INL/EXT-16-39082

AGC-4 Experiment Irradiation Monitoring Data Qualification Interim Report

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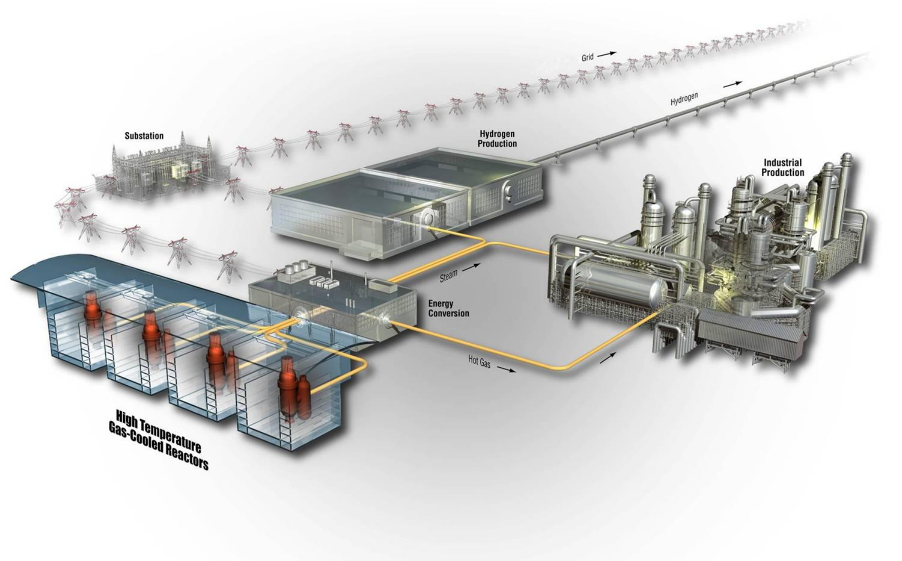

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INL ART TDO Program

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Approved by:

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SUMMARY

The Graphite Technology Development Program is running a series of six experiments to quantify the effects of irradiation on nuclear-grade graphite. The fourth experiment, Advanced Graphite Creep 4 (AGC-4), began with Advanced Test Reactor (ATR) Cycle 157D on May 30, 2015, and has been irradiated for two cycles. The capsule was removed from the reactor after ATR Cycle 158A, which ended on January 2, 2016, due to interference with another experiment. Irradiation will resume when the interfering experiment is removed from the reactor. This report documents qualification of AGC-4 experiment irradiation monitoring data for use by the Advanced Reactor Technologies (ART) Technology Development Office (TDO) Program for research and development activities required to design and license the first high-temperature reactor nuclear plant. *Qualified* data meet the requirements for use as described in the experiment planning and quality assurance documents. *Failed* data do not meet the requirements and provide no useable information. *Trend* data may not meet all requirements but still provide some useable information. Use of *Trend* data requires assessment of how any deficiencies affect a particular use of the data.

All thermocouples (TCs) have functioned throughout the AGC-4 experiment. All temperature data are *Qualified* for use by the ART TDO Program.

Argon, helium, and total gas flow data were within expected ranges and are *Qualified* for use by the ART TDO Program.

Discharge gas line moisture values were consistently low during Cycle 157D. At the start of Cycle 158A, gas moisture briefly spiked to more than 600 ppmv and then declined throughout the cycle. Moisture values are within the measurement range of the instrument and are *Qualified* for use by the ART TDO Program.

Graphite creep specimens were subjected to one of three loads: 393, 491, or 589 lbf. For a brief period during Cycle 157D between 12:19 on June 2, 2015, and 08:23 on June 11, 2015, the load cells were wired incorrectly, resulting in missing stack load data. Missing stack loads were estimated from measured ram pressures using regression equations developed from the existing data from Cycle 157D. Estimated stack loads during this period are considered to be an accurate representation of actual load applied to the stacks. These loads deviate slightly from the planned loads. This deviation does not prevent the data from being *Qualified* for use but must be taken into account when analyzing the effect of load on creep.

Stack displacement increased consistently throughout the first two cycles, with total displacement ranging from 0.4 to 0.8 in. During ATR outages, a set of pneumatic rams raised the stacks of graphite creep specimens to ensure the specimens were not stuck within the test train. This stack raising was performed twice. All stacks were raised successfully each time. The load and displacement data are *Qualified* for use by the ART TDO Program.

Analyses were conducted on correlations between TCs to look for trends and step changes that might indicate instrument degradation or failure. Correlation analysis was used to identify instances when TCs form short circuits, referred to as virtual junctions, which result in TCs reporting temperatures from some location in the capsule other than the location where they were intended to read. No evidence of virtual junctions was found.

A total of 18,743,236 response values were recorded from irradiation monitoring of the first two cycles of the AGC-4 experiment. During the Cycle 158A outage, 176,726 ram gas pressure and raise pressure measurements are *Failed*. Because these occurred during an outage, they do not affect the monitoring of stack loads. All other data are *Qualified* for use by the Advanced Reactor Technologies Technology Development Program.

APPENDIX

FIGURES

TABLES

ACRONYMS

AGC	advanced graphite creep
ART	Advanced Reactor Technologies
ATR	Advanced Test Reactor
CDCS	capsule distributed control system
HTR	high-temperature reactor
HTV	high temperature vessel
NDMAS	Nuclear Data Management and Analysis System
NQA	nuclear quality assurance
QA	quality assurance
R&D	research and development
RDAS	reactor data-acquisition system
TC	thermocouple
TDO	Technology Development Office

AGC-4 Experiment Irradiation Monitoring Data Qualification Interim Report

1. INTRODUCTION

The Advanced Reactor Technologies (ART) Program manages research and development (R&D) for high-temperature reactors (HTRs) and other advanced reactor technologies and ensures U.S. Nuclear Regulatory Commission requirements and stakeholder needs are factored into the R&D effort. Nuclear-grade graphite materials for use in HTRs are being tested and characterized to quantify performance in high-temperature and high-fluence environments. This report presents qualification of irradiation monitoring data collected from the fourth advanced graphite creep (AGC-4) experiment during Advanced Test Reactor (ATR) Cycles 157D and 158A. The AGC-4 experiment capsule was removed from ATR after Cycle 158A because of interference with the Kijang Research Reactor fuel assembly irradiation experiment, causing difficulty in controlling temperatures in the capsule. Irradiation will resume when the Kijang experiment is complete.

1.1 Graphite Technology Development Program

The Graphite Technology Development Program provides data to support the design of graphite core components within the specific reactor service conditions of the HTR (PLN-2497). The Graphite Technology Development Program is running a series of six experiments to quantify the effects of irradiation on nuclear-grade graphite. The objectives of the graphite-irradiation experiments are to demonstrate that commercially available nuclear-grade graphite exhibits acceptable nonirradiated and irradiated properties for use in nuclear reactor structural components and to establish the lifetime under HTR neutron radiation and temperature regimes for specific graphite types.

To meet these objectives, the Graphite Technology Development Program has established the following data-collection tasks:

- Measure the thermophysical properties of graphite specimens before and after irradiation in ATR
- Measure the radiation-induced creep at high temperature and high-radiation dose.

Data collected during specimen irradiation will be used to quantify the temperatures, radiation doses, and compressive stresses experienced by specimens. The data are necessary to develop an understanding of the behavior of graphite in radiation fields.

1.2 Purpose and Scope

Data that will be used to support qualification of nuclear-grade graphite for use in HTRs are collected within a quality assurance (QA) program that implements Nuclear Quality Assurance (NQA)-1-2008/1a-2009, Part I, through PLN-2690, "Idaho National Laboratory Advanced Reactor Technologies Technology Development Office Quality Assurance Program Plan." Data collected per PLN-2690 should be reviewed to determine suitability for intended use by independently verifying that requirements for that use were met (see non-mandatory guidance in NQA-1 2008, Part III, Subpart 3.3, Appendix 3.2, Guidance on the Control of Scientific Investigations). The reviewers should be independent of the data collector, and the results of the review should be documented. MCP-2691, "Data Qualification," describes the process for data qualification.

This report documents the independent review of AGC-4 irradiation monitoring data for the first two cycles of the experiment. The data collected for the experiment are described along with requirements for the data that are contained in experiment planning documents. The approach to data qualification is described, including the steps taken to qualify the data and the specific tests used to verify that the data meet requirements. Finally, the current status of data from the AGC-4 experiment is presented with summarized information regarding qualification decisions.

2. AGC–4 EXPERIMENT

The AGC irradiation test series supports the acquisition of irradiated graphite performance data to assist in selecting the technology used for the HTR. Seven irradiation experiments are planned to investigate compressive creep in graphite subjected to a neutron field and to obtain irradiated mechanical properties of vibrationally molded, extruded, and isomolded graphite for comparison, as identified in PLN-2494 and shown in Figure 1. The major objective of the AGC-4 experiment is to provide irradiation creep data. This requires irradiation of matched pairs of stressed and unstressed specimens, which is achieved using the axial flux symmetry in ATR, with a stressed specimen above the symmetry plane matched to an unstressed specimen placed below the symmetry plane. This arrangement is used in six channels around the periphery of a graphite experiment capsule with a center channel used for additional unstressed specimens.

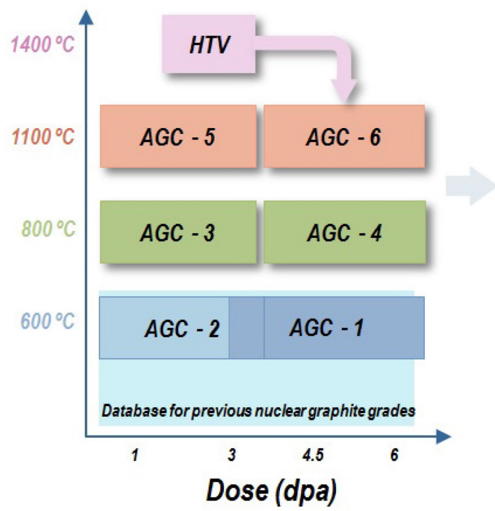

Figure 1. Planned graphite-irradiation experiments.

The AGC-4 experiment follows the design of the AGC-3 experiment very closely. The AGC-4 experiment is being irradiated in the east flux trap of ATR to an eventual peak irradiation dose of about 6 dpa at an intended irradiation temperature of about 800°C. The experiment has been temporarily suspended after two irradiation cycles.

2.1 Requirements

Technical and functional requirements for AGC-4 experiment capsule irradiation monitoring are presented in TFR-509, TFR-510, and TFR-875. The AGC-4 experiment uses the same temperature control and compressive load systems as the three previous AGC experiments and the same technical and functional requirements.

2.1.1 Quality Assurance

The AGC-4 experiment is being conducted within an NQA-1-2008/1a-2009, Part I, compliant QA program as implemented in PLN-2690.

2.1.2 Test Conditions

The as-designed test conditions desired for the experiment are given in TFR-509, TFR-510, and TFR-875.

2.1.2.1 Temperature. Temperature objectives for the AGC-4 experiment are given in TFR-875 but were modified in HJS-04-15, "Advanced Graphite Capsule (AGC-4) Experiment Operating Information Letter." The AGC-4 experiment is operated to maximize the number of specimens at a temperature of 800 ± 15°C along the 1.22-m length of the ATR core. Because the flux decreases rapidly at the ends of the experiment capsule, tungsten gamma heating rods were installed at each end of the graphite specimen stacks to increase heating at the end of the stacks. The time-average maximum temperature for each creep specimen was not to be >850°C, nor was each creep specimen's time-average minimum temperature to be <750°C.

2.1.2.2 Load. A mechanical load is applied to the outer six perimeter stacks to induce accelerated irradiation creep within the graphite test specimens during irradiation. To evenly balance the applied stresses on the graphite body within the AGC-4 experiment capsule, each pair of opposing stacks is stressed to one of three stress levels: 13.3 MPa (379 lbf, 2,000 psi), 16.6 MPa (473 lbf, 2500 psi), or 20.0 MPa (568 lbf, 3000 psi) (Figure 2). No mechanical stress is applied to the center stack.
Six pneumatic rams located in the 5-in. pressure boundary generate the load. Graphite pushrods transmit the force of the ram's piston onto the graphite columns. The loading system has the capability to compensate for thermal expansion and expected graphite shrinkage during the experiment. This is accomplished by using administrative feedback from in-line load cells (determining pressure response) between the pneumatic rams and pushrods to maintain the correct loading on the columns via the correct pressure in the cylinders.

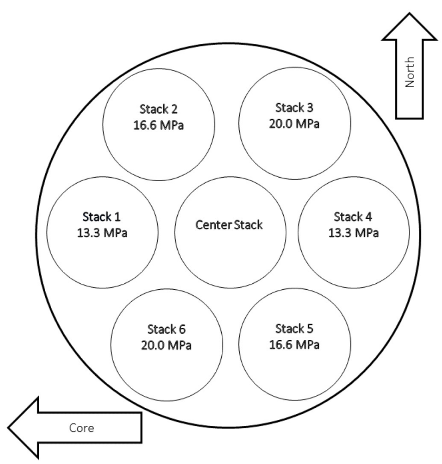

Figure 2. AGC-4 experiment stack numbers and loads with stack orientation at start of irradiation.

2.1.2.3 Fluence. Specimen exposure to fast neutron fluence (E >0.1 MeV) is planned to be between 0.5E + 21 n/cm^2 and 5.5E + 21 n/cm^2. The fluence difference between graphite specimens at equal distances above and below the ATR core centerline should not exceed 10%. Fluence, determined by computer modeling of reactor physics, will be verified by flux wires installed in the AGC-4 experiment capsule.

2.1.3 Measurements

Performance criteria for instrumentation are described in this section.

2.1.3.1 Temperature. Thermocouples (TCs) record AGC-4 experiment capsule temperatures and were selected based on operating range and the ability to withstand the effects of the high neutron fluences planned for the irradiation. Temperature is measured at 12 locations throughout the vertical extent of the capsule (Figure 3).

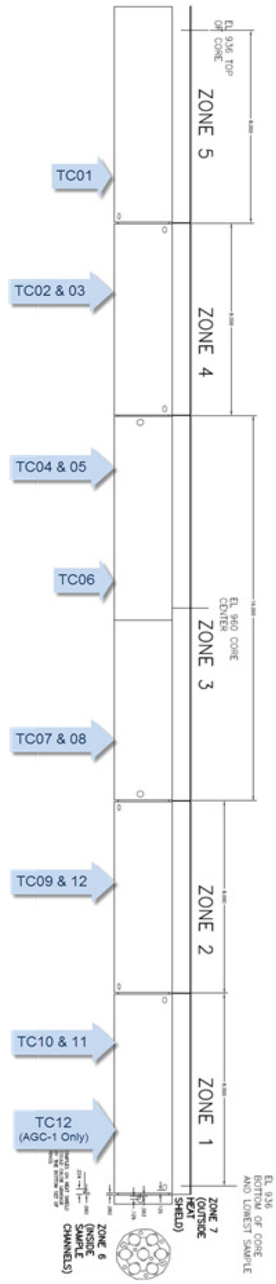

Figure 3. Temperature control gas zones and TC locations in AGC-4 capsule.

2.1.3.2 Temperature-Control Gas. All temperature-control gases entering the AGC-4 experiment capsule are filtered to remove oxygen and moisture. The gas is designed to contain <5 ppmv O_2 and <10 ppmv moisture prior to entering the experiment. The gas is a mixture of helium and argon with the ratio adjusted based on feedback from TCs located in the test train. Gas flow rates, line pressures, and outlet moisture are recorded at 1-minute intervals.

To create an even temperature distribution along the length of the capsule, the capsule is divided into five zones vertically (Figure 3). A TC in each zone provides feedback to the associated gas controller to adjust the argon/helium gas ratio in that zone to control temperature at the desired level. Two additional gas channels provide gas to the capsule, one inside the graphite holder and one outside the heat shield.

2.1.3.3 Load. The pneumatic rams apply stress to the six stacks of graphite specimens and are controlled by applying the desired load within ±5%. The load cells have a maximum load rating of ±1,000 lbf with no more than a ±5% error in load measurement. During ATR outages, the compressive load from the upper pneumatic rams is removed, and lower pneumatic rams raise the specimen stacks to ensure that the graphite stack is not lodged or jammed in the graphite holder. Experiment data are recorded at 1-minute intervals.

2.1.3.4 Advanced Test Reactor Operating Conditions. ATR data that described the core neutronics and thermal-hydraulics environment are gathered. These data will assist the physics analysis necessary for the final test report. Data include individual lobe powers and shim cylinder positions. These data are recorded and backed up on a separate storage device once every minute.

2.1.3.5 Neutron Dosimetry. The volume average fast neutron fluence for the graphite specimens will be inferred from physics calculations normalized by the flux wire measurements performed after AGC-4 experiment capsule disassembly. The flux wires were chosen to measure the fast spectrum >0.1 MeV.

2.1.4 Data Qualification

Irradiation monitoring data are categorized as Type A[a] data. Data must be independently reviewed to verify conformance to requirements, and the review must be documented.

2.1.5 Time-Critical Data

Technical staff need access to AGC-4 experiment capsule monitoring data to evaluate whether experimental parameters are within specifications, determine whether instruments are functioning as planned, and assess the experiment's progress. TC temperatures, pneumatic ram gas pressures, load cell output, stack position, constituent temperature-control-gas flow rates and pressure, and gas moisture are displayed on a website to provide access to the data during the experiment.

2.2 Experiment and Data Structure

The AGC-4 experiment consists of four data streams: pre-irradiation characterization, irradiation monitoring, post-irradiation examination, and thermal and neutronics calculations. This report addresses qualification of the irradiation monitoring data stream of the AGC-4 experiment.

2.3 Instrumentation and Measurements

Data are divided into response and attribute elements. Response elements are numeric values that describe the response of the object or system such as pressure, temperature, and elastic modulus. Attribute elements generally describe the object or system being measured, or they provide category or spatial information about the object such as graphite grade or irradiation position. Both response and attribute values are associated with a component—the generic name for the object or system being measured. Examples of components are a capsule, an outer gas annulus, or a TC. The components established for the AGC-4 experiment irradiation monitoring data stream are listed in Table 1. Multiple response variables can be associated with a single component.

a. Type A data are data collected within an NQA-1-2008/1a-2009, Part I, QA program to meet specific requirements with regard to fuel licensing with independent verification that those requirements were met.

Table 1. Components and response variables monitored for AGC-4 experiment.

Component		Location	Response Variables
Capsule		Capsule	Raise pressure (psig)
TCs	TC01	45.7 cm above ATR core centerline	Temperature (°C)
	TC02	33.0 cm above ATR core centerline	
	TC03	33.0 cm above ATR core centerline	
	TC04	15.2 cm above ATR core centerline	
	TC05	15.2 cm above ATR core centerline	
	TC06	5.1 cm above ATR core centerline	
	TC07	15.2 cm below ATR core centerline	
	TC08	15.2 cm below ATR core centerline	
	TC09	28.6 cm below ATR core centerline	
	TC10	45.7 cm below ATR core centerline	
	TC11	45.7 cm below ATR core centerline	
	TC12	28.6 cm below ATR core centerline	
Channels	1	West	• Ram gas pressure (psig) • Load (lbf) • Specimen position (in.)
	2	Northwest	
	3	Northeast	
	4	East	
	5	Southeast	
	6	Southwest	
	Center	Center	
Gas zones	1	61 to 41 cm below ATR core centerline	• Helium gas flow (sccm) • Argon gas flow (sccm) • Total gas flow (sccm) • Gas pressure (psia)
	2	41 to 20 cm below ATR core centerline	
	3	20 cm below to 20 cm above ATR core centerline	
	4	20 to 41 cm above ATR core centerline	
	5	41 to 61 cm above ATR core centerline	
Gas annulus inside heat shield		Zone 6	• Helium gas flow (sccm) • Argon gas flow (sccm) • Total gas flow (sccm) • Gas pressure (psia)
Gas annulus outside heat shield		Zone 7	• Helium gas flow (sccm) • Argon gas flow (sccm) • Total gas flow (sccm) • Gas pressure (psia)
Outlet gas line		Outlet gas line	• Moisture content (ppmv) • Gas pressure (psia)

The AGC-4 experiment capsule is approximately 1.22 m long and contains seven channels that were filled with stacks of graphite specimens. A stress is applied to the stressed creep specimens in the upper housing of the six peripheral channels, which are paired with unstressed graphite specimens in the lower housing (TFR-875). In addition to the unstressed creep control specimens, each specimen stack contains a number of smaller piggyback specimens of other HTR-relevant graphite. The central channel contains unstressed piggyback specimens, a few specimens of highly oriented pyrolytic graphite, and a few experimental graphite specimens with silicon carbide coatings.

Components are selected to represent the physical system collecting the data. The components consist of 12 TCs, seven channels, five gas zones, a gas annulus inside the heat shield, a gas annulus outside the heat shield, and an outlet gas line (Table 1).

TCs and gas zones have attributes that identify the relevant location in the AGC capsule. The position of the TC in the capsule is given in terms of distance from the core centerline. For gas zones, the location is described by the vertical elevation range over which the zone extends (for Zones 1 to 5) or the position of the zone relative to the heat shield (Figure 3).

Response variables, the parameters monitored on capsule systems, are also specified in Table 1. Units are those in which the data are recorded. Pneumatic rams provided the compressive load on the stressed specimens in the six specimen stacks (TFR-510). The upper rams and lower bellows were located away from the high neutron and gamma fields of the ATR core. Stainless-steel pushrods in the leadout to graphite pushrods inside the high-temperature graphite holder transmit the force exerted on the specimens. An in-line load cell, located above the ATR core and between the pneumatic rams and the push bars, monitors the force on the graphite specimens in each stack. The pushrod position was monitored to record the compression of the graphite specimens.

Twelve TCs are distributed between the specimen stacks and arranged throughout the height of the capsule to monitor temperature during irradiation. The TCs are installed as deemed appropriate to monitor and control the specimen temperatures during irradiation.

The temperature inside the capsule is controlled by altering the thermal conductivity of gas in the five gas zones and the annulus around the capsule. The gas flow control system uses temperature readings from selected TCs to control the experiment temperature in each zone by adjusting the argon-to-helium gas ratio in the five vertical zones along the annulus of the experiment capsule (TFR-509). The helium and argon gas flow rates, total gas flow, and gas pressure are monitored. The composition of the gas stream will be used in heat transport simulations to calculate the average temperature at the specimen locations.

2.4 Data Transfer

Two data-acquisition systems at ATR collect AGC-4 experiment irradiation monitoring data. The reactor data-acquisition system (RDAS) collects ATR power and control data, and the capsule distributed control system (CDCS) collects capsule monitoring data. Requirements for transfer of data between ATR and the Nuclear Data Management and Analysis System (NDMAS) are documented in TFR-747. CDCS data files are placed on the \\FDAS server every hour, and RDAS data files are placed on the \\FDAS server every 2 hours. Both types of files are placed on the server 55 minutes after the hour. A batch file invoked by Windows Task Scheduler triggering every hour on the hour executes the download. The batch process creates two folders, “Data” and “Log,” for storing the incoming files and the activity log and copies the incoming files into these folders. These folders are moved and zipped into an archive folder once the download is complete.

3. DATA PROCESSING

Data received from ATR are archived on the NDMAS server, as shown in Figure 4. The native files are then read, and the data are captured to the NDMAS Microsoft Structured Query Language database (also known as "the vault"). A complete description of NDMAS and the NDMAS processes is in Hull (2012) and PLN-2709, "Nuclear Data Management and Analysis System Plan."

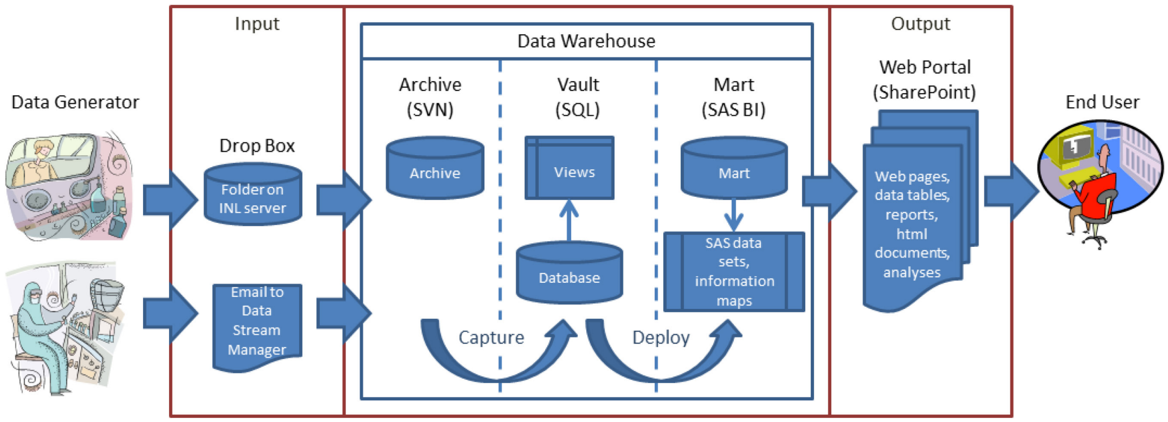

Figure 4. Stages of data processing and storage in NDMAS.

3.1 Data Capture

Two custom applications were developed in C# to capture data. These applications are installed on C:\program files\INL\NDMASImporter\ as the application root folder on the \\ISASAP server. One of the two applications is a service base application that ensures the second application is running and available to process data files to the database. This service base application is called NDMASService.exe, registered as a system service, and launched automatically when the system boots up. The second application is called NDMASImporter.exe, which watches a specified set of folders for new data files.

Data capture is performed using computer codes that are tested, reviewed, and maintained in a controlled program repository. The codes are tested by manually comparing data pulled from the NDMAS database to the original data in the native RDAS and CDCS files. When changes are made to the capture codes, the manual verification is performed again. The verified code is stored under configuration control to ensure the same verified project is used to capture subsequent files. Once the capture of the data is verified, the Data_State_EID is changed from raw to capture passed.

3.2 Advanced Test Reactor Operating Conditions

Data regarding ATR operating conditions were collected under an NQA-1-2008/1a-2009, Part I, QA program maintained by ATR Operations. The ART Technology Development Office (TDO) performed an independent assessment of the ATR QA program (Inspection Report IAS121679) and determined the ATR RDAS and CDCS data conform with NQA-1 requirements. Additionally ,PDD-13000 "Quality Assurance Program Description" requires scheduled QA audits using approved triennial topics to ensure all applicable QAP elements are audited within a 3 year timeframe. Report IAS16450, *INL QA Program Implementation at ATR No 1*, was completed on February 24, 2016. Effective power at the east flux trap was calculated as the average of the lobe powers at the southeast, northeast, and center lobe. Effective power is shown in Figure 5. The AGC-4 experiment capsule was removed from ATR following Cycle 158A.

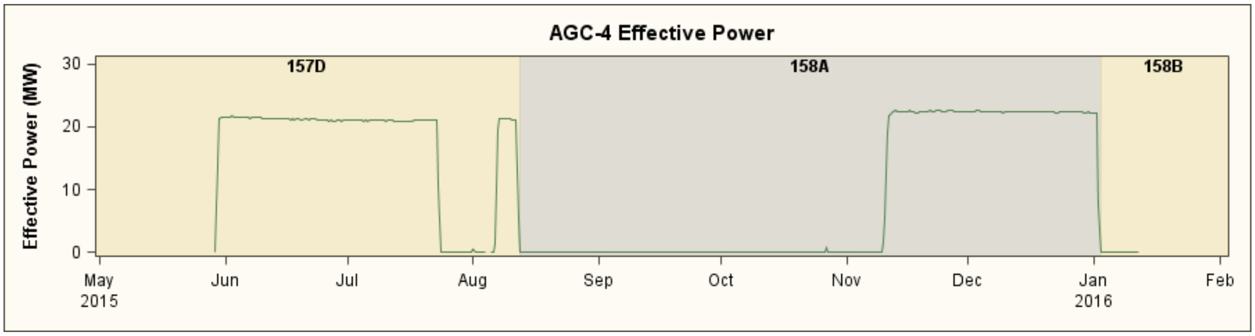

Figure 5. Effective power at east flux trap during AGC-4 experiment.

3.3 Examining Data Anomalies

Once the irradiation monitoring data are captured in the NDMAS database, a number of tests are run to examine the data for anomalies. Anomalies are data with values outside the range of expected behaviors. Anomalies may be errors in recording the value. Anomalies can also be generated by transient events that produce real data outside of normal ranges. The anomalies are reviewed as part of the data qualification process. This section discusses the tests and basis for the tests and presents the test results. Qualification decisions based on the test results are presented in Section 4. Tests developed to verify data are listed in Table 2.

Table 2. Tests established for evaluating experiment irradiation monitoring data.

Test Type	Test Name	Test Description	Applied To
Accuracy	Irradiation monitoring range	Compares response values to anticipated acceptable ranges from the experiment. Identifies anomalous values that fall outside the expected range.	Temperature, gas flow, gas pressure, humidity, upper ram gas pressure, compressive load, and specimen position.
	Instrument failure	Fails data collected from an instrument deemed to no longer provide reliable data.	All response variables as needed.
Analysis	TC spatial correlation	Calculates correlations between daily average temperatures. TCs adjacent to each other should be more highly correlated than TCs at different elevations.	TC01 through TC12.
	TC difference control charts	Charts the temperature difference between TCs, which should be similar over time. Trends and discontinuities in the data suggest that one of the TCs is drifting or failing.	Insufficient data to apply this test after only two cycles.
	Load cell difference control charts	Charts the load difference between channels, which should be similar over time. Trends and discontinuities suggest that a load cell is drifting or failing.	Insufficient data to apply this test after only two cycles.

3.3.1 Compare Data to Expected Ranges

The range tests evaluate whether instrument readings fall within an expected range of values. The expected ranges for instruments are listed in Table 3. Range tests do not test for conformance to specifications, so the range values listed do not match specifications for test parameters.

Table 3. Test ranges applied to AGC-4 experiment irradiation monitoring data.

Response Variable	Expected Range	Comments
Temperature	0 to 1,200°C	The minimum temperature for TCs should be the ambient ATR coolant temperature, which is on the order of 30°C. However, TCs designed for high temperatures may have some bias at low temperatures, so the lower limit is set lower than 30°C.
Gas flow	−2 to 102 sccm	Gas flows for temperature control normally fall between 0 and 50 sccm. Lower limit is negative to account for flow meter uncertainty at zero flow rate. During ATR shutdown, the helium gas flow is increased to 100 sccm.
Gas pressure	10 to 25 psia	Gas pressure is specified to be ≤14.7 psia.
Moisture	0 to 22,000 ppmv	Valid operating range of the moisture monitoring sensor.
Ram gas pressure	−10 to 300 psig	Excursions well above the highest expected ram gas pressure of 250 psig.
Load cell	−15 to 700 lbf	Excursions well above the highest expected load of 600 lbf.
Stack position	1.0 to −3.0 in.	Excursions in stack position outside the expected range.

3.3.1.1 Temperature. No temperature measurements fell outside the range of expected values (Figure 6). Ten temperature values reported as NULL have been deleted from the NDMAS database. The desired temperature range in the AGC-4 experiment capsule was 800 ± 15°C. The vertical temperature variation through the ATR core was very slight as a result of being able to control the temperature in five zones distributed along the length of the capsule. In addition, tungsten gamma heat rods are installed at the top and bottom of the test train to increase temperatures at the top and bottom of the capsule.

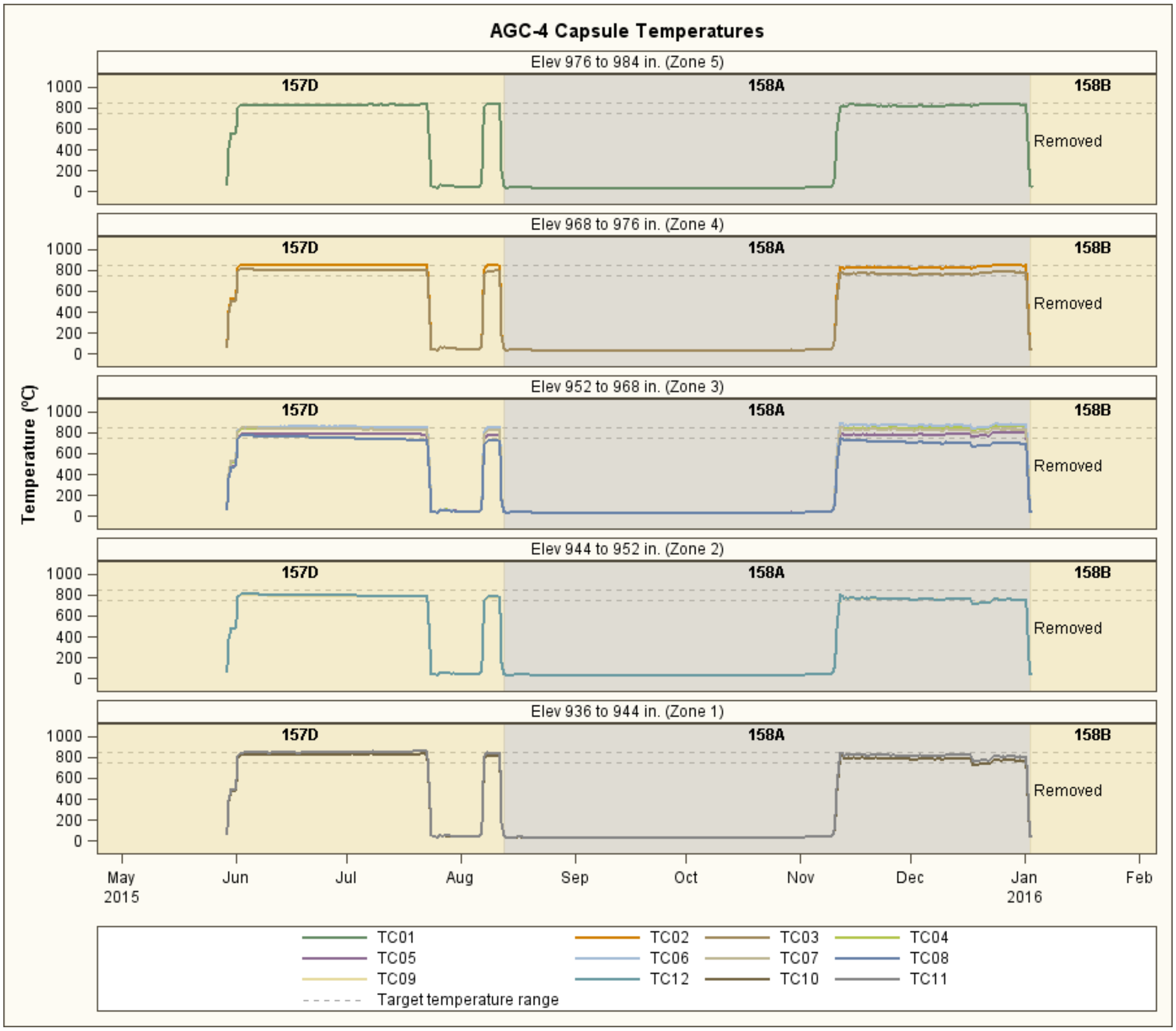

Figure 6. Temperature measured by TCs distributed in five vertical zones in AGC-4 experiment capsule.

3.3.1.2 Moisture. Moisture concentrations were low through Cycle 157D, increased abruptly on November 3, 2015, and gradually declined through the end of Cycle 158A. Moisture values exceeded 600 ppmv for 1 minute and then declined. Figure 7 shows a plot of gas moisture averaged over 12 hours. The moisture peak was very short, and the maximum 12-hour average was 51.5 ppmv. Comparison of the moisture concentrations to reactor power (Figure 8) and gas flow (Figure 9) are also shown. No values exceeded the instrument operating range.

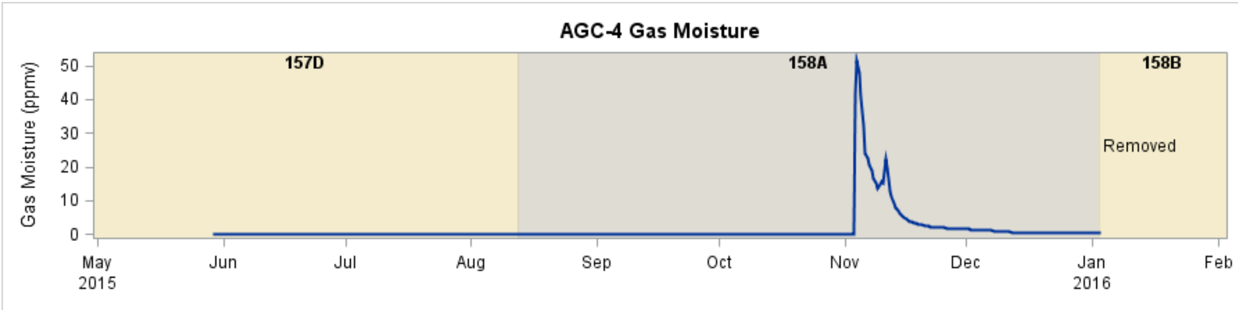

Figure 7. Water vapor concentration in effluent gas line.

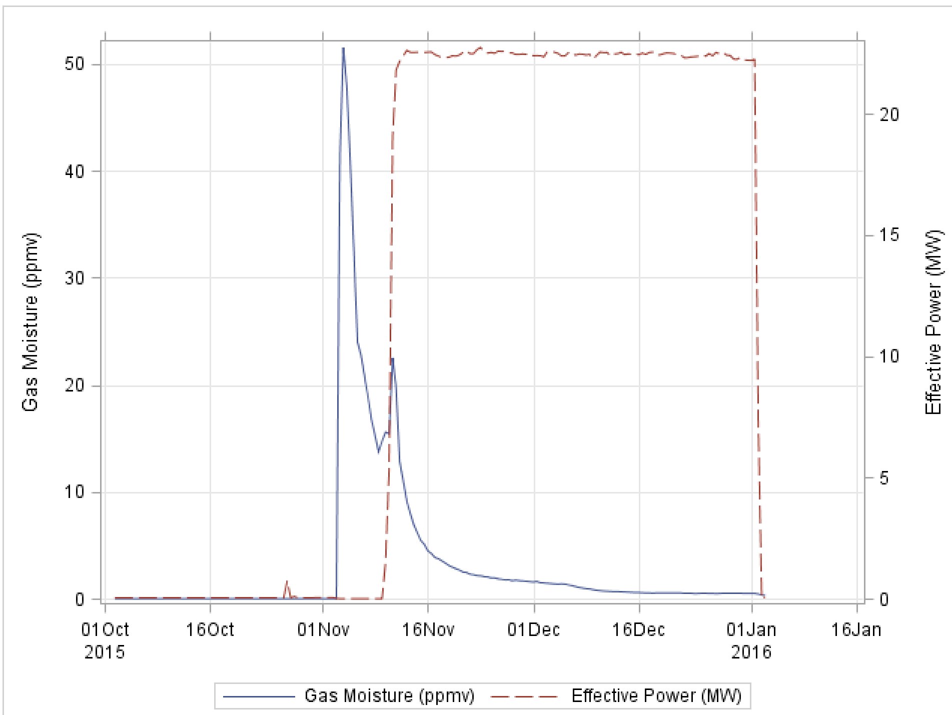

Figure 8. Plot of gas moisture and effective power at the beginning of ATR Cycle 158A.

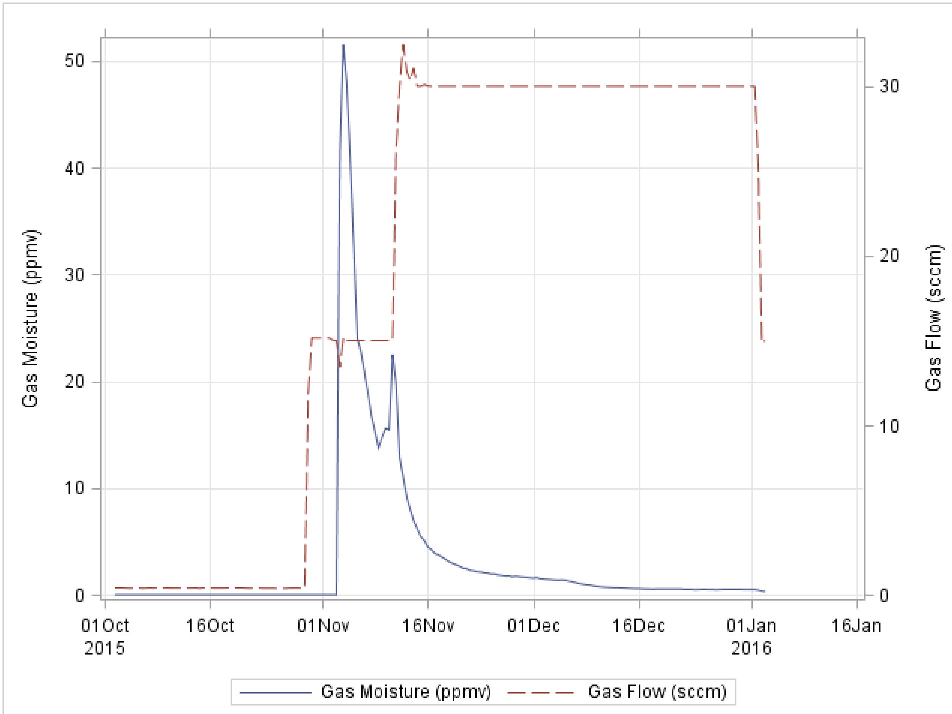

Figure 9. Plot of gas moisture and total gas flow at the beginning of ATR Cycle 158A.

3.3.1.3 Gas Flow. Argon and helium gases at variable ratios (Figure 10) were passed through the AGC-4 experiment capsule to control the temperature by altering the thermal conductivity in response to variation of the graphite heat rate during irradiation. Seven gas feeds are supplied to provide temperature control along the length of the capsule (Figure 10). During ATR shutdowns, helium flow was increased to 100 sccm. Helium and argon gas flow values fell below 0 sccm at times throughout the experiment. The negative gas flows are all just slightly below zero, ranging between −1.01 and 0.0 sccm. These negative gas flow values are within the uncertainty range of the instrument and are not considered to be different than zero. All gas flow data are consistent with planned gas flow conditions and expected values.

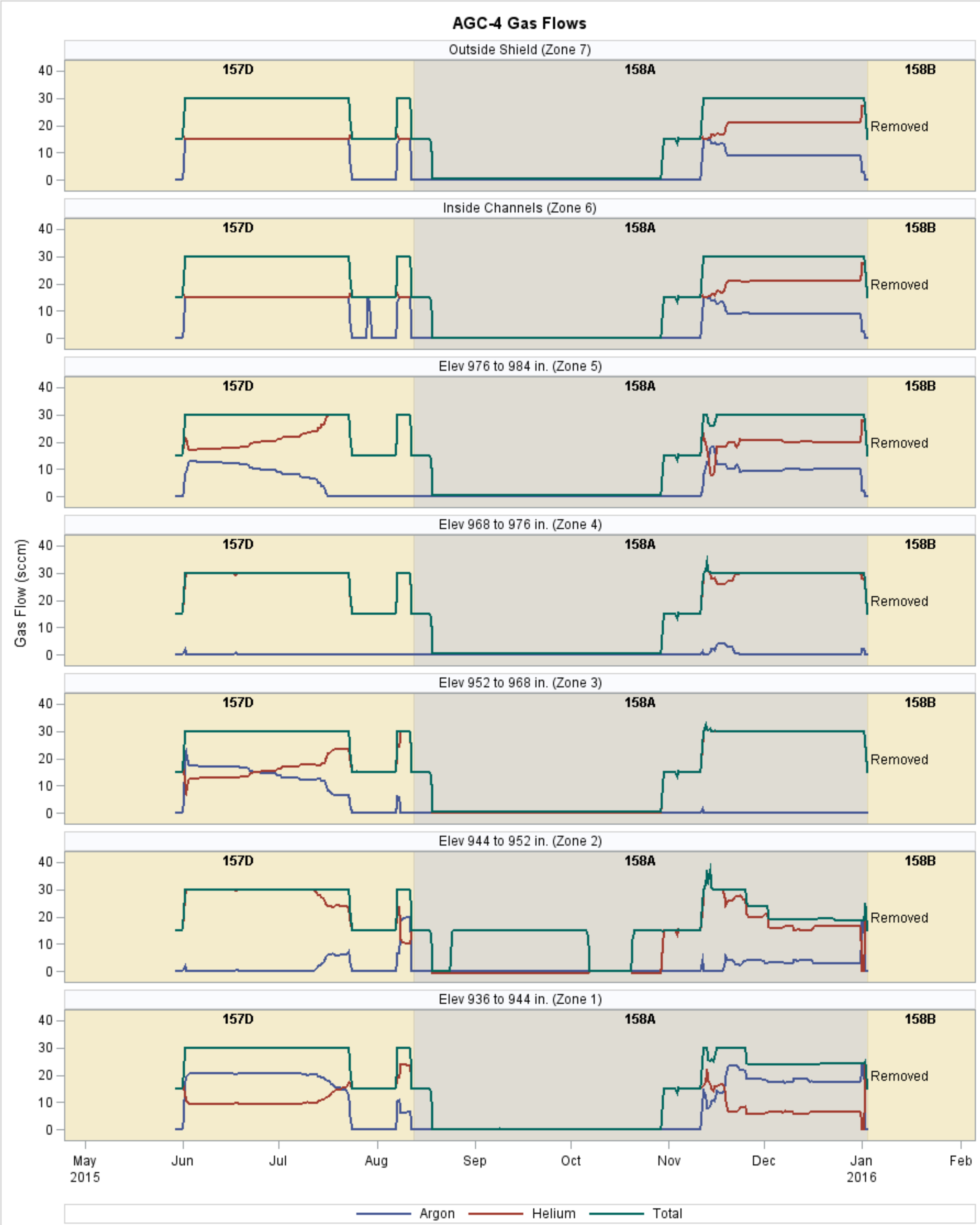

Figure 10. Plots showing argon, helium, and total gas flows through seven zones.

3.3.1.4 *Gas Pressure.* Gas pressure values are within expected ranges, as shown in Figure 11.

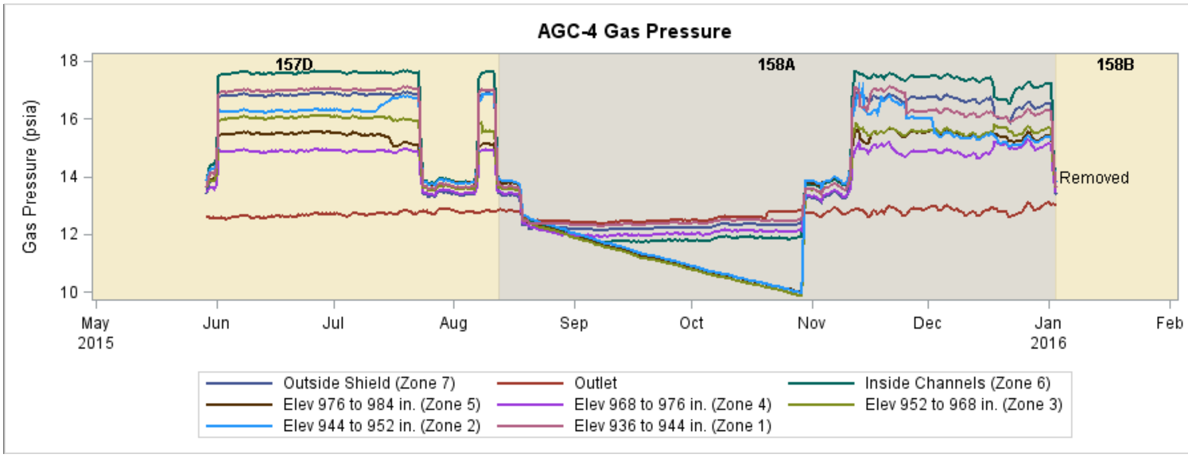

Figure 11. Gas pressure.

3.3.1.5 *Temperature-Control-Gas Chemical Constituents.* Gas samples collected for analysis of carbon dioxide and carbon monoxide have not yet been analyzed. Results of gas sampling will be reviewed in a separate report.

3.3.1.6 *Load Cell and Displacement Data.* The experiment design includes loads to the six outer stacks at three different load levels, with diametrically opposed stacks loaded the same amount. Stacks 1 and 4 are loaded to 13.8 MPa (390 lbf; 2,000 psi), Stacks 2 and 5 are loaded to 17.2 MPa (4,909 lbf; 2,500 psi), and Channels 3 and 6 are loaded to 20.7 MPa (590 lbf; 3,000 psi). Measurement errors are specified at ±5%. The measured loads are plotted in Figure 12. Load data are generally within 5% of the specified load. Loads to the paired stacks are very similar.

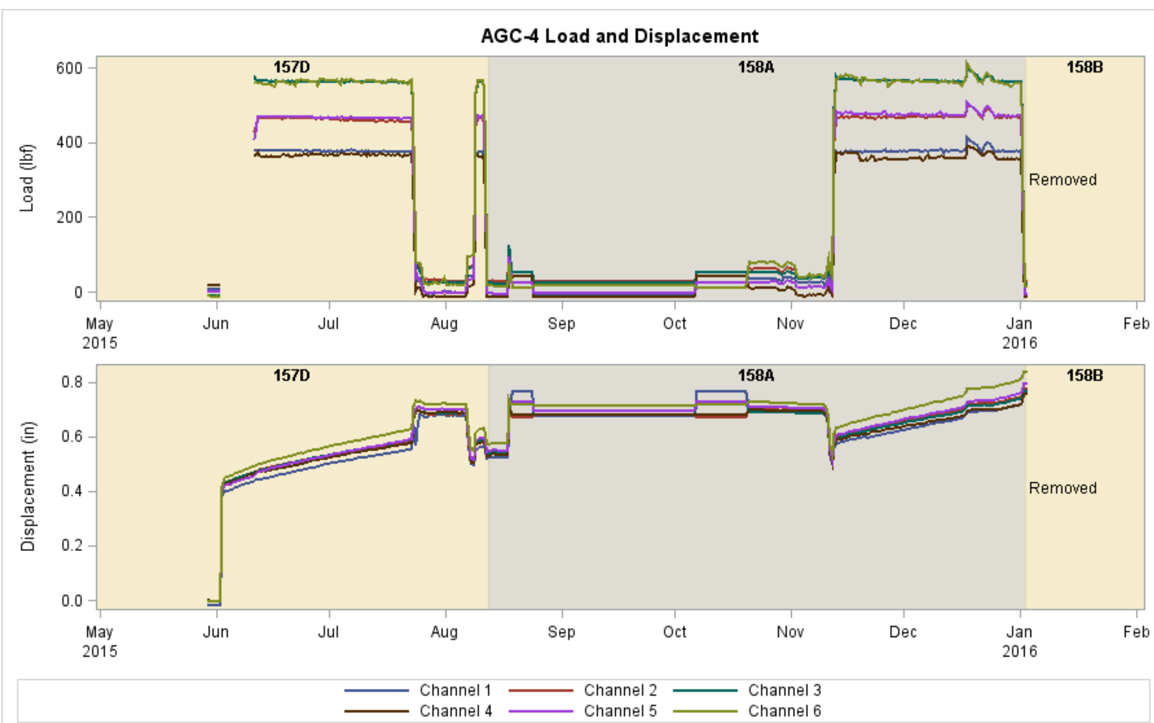

Figure 12. Load and displacement data.

During the Cycle 158A outage, ram pressure and stack-raising pressure values were stuck at a constant, very negative value for several weeks. Load was not being applied to the stacks during the outage, so these ram pressures do not reflect actual applied pressure or stack-raising pressure. There are 168,312 erroneous ram pressure values and 8,414 erroneous raise pressure values. The remaining ram pressure values were within the expected range.

Stack displacement increased consistently throughout the experiment, with total displacement ranging from about 0.4 in. to about 0.8 in. (Figure 12). No anomalous values are identified.

During the period between 12:19 on June 2, 2015, and 08:23 on June 11, 2015, which is the start of the first AGC-4 irradiation cycle, load cells did not respond to the applied ram pressure, so no stack load measurements were recorded during this time. Stack load versus ram pressure for the first AGC-4 cycle is plotted in Figure 13. Group 0 data show the expected correlation between ram pressure and load. Group 1 data show no response in load to ram pressure. Load cells were wired up incorrectly at the beginning of the AGC-4 experiment and did not provide data on stack load. A total of 75,324 points across all channels showed the same behavior.

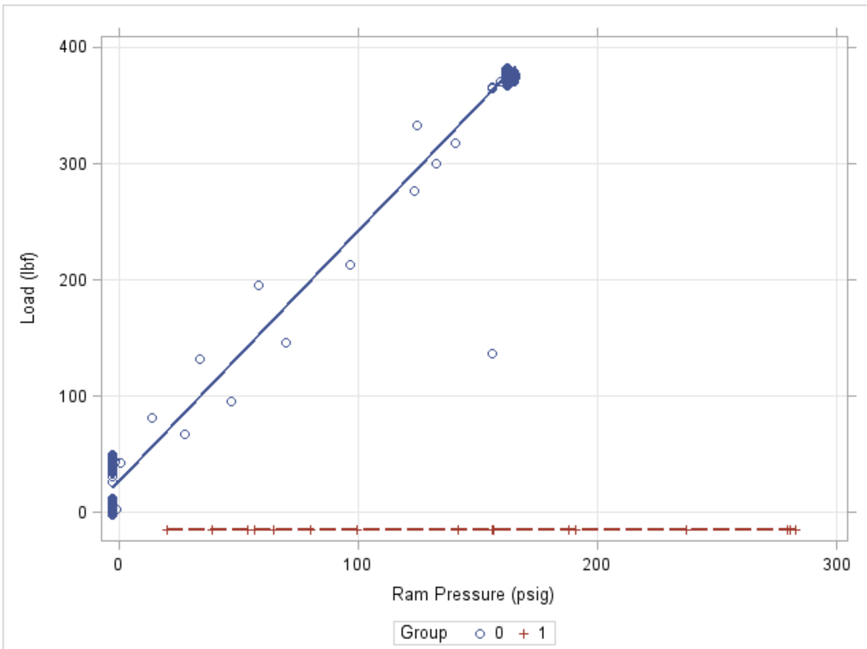

Figure 13. Correlation between ram gas pressure and stack load for Stack 1 during ATR Cycle 157D showing the observations where the load cells were configured incorrectly.

Because there is a strong correlation between ram pressure and stack load, the missing stack loads at the beginning of the first AGC-4 cycle can be estimated from the ram gas pressures. A linear regression was performed to fit a linear function of ram gas pressure to Group 0 stack load data (available stack load data) from each stack. The resulting coefficients for the regression equations are listed in Table 4. The regression equations were used to estimate the missing load values from the measured ram gas pressure values. The regression equations are all statistically significant, with all probabilities <0.0001 of obtaining the fits by chance and fitting the data extremely well. This is indicated by the R^2 values of 0.989 or greater and standard errors of the coefficients generally much less than 1%. Using the regression equation to estimate the load values introduces errors within the 5% instrument uncertainty range. Examples of the excellent fit for two of the stacks are shown in Figure 14 and Figure 15.

Table 4. Intercepts and slopes for estimation of missing stack load data from ram gas pressure.

Stack	Intercept	Std Error	Slope	Std Error	R^2	Probability
Stack 1	25.938	0.213	2.160	0.001	0.997	<0.0001
Stack 2	22.960	0.472	2.403	0.003	0.991	<0.0001
Stack 3	19.028	0.422	2.344	0.002	0.995	<0.0001
Stack 4	16.603	0.110	2.104	0.001	0.999	<0.0001
Stack 5	15.744	0.202	2.236	0.001	0.998	<0.0001
Stack 6	31.652	0.605	2.170	0.003	0.989	<0.0001

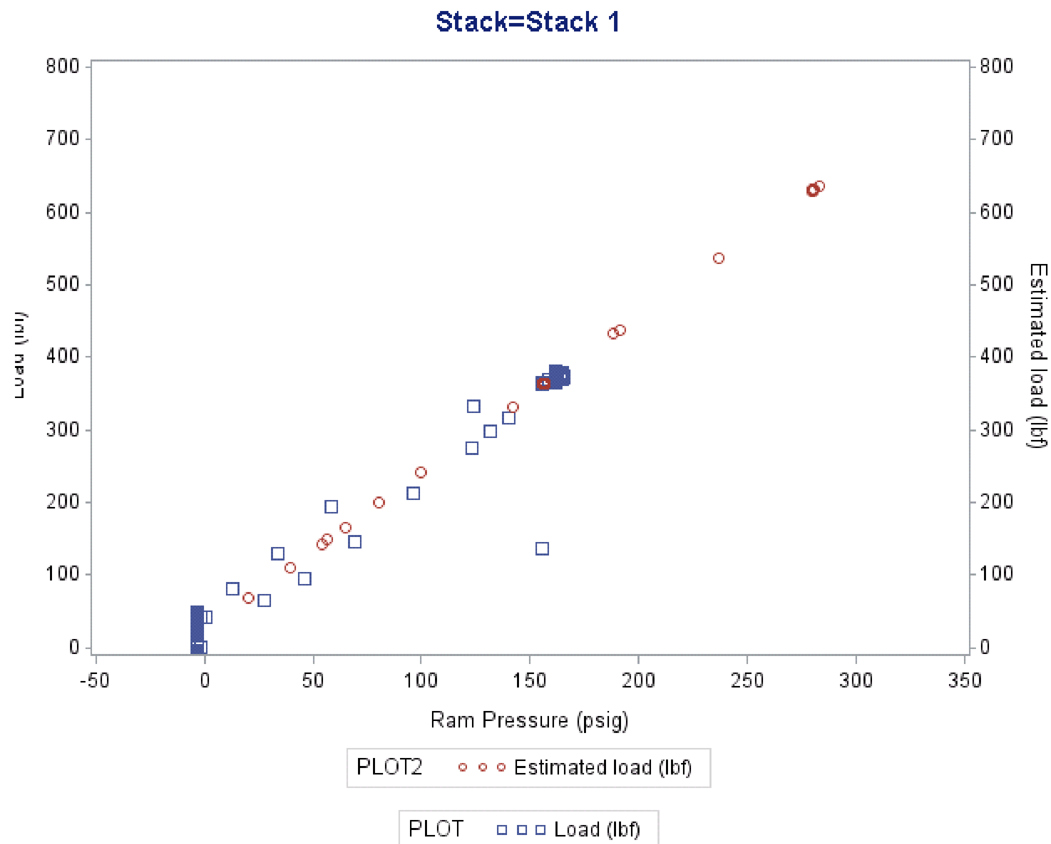

Figure 14. Comparison of predicted stack load in Stack 1 for Cycle 157D to measured stack load.

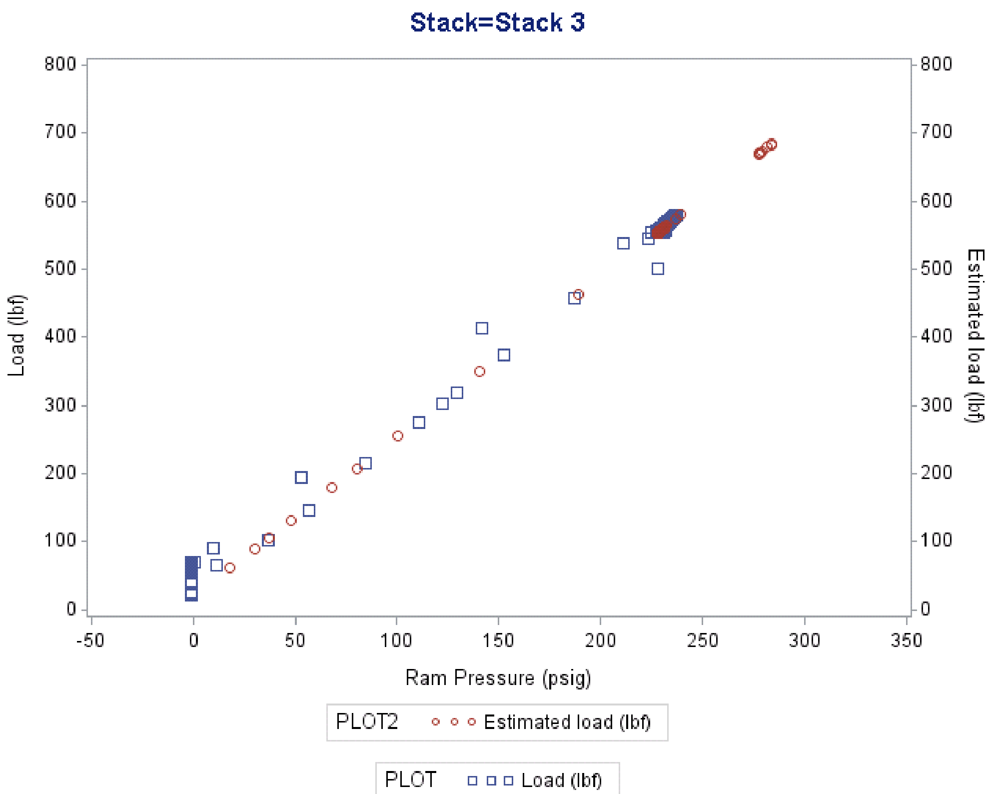

Figure 15. Comparison of predicted stack load in Stack 3 for Cycle 157D to measured stack load.

One effect of the load cells not being hooked up correctly is that ram gas pressures exceeded the normal range, resulting in stack loads higher than the design loads. Figure 16 shows a plot of the estimated stack load for Stack 1 and the transition to measured loads when the load cells were rewired. Stack load exceeds the design load from about 13:40 on June 2 to about 15:15 on June 2, or about 90 minutes. Loads deviate to some extent from design loads until the load cells were hooked up and the ram pressures could be adjusted accordingly. The system was functioning after 08:24 on June 11, 2015.

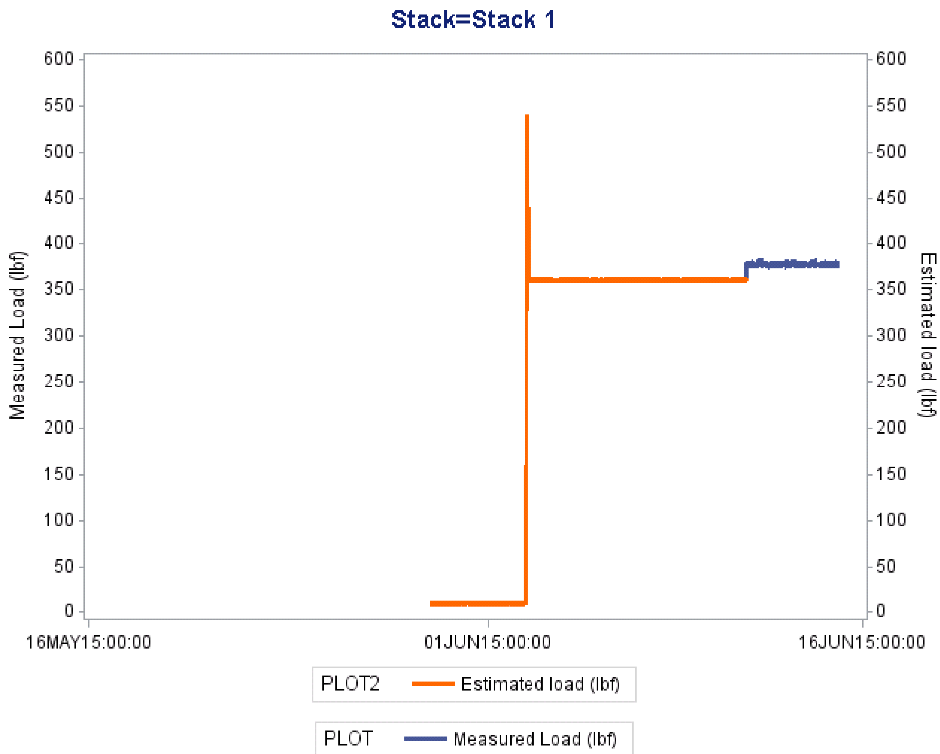

Figure 16. Load estimated using linear regression coefficients and measured load for the beginning of Cycle 157D.

3.3.2 Instrument Failure

When an instrument fails during the irradiation and the date and time of failure are verified during the data-qualification process, all data collected after the failure time from the failed instrument are *Failed*. No instruments have failed to date during the AGC-4 experiment.

3.3.3 Stack Raise Pressure

During ATR outages, the stacks of stressed graphite specimens are raised from below to ensure that the specimens are not wedged into the channels. An upper ram pressure of 50 psi is applied to all stacks, and then pressure is applied to each individual stack from below while the compression ram pressure is reduced to zero. Each stack is raised individually, thus ensuring that the stack is free to move. The pressure on the lower rams is not differentiated by channel, so only total raise pressure is recorded. As ram gas pressure is removed from each channel, the corresponding stack rises by about 0.1 to 0.4 in. The rise in the stack when pressure is applied indicates that the stack is not stuck in the channel.

Stacks were raised during a mid-cycle scram in Cycle 157D, as shown in Figure 17, and during the outage at the beginning of Cycle 158A, as shown in Figure 18. This demonstrates that the specimens are free during the previous cycle. Both stack-raising episodes showed that the stacks are free within the channels. All load data are therefore considered representative of the compressive load applied to the specimens.

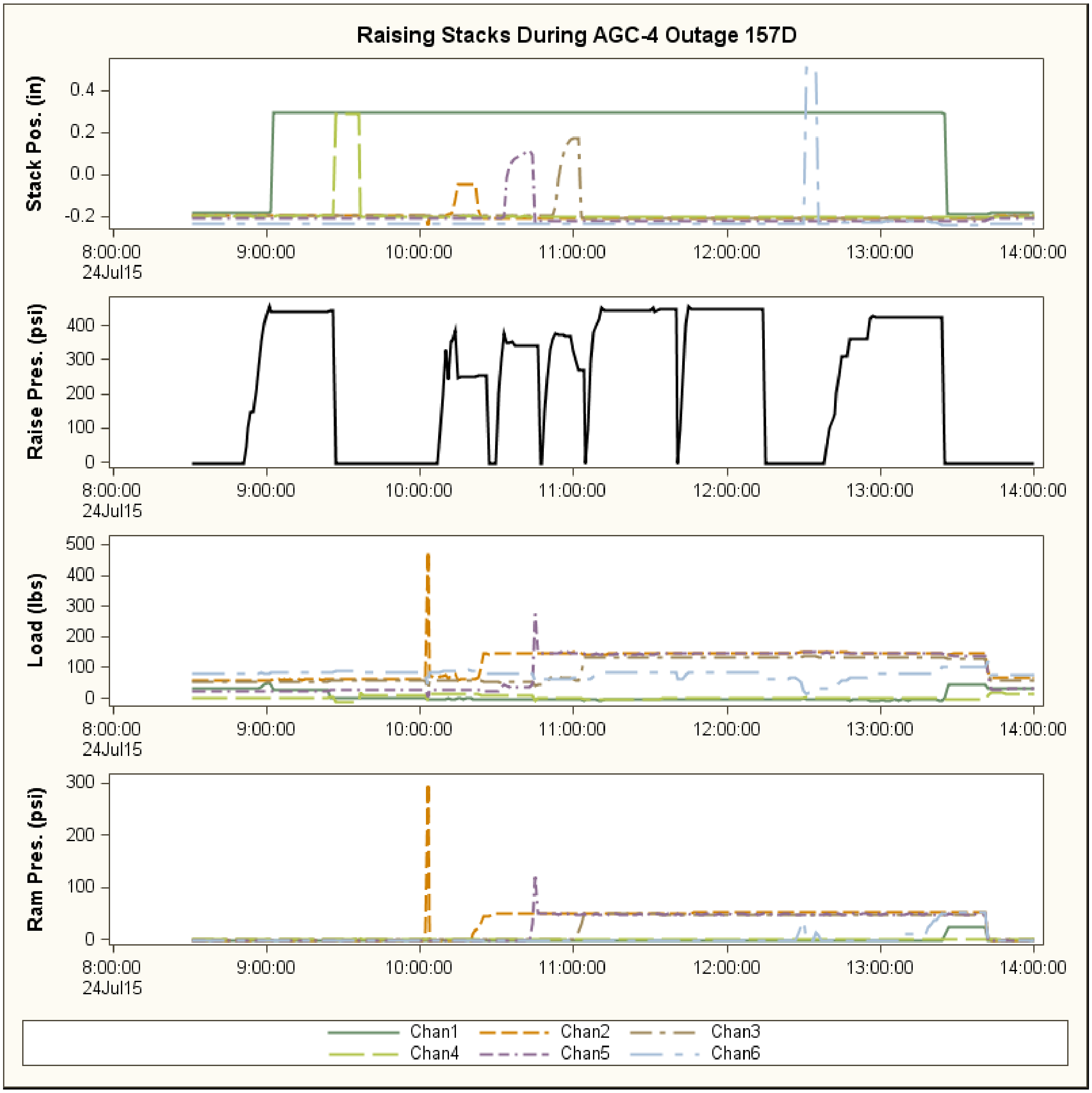

Figure 17. Change in stack position, raise pressure, stack load, and ram gas pressure for stack raising during Cycle 157D.

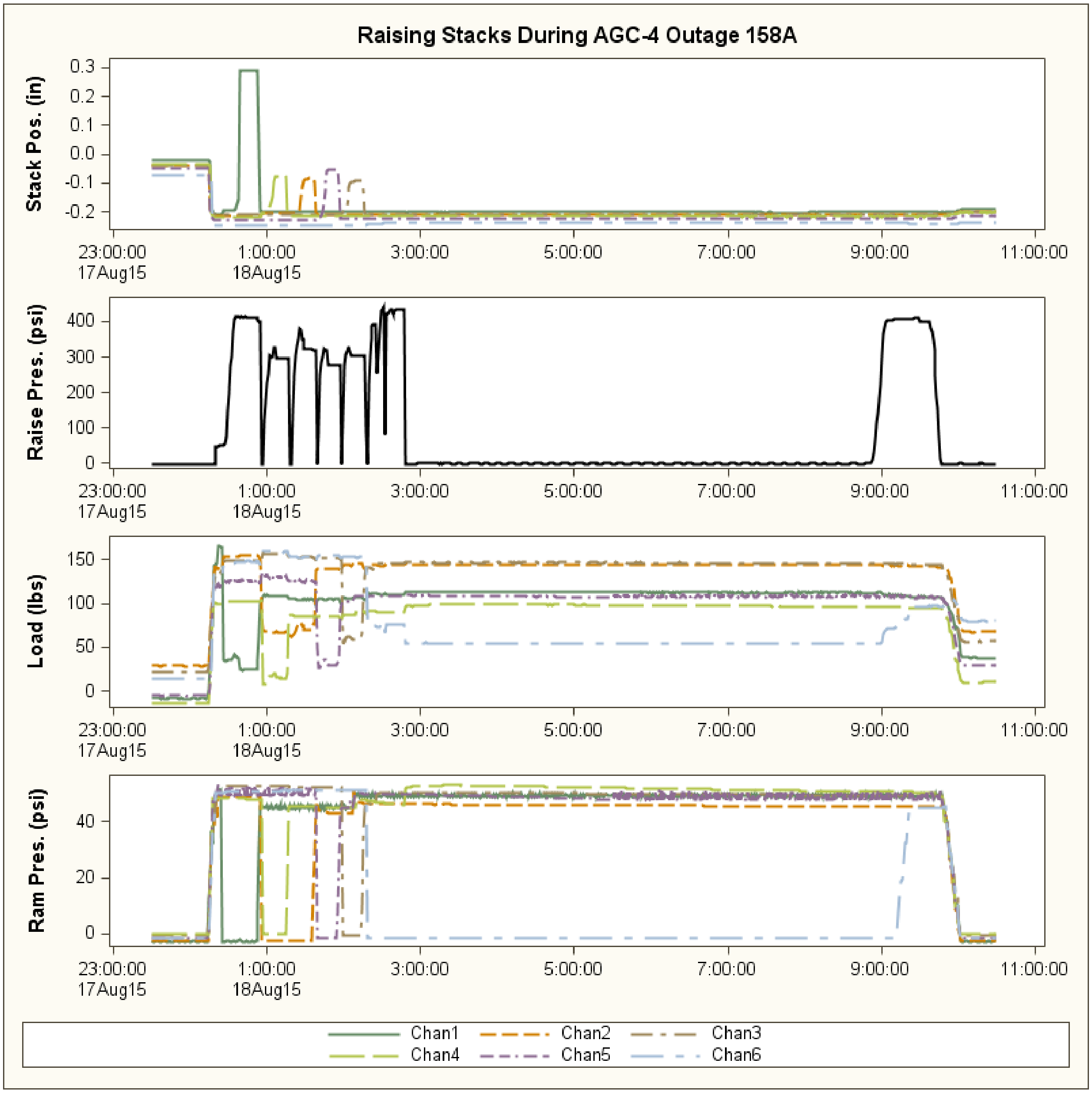

Figure 18. Change in stack position, raise pressure, stack load, and ram gas pressure for stack raising during the outage for Cycle 158A.

3.3.4 Thermocouple Correlation Analysis

During the first AGR-1, a number of the TCs formed virtual junctions outside the capsule in which they were installed, causing them to give erroneous readings (Pope 2012). One way this was detected was when the TC switched from being highly correlated to adjacent TCs in the capsule to being highly correlated to TCs farther away. The basis of this comparison is that temperatures measured at a TC will be more highly correlated to TCs installed at the same elevation, or at immediately adjacent elevations, than to TCs installed at more remote elevations. This comparison was applied to the TCs installed in the AGC-4 experiment capsule.

A correlation of each TC with all other TCs was calculated daily during power cycles. The highest correlation coefficient was selected for each day and plotted on the graphs shown in Figure 19 through Figure 30. Each graph shows the vertical position of the base TC as a solid green line and the daily maximum correlations to other TCs as circles. Using Figure 19 as an example, TC01 was installed at a height of 978 in. in the ATR core at Level 8. TC01 was most highly correlated with the TCs installed at Level 7 in the core. This behavior was fairly consistent throughout the first two cycles of the AGC-4 experiment. Therefore, there was no evidence that TC01 had formed a virtual junction at a different position within the capsule.

Reviewing Figure 19 through Figure 30, the TCs where two TCs are installed at the same level in the capsule are most highly correlated to each other (TC02 with TC03 at Level 7, TC04 with TC05 at Level 6, TC07 with TC08 at Level 4, TC09 with TC12 at Level 3, and TC10 with TC11 at Level 2). Where only one TC was installed at a given level, the TC was most closely correlated to a TC immediately adjacent to (either above or below) that TC. There appeared to be no evidence of formation of virtual junctions in the AGC-4 experiment capsule.

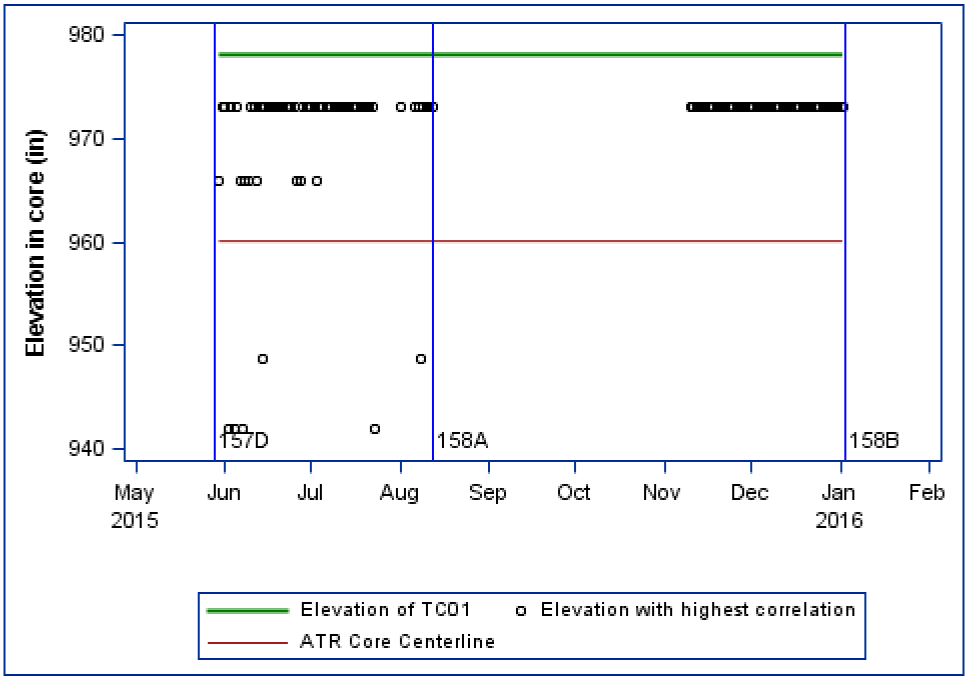

Figure 19. Level of TC with highest correlation to TC01 at Level 8 (978 in.).

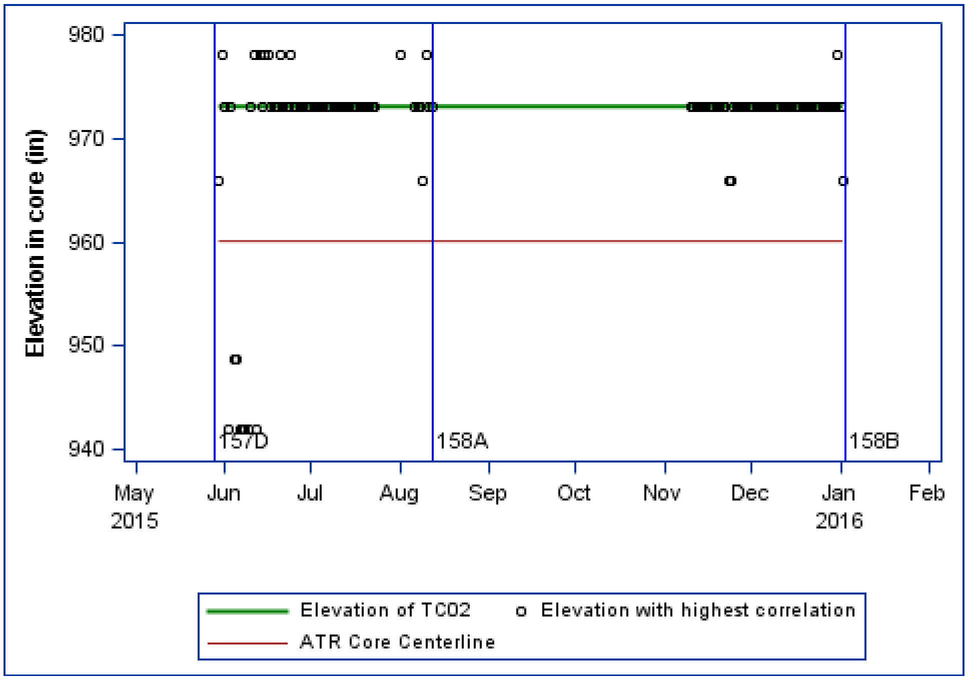

Figure 20. Level of TC with highest correlation to TC02 at Level 7 (973 in.).

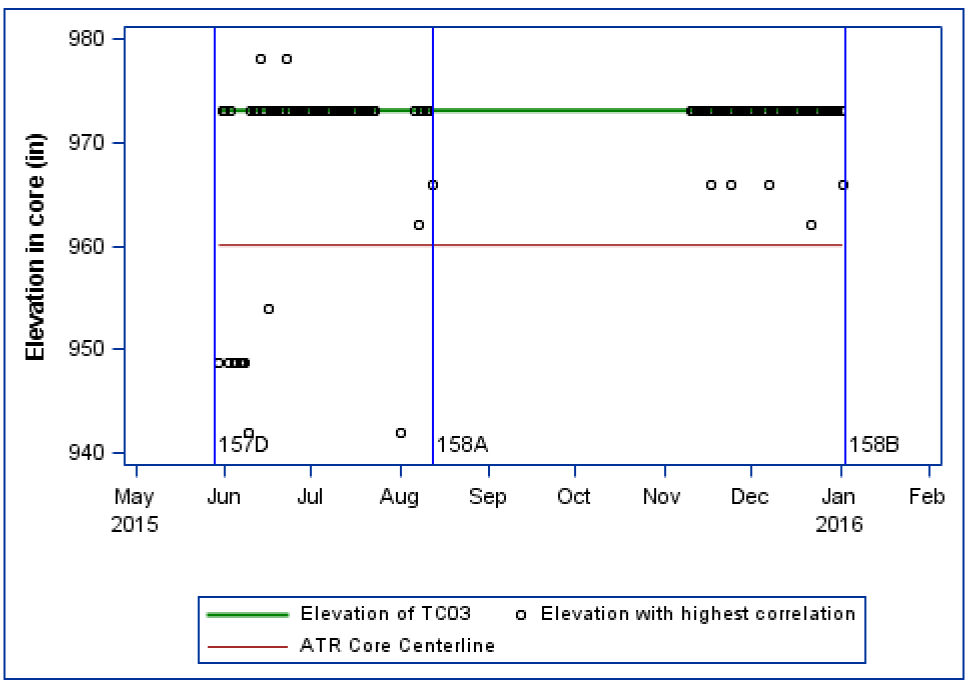

Figure 21. Level of TC with highest correlation to TC03 at Level 7 (973 in.).

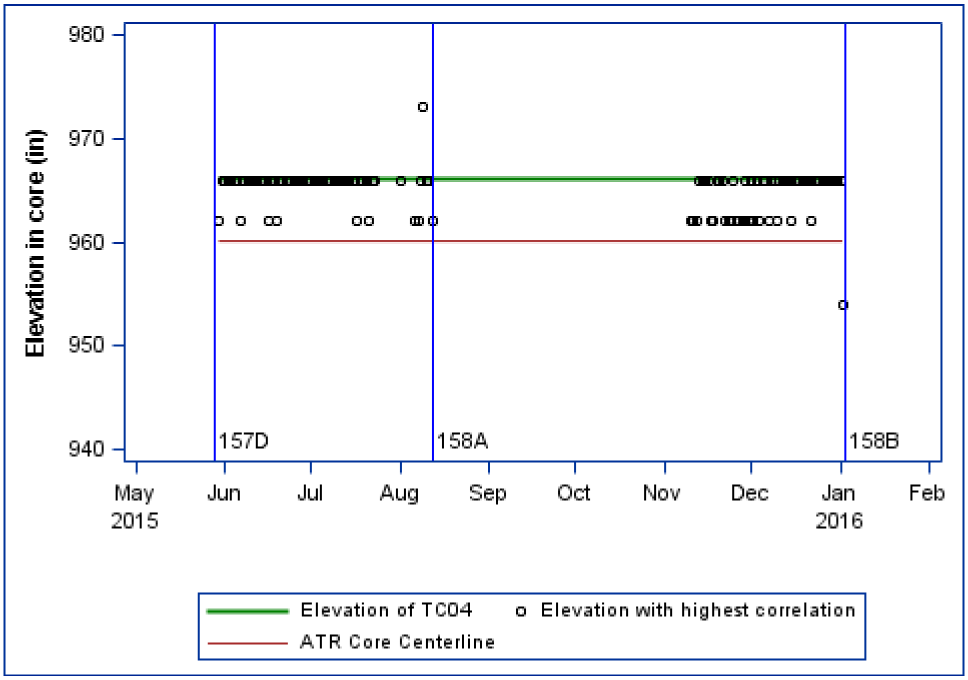

Figure 22. Level of TC with highest correlation to TC04 at Level 6 (966 in.).

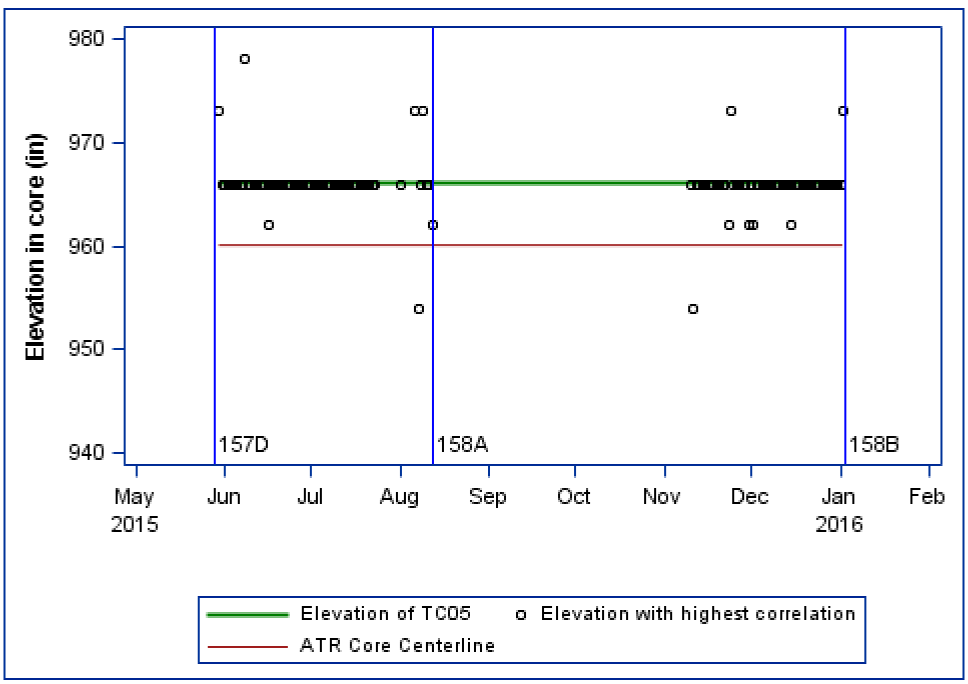

Figure 23. Level of TC with highest correlation to TC05 at Level 6 (966 in.).

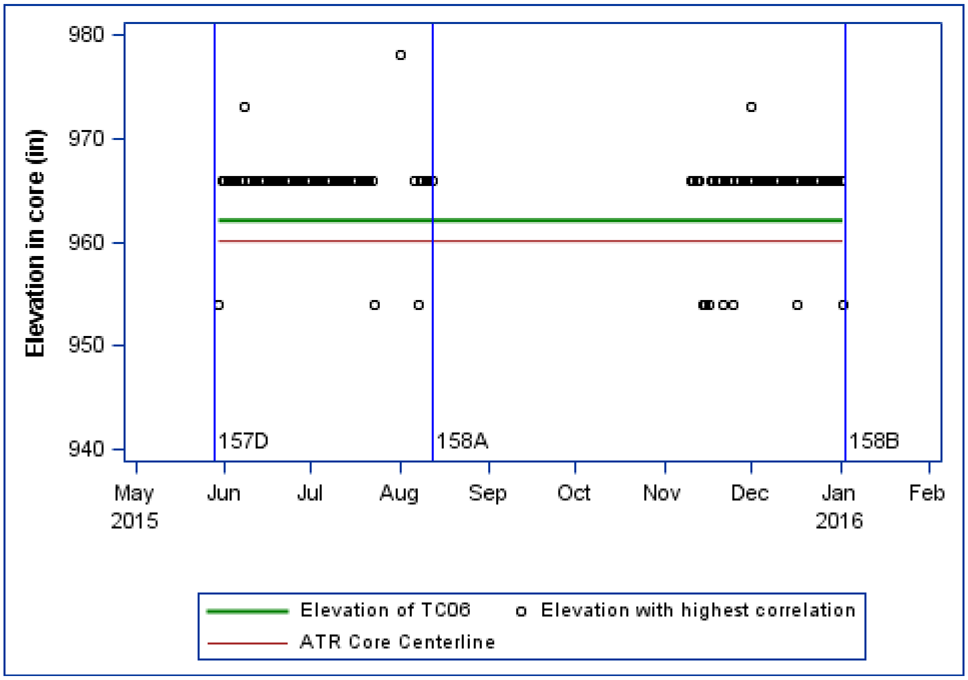

Figure 24. Level of TC with highest correlation to TC06 at Level 5 (962 in.).

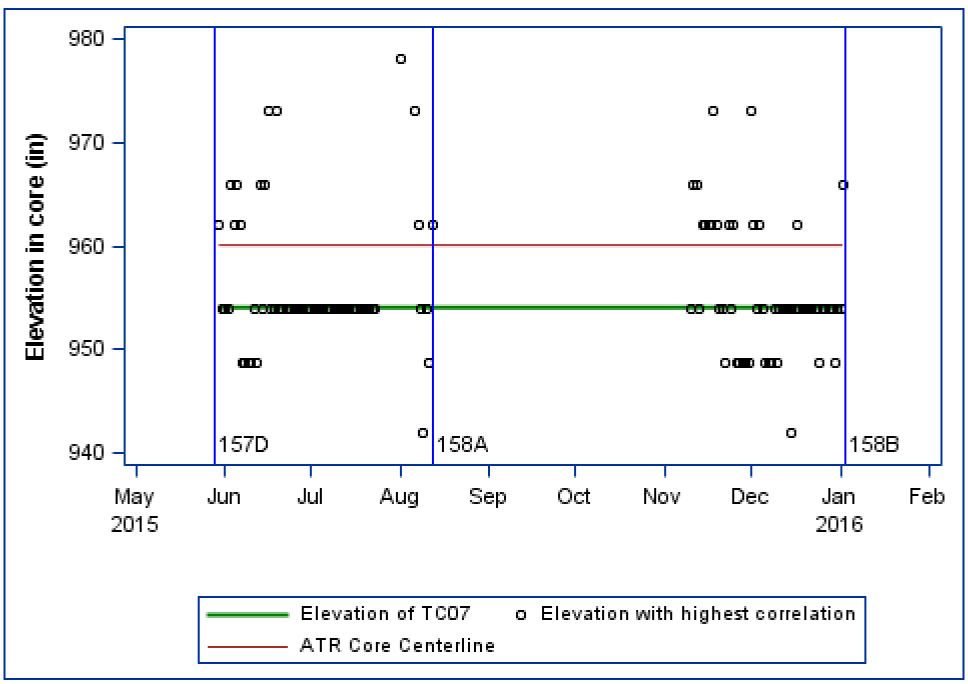

Figure 25. Level of TC with highest correlation to TC07 at Level 4 (954 in.).

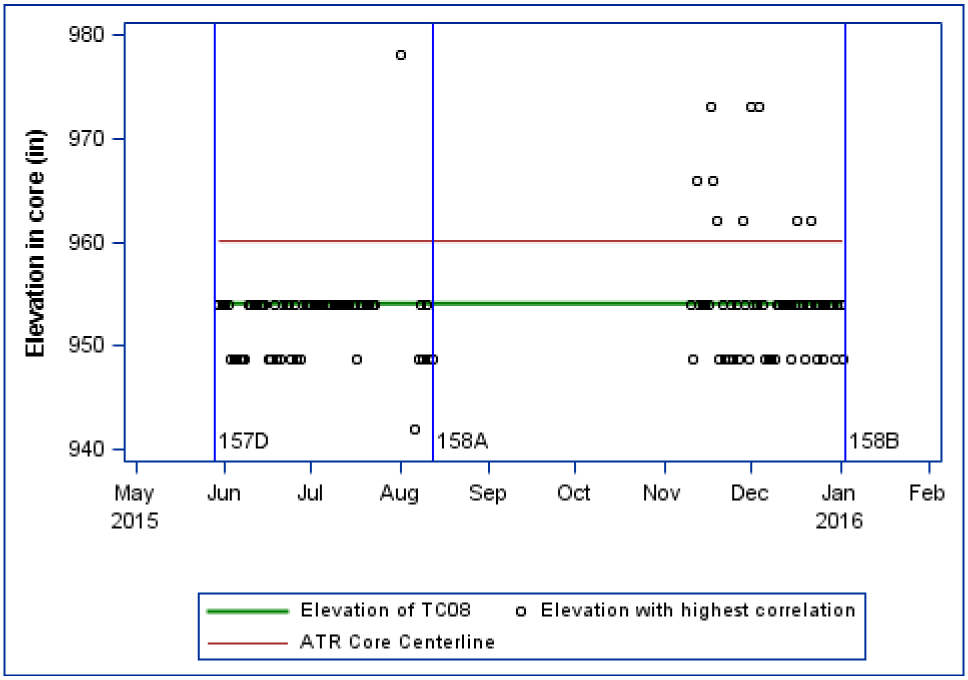

Figure 26. Level of TC with highest correlation to TC08 at Level 4 (954 in.).

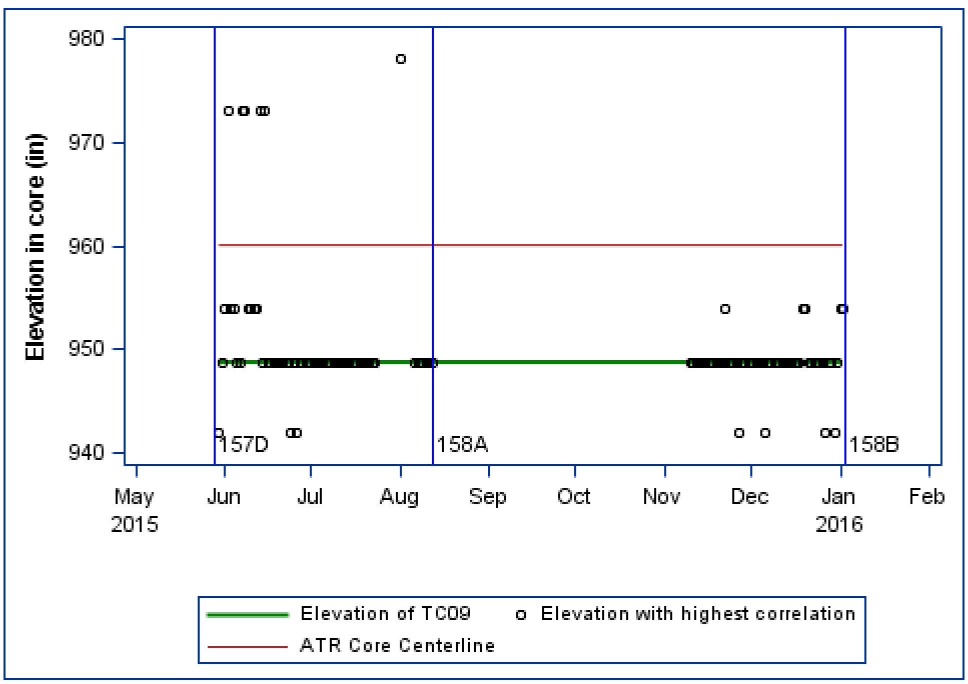

Figure 27. Level of TC with highest correlation to TC09 at Level 3 (948.75 in.).

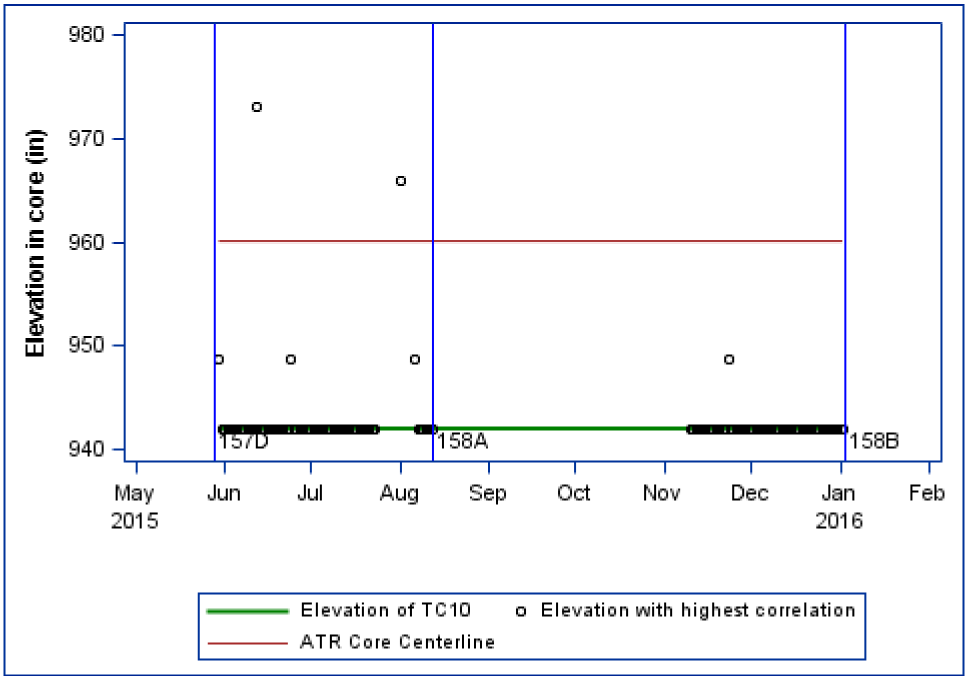

Figure 28. Level of TC with highest correlation to TC10 at Level 2 (942 in.).

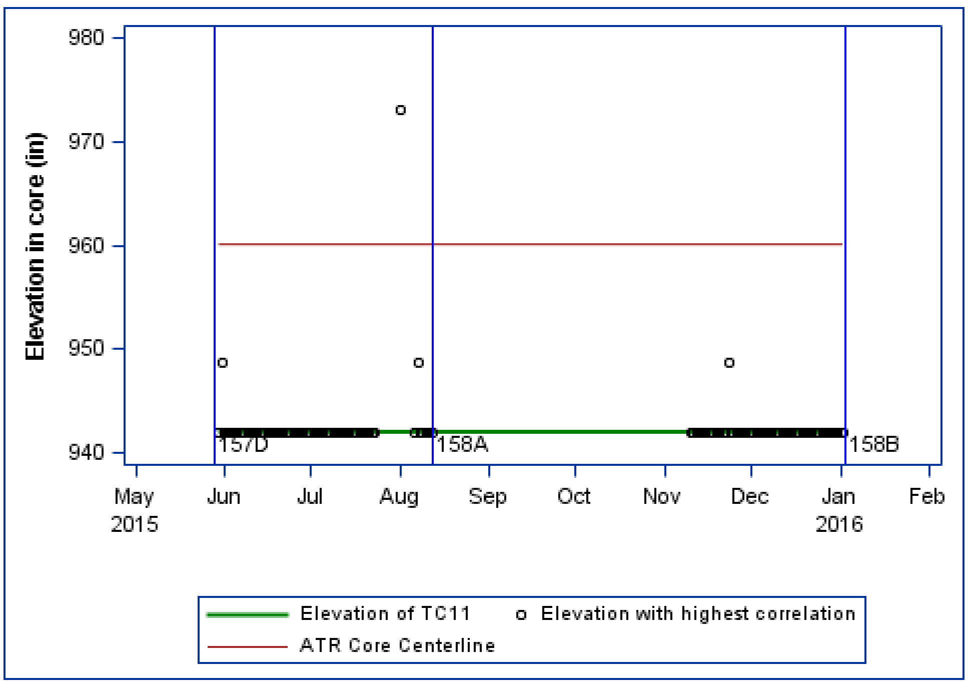

Figure 29. Level of TC with highest correlation to TC11 at Level 2 (942 in.).

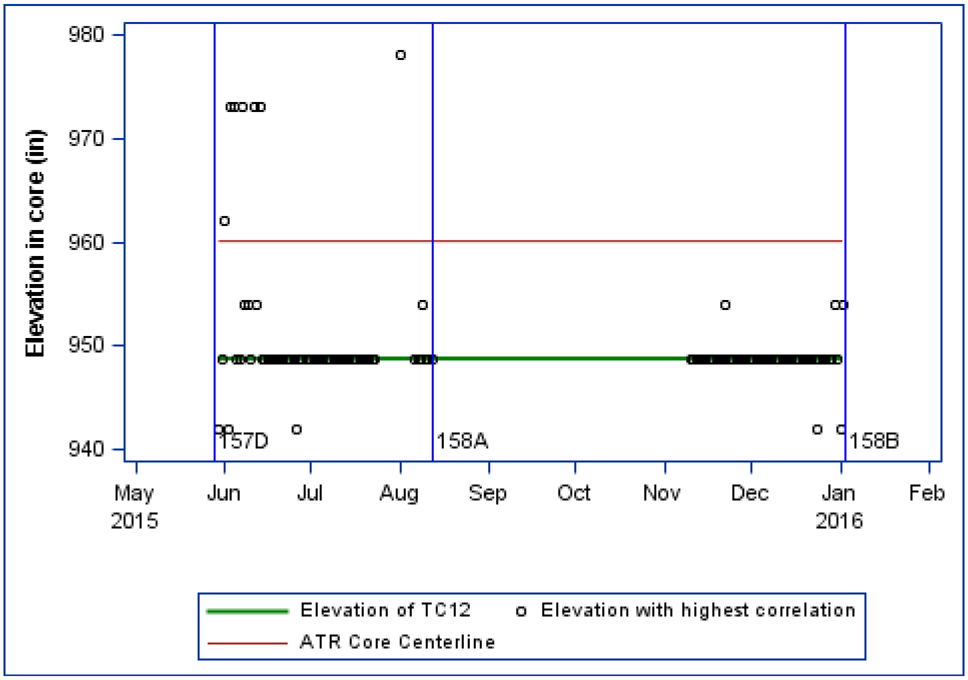

Figure 30. Level of TC with highest correlation to TC12 at Level 3 (948.75 in.).

3.3.5 Control Charts

Control charts allow simple detection of events that are indicative of actual process changes. This simple detection can be difficult where the process characteristic is continuously varying. Control charts provide statistically objective criteria for detecting changes. When a change is detected and considered valid, its cause should be identified. With only two cycles of data collected from AGC-4 to date, data are insufficient to apply control chart analysis.

4. DATA QUALIFICATION

Data qualification refers to the process of verifying that the data meet the requirements for the intended use. All AGC-4 experiment irradiation monitoring data are Type A data collected within an approved NQA-1-2008/1a-2009, Part I, QA program. This section discusses the results of data qualification for the first two cycles of AGC-4 experiment irradiation monitoring data. The result of the data-qualification process is the assignment of a data element to one of the following three categories:

- *Qualified*. Independent verification documents that the data meet the requirements for a specific end use, as defined in a data-collection plan, and that the data are collected within an NQA-1-2008/1a-2009, Part I, or equivalent, QA program. Any nonconformance has been assessed and determined not to affect the usability of the data.
- *Trend*. Independent verification identifies minor flaws or gaps in meeting requirements for data use. Even so, the data provide information that can be used. Data are collected within an NQA-1-2008/1a-2009, Part I, or equivalent, QA program.
- *Failed*. Independent verification identifies major flaws in meeting data-collection requirements. Data do not provide information about the system or object. Data are not useable.

4.1 Data Conformance to NQA-1-2008/1a-2009, Part I, Quality Assurance Program

The verification of data with regard to meeting NQA-1-2008/1a-2009, Part I, QA requirements involves tracing the documentation trail of the data. The process of collecting data involves writing a data-collection plan and the QA and quality control activities associated with those data. Review of the data-collection plan ensures that the planned work will generate data of appropriate quality for use in the Graphite Technology Development Program. During data collection, auditors and line managers evaluate the work and ensure it is conducted according to the data-collection plan. Metadata generated by the initial documentation, audits, and acceptance inspection provide the evidence that data meet the requirements of an NQA-1-2008/1a-2009, Part I, data-collection program. Documentation of compliance is accomplished by reference to documents that include plans, audit reports, nonconformance reports, and engineering design files.

The following documents provide the evidence that the AGC-4 experiment data meet the QA requirements of NQA-1-2008/1a-2009, Part I:

- PLN-2690—Defines a QA program that complies with NQA-1-2008/1a-2009, Part I.
- PLN-2497—Provides an overall program plan for the graphite technology R&D area.
- TFR-509, TFR-510, and TFR-875—Provide technical and functional requirements for the irradiation phase of the AGC-4 experiment.
- Inspection Report IAS121679—Reports results of a review of the ATR data source streams. The inspection determined that the equipment used to collect data is calibrated as required by the ATR technical specifications and operating requirements, data collection and transfer systems are verified to function through system testing and operational checks, and software systems meet configuration control and testing requirements.

4.2 Design and Instrument Specifications

Project plans and design documents contain requirements for the construction and instrumentation of the AGC-4 experiment capsule. To ensure conformance to these requirements, engineering work instructions are prepared as a detailed checklist with signoffs for each step with hold points for QA review and approval. Completion and acceptance of the engineering work instructions by management and QA provided independent verification that the requirements for construction and instrumentation are met. This included verifying instrument calibration and testing instruments after installation to ensure they are functional. The completed engineering work instructions are filed in the Idaho National Laboratory Electronic Data Management System under the title “Engineering Work Instructions for Assembling the AGC-4 Experiment.” All requirements for construction and instrumentation for the AGC-4 experiment capsule are met and documented in the engineering work instructions.

4.3 Data Qualification Determination

This section summarizes the data qualification decisions. Detailed information on the data and technical basis for the decisions are discussed in Section 3. A total of **!The Formula Not In Table** response values have been recorded from irradiation monitoring of the AGC-4 experiment (Table 5). Of these, **!The Formula Not In Table** responses are considered to not represent the system or object being measured. All of the *Failed* data occurred during the Cycle 158A outage and have no impact on the irradiation monitoring results. Load cells were wired incorrectly at the beginning of the experiment, resulting in **!The Formula Not In Table** missing values. A strong correlation exists between ram pressure and load for the remainder of Cycle 157D. Load values, therefore, can be reliably estimated from the ram pressure values using a linear regression analysis. Uncertainties in the estimated load data are no more than the uncertainties in the measured load data; therefore, the estimated loads are considered to provide an accurate estimate of load applied to the stacks at the beginning of Cycle 157D. All load data are considered *Qualified* for use. All other data are *Qualified* for use by the Graphite Technology Development Program.

Table 5. Number and data state assignment of records with reasons for failure for AGC-4 experiment.

Response Parameter	Total Number of Values	Number of *Failed* Values	Number of *Trend* Values	Reason for Failure/Trend
Gas flow	6,498,177	0	0	
Gas moisture	309,437	0	0	
Gas pressure	2,475,496	0	0	
Temperature	3,713,244	0	0	
Load	1,814,856	0	0	
Position	1,814,820	0	0	
Ram pressure Stacks 1–6	1,814,748	168,312	0	During the Cycle 158A outage, ram pressures for all stacks were stuck at constant, large negative values. No impact occurred, because all data were collected during the outage.
Raise pressure	302,458	8,414	0	During the Cycle 158A outage, after the stack raising was complete, raise pressure was stuck at a constant, large negative value.
Total	18,743,236	176,726	0	

4.3.1 Failed Data

Ram gas pressures and raise pressures were stuck at large, negative values during the Cycle 158A outage. No load was being applied to the capsule during the outage. These data points are *Failed*. Because the failed points occurred during an outage, they do not affect the measurement of load on the graphite stacks.

4.3.2 Trend Data

No data are identified as *Trend* in this data set.

4.3.3 Qualified Data

All other data collected from the AGC-4 experiment for the response variables discussed in this report are judged to meet the requirements specified in the data-collection plans. From June 2, 2015, at 12:18 to June 11, 2015, at 08:23, the load cells were incorrectly wired. Missing load cell measurements for that period were estimated from the ram pressures using regression equations developed from the remaining period of Cycle 157D. The regression equation provides acceptable estimates of stack load, which are considered to be suitable for use. The response variables *Qualified* for use by the Graphite Technology Development Program are TC temperatures, pneumatic ram pressures, load cell output, stack position, constituent temperature-control-gas flow rates, gas moisture, and gas pressure.

4.4 Corrective Actions

No corrective actions are identified.

5. DATA ACCESS

Graphite irradiation monitoring data have been uploaded to the NDMAS web page for easy access by Graphite Technology Development Program participants. A tab has been created on the web page dedicated to the graphite irradiation experiment data. The graphical summary plot on the web page provides experiment-long figures for temperature, gas flows, and creep specimen loading. Links on the web page provide access to temperature, gas-flow, and load data that can be downloaded for analysis.

6. QUALITY ASSURANCE

NDMAS activities are conducted within the requirements of PLN-2690. Software QA requirements for NDMAS are contained in LWP-20000-01, "Conduct of Research Plan." Because graphite will be used as a structural component in the core of a nuclear reactor, the data-collection program was conducted within an NQA-1-2008/1a-2009, Part I, QA program. The Idaho National Laboratory data quality level for graphite data is Quality Level 2.

7. REFERENCES

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Appendix A

Credentials of Technical Reviewer

Appendix A

Credentials of Technical Reviewer

Kevin Clayton

Kevin has more than 25 years of experience in the various aspects of reactor experiment design, analysis, and operation. Kevin's experience includes several innovative and unique designs of the more complex capsules and support systems installed in the Advanced Test Reactor. Kevin is knowledgeable of the Advanced Test Reactor authorization basis, American Society of Mechanical Engineers code and analysis requirements, Idaho National Laboratory welding and inspection requirements, and both industry and Idaho National Laboratory design processes. Kevin has chaired or participated in several design-verification processes based on experience in experiment design and fabrication.