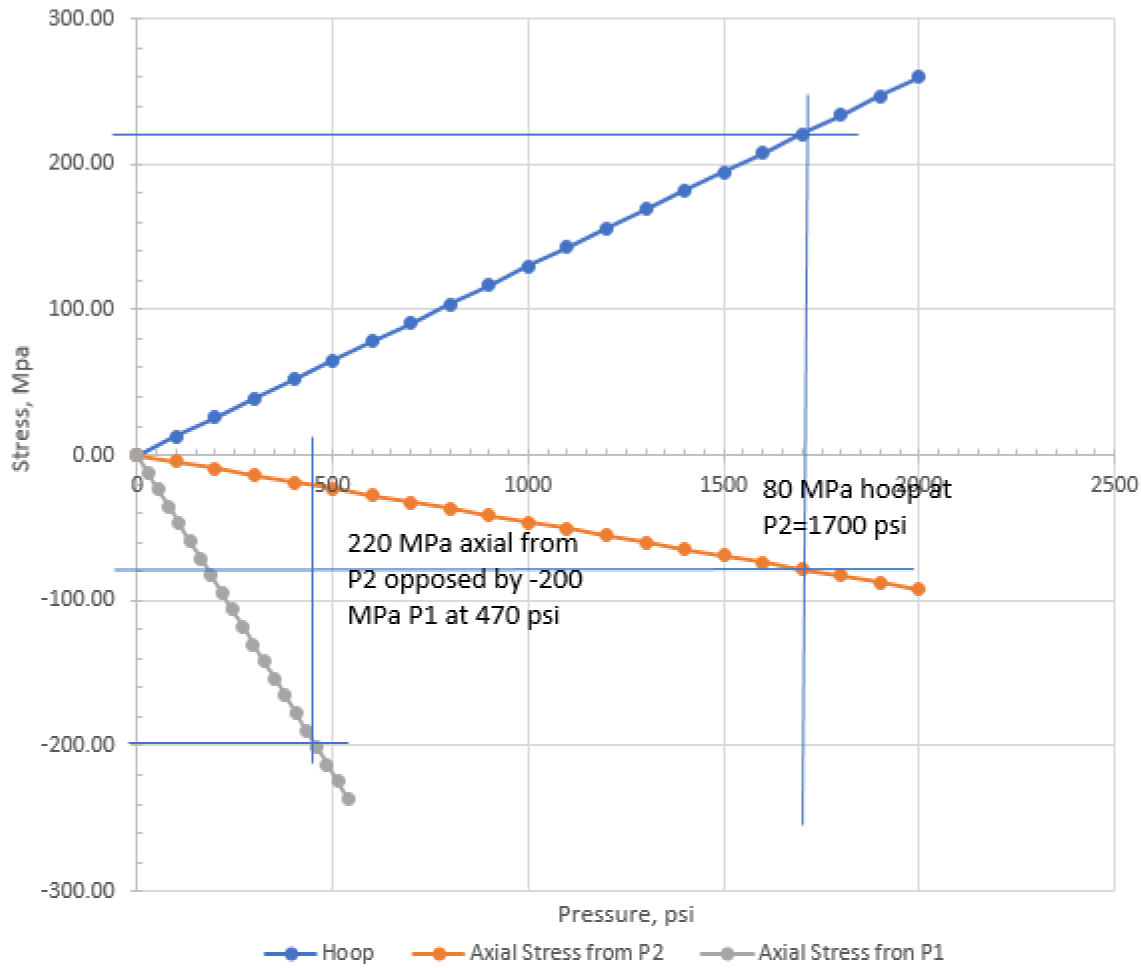


Figure 18. Induced axial and hoop stress arising from both P1 and P2 for the 1:-4 stress ratio case.

The desired hoop stress of ~80 MPa is achieved with an applied P2 pressure of ~1690 psi (11.653MPa). This also causes an axial tensile stress of 220 MPa, which must be opposed by a compressive axial stress from P1 of -200 MPa (at P1 = 470 psi [3.240]), producing a net axial stress of 20 MPa tension.

The final Q2 stress ratio is the pure hoop stress case of 0:-1, which is also the first ratio in Q3 (Figure 14); the required stresses and pressures are shown in Figure 19.

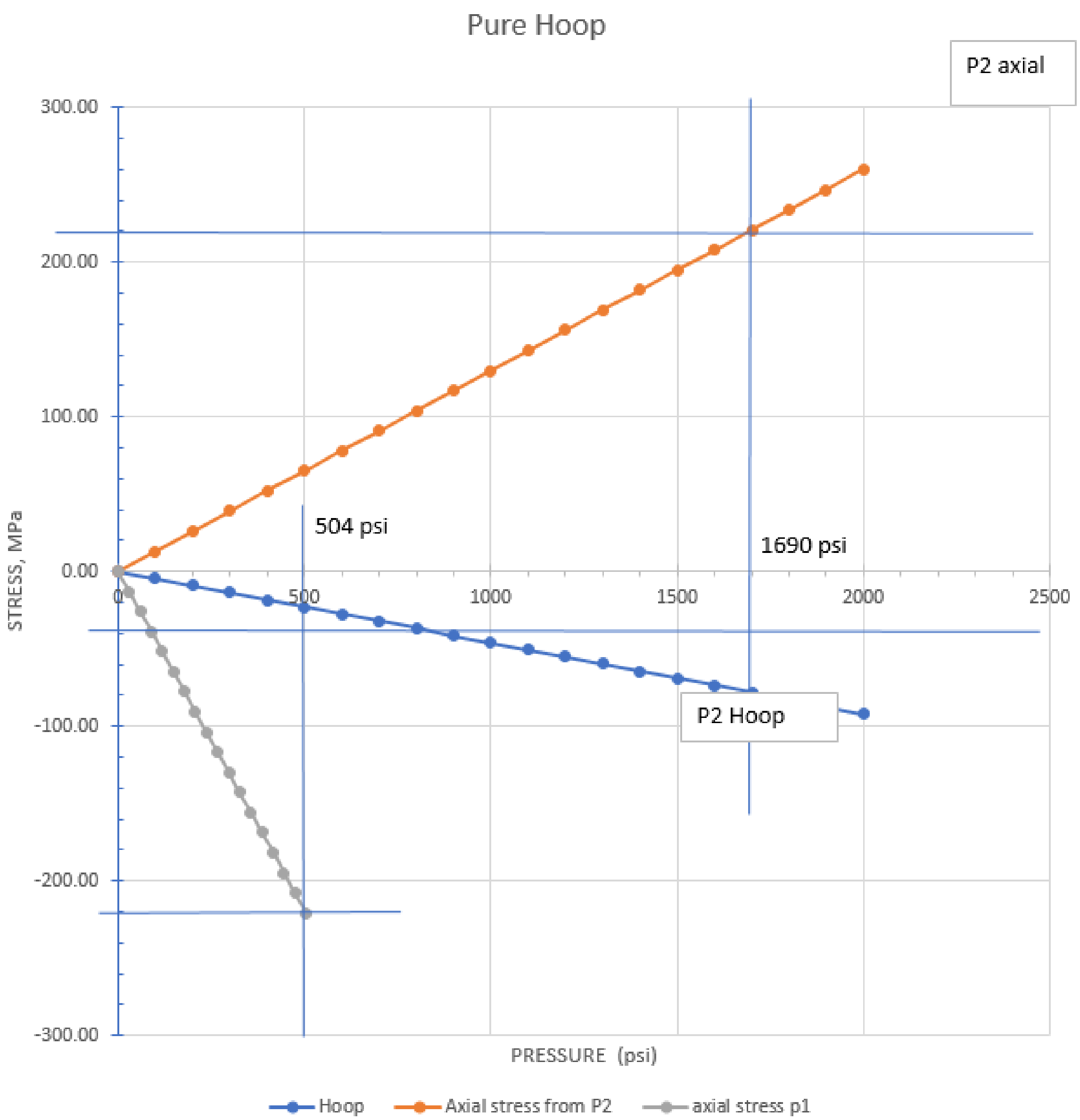


Figure 19. Induced axial and hoop stress arising from both P1 and P2 for the 0:-1 stress ratio case.

The desired hoop stress of ~80 MPa is achieved with an applied P2 pressure of ~1700 psi (11.653MPa). This also causes an axial tensile stress of 220 MPa, which must be opposed by a compressive axial stress from P1 of 220 MPa (at P1 = 504 psi [3.475 MPa]), producing a net axial stress of 0 MPa tension (i.e., pure hoop stress).

5.4 THIRD STRESS QUADRANT

The desired Q3 stress ratios are shown in Figure 14. The pure axial compression case is again achieved by drilling two small holes through the specimen wall (adjacent to the aluminum plug) at each end of the specimen to ensure there is no pressure differential across the wall and hence no hoop stress from P2. P1 induces a compressive stress. The required stresses and pressures are shown in Figure 20.

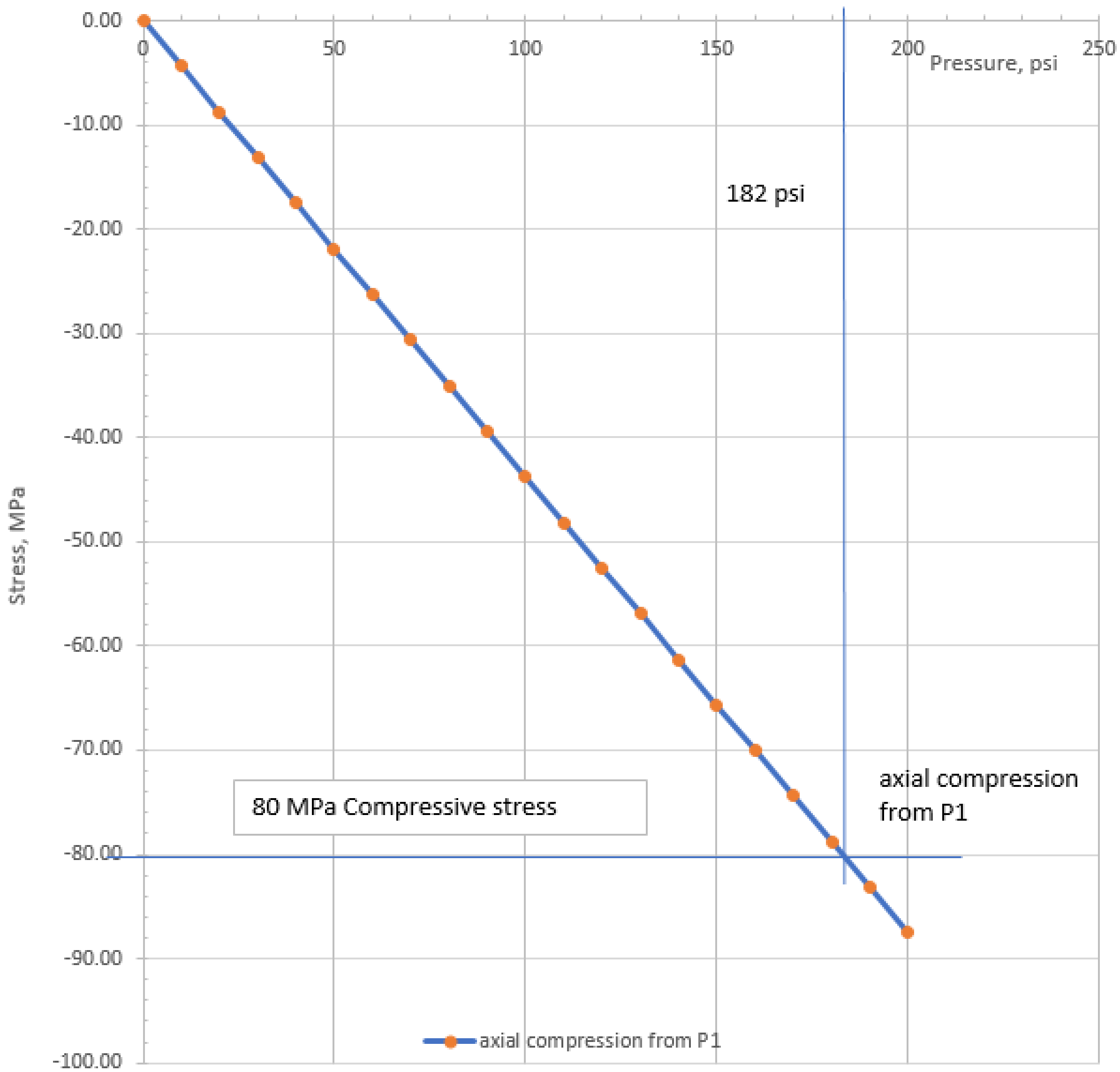


Figure 20. Induced axial and hoop stress arising from both P1 and P2 for the -1:0 stress ratio case.

The desired axial compressive stress of 80 MPa is achieved at an applied P1 pressure of 182 psi (1.255 MPa).

To obtain the -2:-1 or -1:-0.5 (-78:-40) (Figure 14), we require a hoop stress of 40 MPa, which is attained at a P2 pressure of 850 psi (5.861 MPa). This in turn gives rise to an axial stress of ~110 MPa. This must be opposed by an induced axial compression from P1 of -190 MPa, yielding a net axial stress of -80 MPa at P1 = ~427 psi (2.944 MPa). This is illustrated in Figure 21.

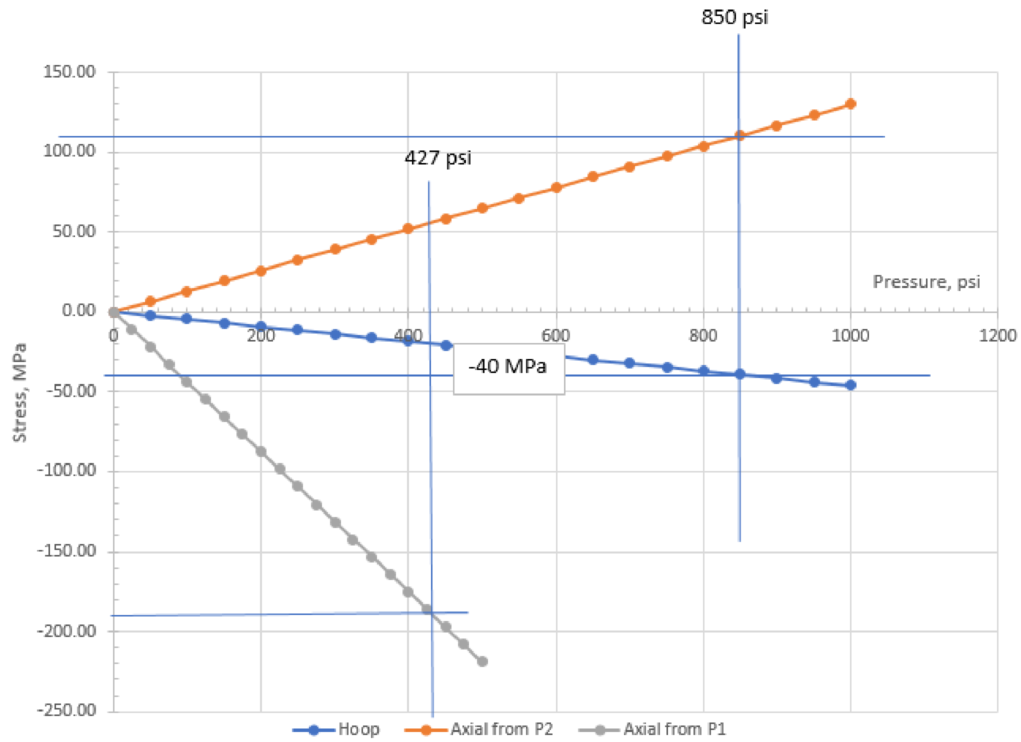


Figure 21. Induced axial and hoop stress arising from both P1 and P2 for the -1:-0.5 stress ratio case.

The -1,-1 stress ratio (Figure 14) (i.e., -78:-78 MPa) is plotted in Figure 22. At ~1690 psi (11.653 MPa), applied P2 gives 80 MPa hoop stress and 220 MPa axial tension. This opposed by P1 at 630 psi (4.344 MPa), which produces a stress of ~280 MPa and a net axial stress of -80 MPa.

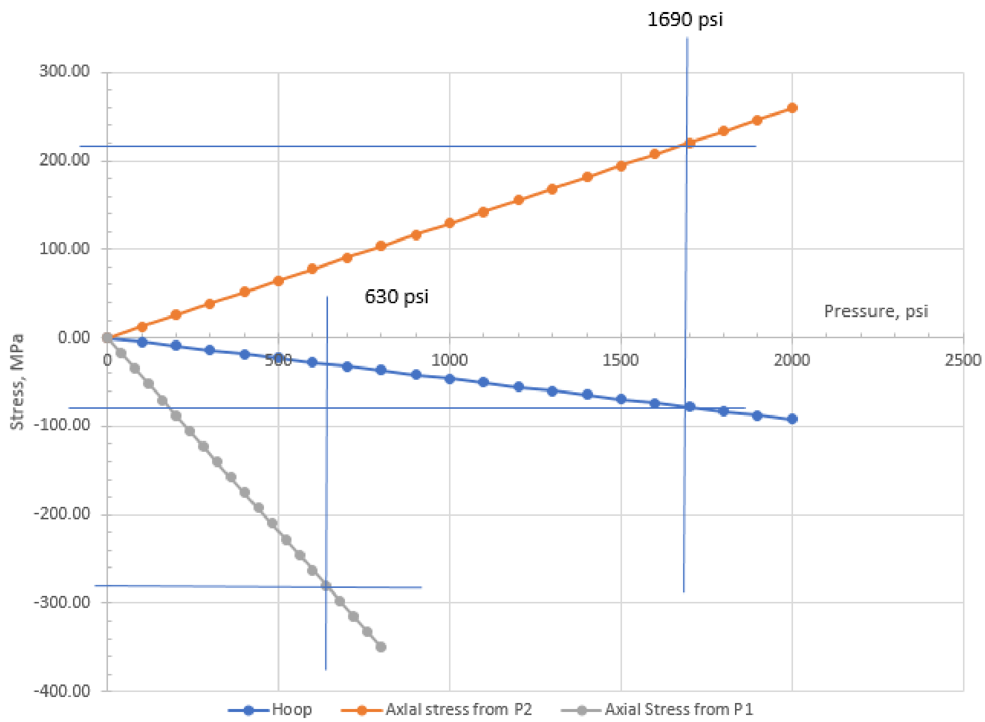


Figure 22. Induced axial and hoop stress arising from both P1 and P2 for the -1:-1 stress ratio case.

The -1:-2 (-40 MPa axial:-80 MPa hoop) stress ratio is illustrated in Figure 14. The desired stresses and gas pressures are shown in Figure 23.

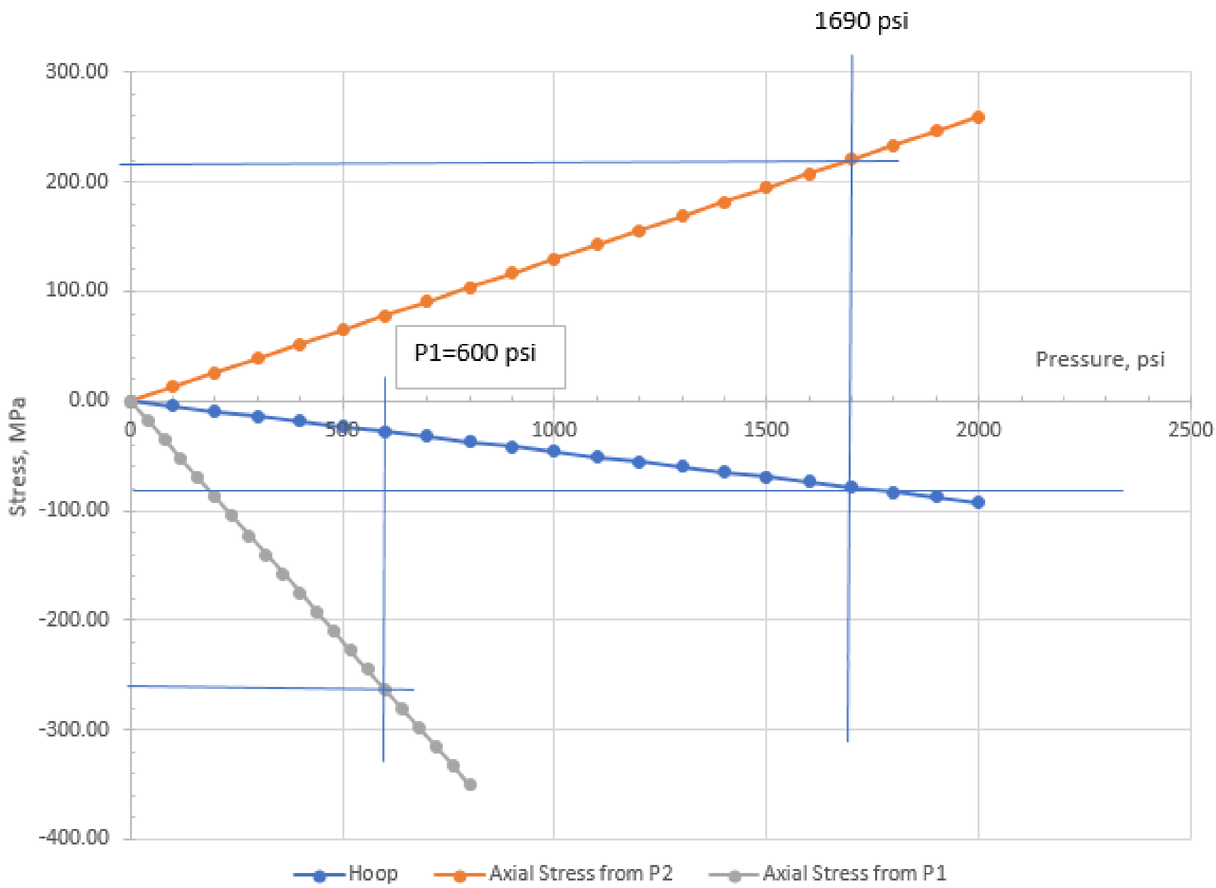


Figure 23. Induced axial and hoop stress arising from both P1 and P2 for the -1:-2 stress ratio case.

A P2 pressure of ~1690 psi (11.65 MPa) causes a hoop stress of ~80 MPa and an axial tension of ~220 MPa. This is opposed by a P1 pressure at 600 psi (4.137 MPa) causing a compressive stress of ~-260 MPa; thus a net axial stress of -40 MPa is attained.

The -1:-4 or -0.25:-1 (~-20 MPa:-80 MPa) (Figure 14) ratio pressures are shown in Figure 24. A hoop stress of ~80 MPa is achieved at P2 = 1690 psi (11.65 MPa), which also yields an axial stress of 220 MPa. This is opposed by the axial stress of -240 MPa induced by P1 at ~520 psi (3.585 MPa).

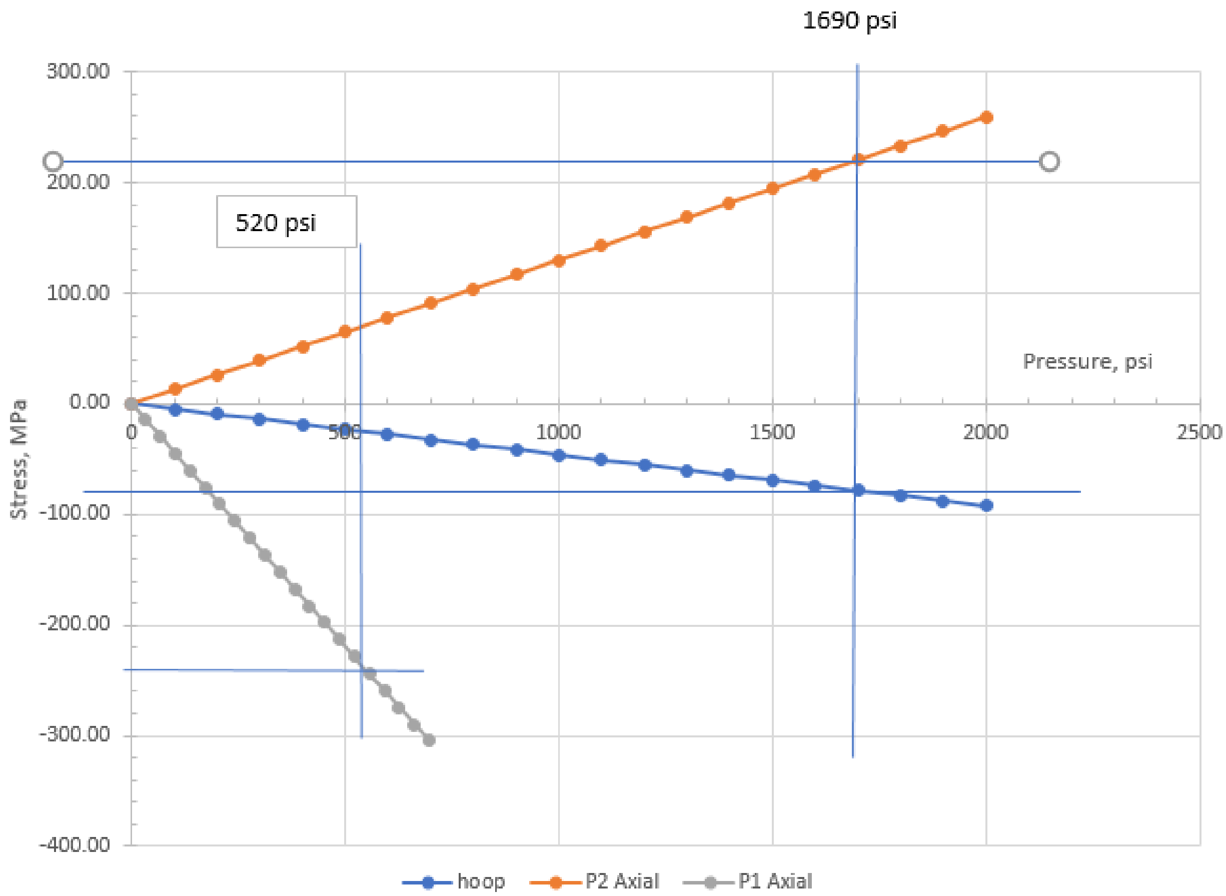


Figure 24. Induced axial and hoop stress arising from both P1 and P2 for the -1:-4 stress ratio case.

The case of pure (compressive) hoop, (0;-78) is shown in Figure 25. P2 at 1690 psi (11.653 MPa) produces a hoop stress of ~80 MPa and an axial stress of 220 MPa. This is opposed by a stress of -220 MPa from P1 set to 500 psi (3.448 MPa).

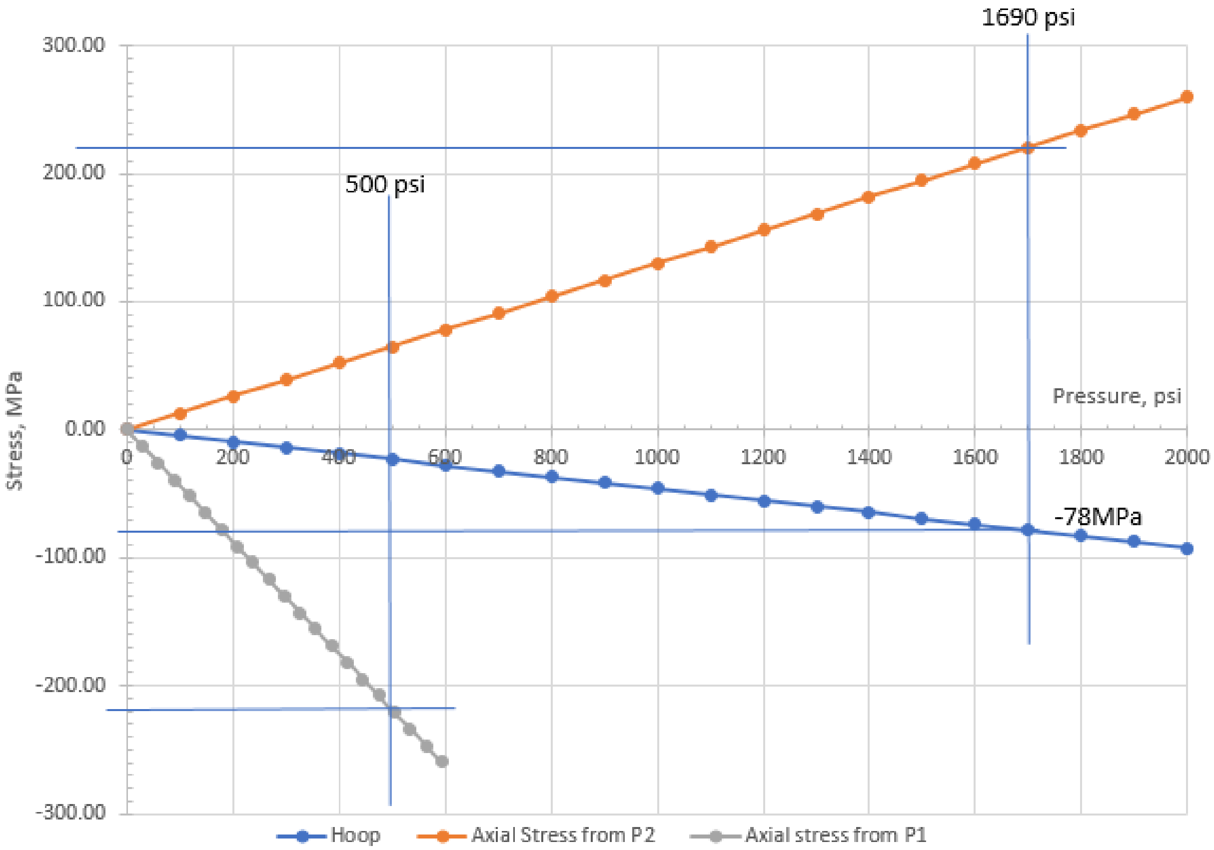


Figure 25. Induced axial and hoop stress arising from both P1 and P2 for the 0:-1 stress ratio case.

Great care must be taken when adjusting P1 and P2 to avoid premature specimen failure from unbalanced stresses that exceed the graphite's strength.

6. SPECIMEN TESTING QUANTITIES

6.1 BIAXIAL SPECIMENS

A total of 44 specimens are need to complete testing in Q2 and Q3 (allowing four spares), as detailed in Table 1.

Table 1. Biaxial specimen needs

Axial stress	Hoop stress	Stress ratio (axial/hoop)	Number of specimens	Test status
First stress quadrant				
20	0	pure tension	5	Tested
0	23	pure hoop	4	Tested
11.27	11.13	1:1	3	Tested
15.5	10.6	1:0.67	5	Tested
15.4	8	2:1	4	Tested
8.7	18	1:2	5	Tested
Second stress quadrant				
0	-78	pure hoop	4	To be tested
20	0	pure tension	4	To be tested
20	-20	1:-1	4	To be tested
20	-40	1:-2	4	To be tested
20	-78	1:-4	4	To be tested
Third stress quadrant				
0	-78	pure hoop	4	To be tested
-78	0	pure compression	4	To be tested
-78.0	-39	-1:-0.5	4	To be tested
-78.8	-78	-1:-1	4	To be tested
-40.0	-78	-1:-2	4	To be tested
-20.0	-78	-1:-4	4	To be tested
Fourth stress quadrant				
0	19.5	pure hoop	3	Tested
-19.3	19	-1:1	5	Tested
-36.8	18.2	-2:1	6	Tested
-65.6	13	-4:1	5	Tested
-78.3	0	pure compression	5	Tested

6.2 UNIAXIAL SPECIMENS

The 48 cores available from testing in Q2 and Q3 shall be quartered and provide 192 type-113 ASTM C749[4] specimens (Figure 11).These 192 tensile test specimens will be tested following the method prescribed in ASTM C749.[4]

7. SCHEDULE

Use of the existing Q2/Q3 test system (Figure 3) will be demonstrated before the commencement of biaxial testing (i.e., shakedown testing will be conducted in early 2019). Q2 testing is scheduled to be completed in 2019, and Q3 testing will occur in 2020.

8. QUALITY ASSURANCE

The described technical work scope and related activities shall be conducted in accordance with the applicable quality assurance requirements of the Idaho National Laboratory quality assurance program and the Advanced Reactor Technology quality assurance program plan that meets the requirements of ASME NQA-1-2008/1a-2009, *Quality Assurance Requirements for Nuclear Facilities.* Applicable quality assurance program requirements were flowed down to Oak Ridge National Laboratory (ORNL) through Memorandum Purchase Order No. 00153522. Work scope at ORNL was performed to the QAP-ORNL-NR&D-01, *Quality Assurance Plan for Nuclear Research and Development Conducted at the Oak Ridge National Laboratory*, requirements which meet NQA-1-2008/1a-2009.

9. REFERENCES

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4. American Society for Testing and Materials. C749-15 (2016). “Standard Test Method for Tensile Stress-Strain of Carbon and Graphite.” *Annual Book of ASTM Standards*. West Conshohocken, PA: ASTM International.