UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, DC 20555 - 0001

August 8, 2012

MEMORANDUM TO: ACRS Members

FROM: Cayetano Santos, Chief ***/RA/***
Technical Support Branch
Advisory Committee on Reactor Safeguards

SUBJECT: FIFTH ANNUAL VERY HIGH TEMPERATURE REACTOR (VHTR) RESEARCH AND DEVELOPMENT TECHNICAL REVIEW MEETING

The enclosed trip report summarizes highlights from Maitri Banerjee's trip to the subject meeting on May 22-24, 2012, with a focus upon Next Generation Nuclear Plant (NGNP) fuel research updates. The presentation slides were distributed to the members in a CD at the June ACRS meeting. Please note that, barring any objections, we will not have a subcommittee meeting on fuels research.

For more information, please contact Maitri Banerjee at maitri.banerjee@nrc.gov.

Enclosure: As stated

cc: E. Hackett
H. Nourbakhsh
J. Flack
A. Dias
TSB

TRIP REPORT

MEETING: Fifth Annual VHTR R&D Technical Review Meeting

ATTENDEE: Maitri Banerjee, Senior Staff Engineer, ACRS

The 5th Annual Very High Temperature Reactor (VHTR) R&D technical review meeting, organized by the Idaho National Laboratory (INL), was held in Salt Lake City on May 22-24, 2012. I attended the meeting with two other NRC staff from RES and NRO. It appears that the much reduced NRC attendance, compared to previous years, resulted from the management decision to do only the work required to wrap-up and record the work completed in the NGNP program. The three day meeting provided a progress report on the NGNP R&D. The presentation slides of the opening plenary and the breakout sessions (fuels, graphite, high temperature materials, method & experimental V&V) are available on the INL website https://secure.inl.gov/VHTRRDTR12/default.aspx. A CD containing the presentations was made available to the members during the June 2012 ACRS meeting. I attended the fuels breakout session only, hence the following report does not address other breakout sessions.

SUMMARY

DOE requested $21 million for 2013 NGNP budget compared to $40 million for 2012. Consolidation to a single ATR (advanced test reactor) irradiation location for fuel and graphite irradiations is being done to reduce program costs. The industry alliance (several members attended the meeting) indicated that they plan to go to Congress to request funding for NGNP commercialization. NGNP is preparing for the worst case (under the Senate proposed budget): document the work completed and shelve the program.

The AGR-1 irradiation demonstrated performance similar to the German data at twice the burn-up. The ongoing AGR-1 PIE (post irradiation examination) and safety testing are generating lots of data and shaking down the methodology. However, it will take further analysis to understand the phenomena at play and reach meaningful conclusions. The code predictions need to be fine-tuned with results from the PIE and safety testing. An overview of AGR fuel and source term research is presented in the paragraphs below. Some data needs are being addressed for the methods V&V, but additional R&D will be needed. Some members of the industry alliance noted that they were moving forward with the AREVA prismatic reactor design. As a plan is being developed, DOE may be looking for university involvement to complete the moisture and air ingress experiments. Japan seems to be proposing the “naturally safe” HTGR (high temperature gas reactor) concept as one response to the Fukushima accident and emphasizing deterministic over the probabilistic licensing approach for public acceptance. NGNP would like to brief the ACRS on licensing issues in the last quarter of CY 2012; however, NRO does not seem to have a budget for much NGNP work in 2013.

OVERVIEW OF NGNP PROJECT

Dave Petti, INL, provided a status overview of the NGNP fuel research. The fuel fabrication vendor is expected to be selected by the end of 2012, technologies needed to establish a pilot line will be in industrial hands by the end of 2012, and industrial scale fuel for qualification will be produced in 2013. He noted that the AGR-1 irradiation was completed with no particle failure at peak burn-up. It had 6 capsules with 12 cylindrical fuel compacts in each. PIE and safety testing at accident conditions, which are underway at INL and ORNL (Oak Ridge National Laboratory), will continue through 2013. Some compacts were sent to ORNL for confirmatory

testing. PIE of fuel capsules, compacts, and TRISO particles are producing valuable results regarding fission product release and retention for future validation of predictive methods.

Calculated results for burn-up, fast fluence, and nuclide inventory using a detailed depletion methodology developed at INL shows generally good agreement with AGR-1 PIE data. Capsule fission product inventory measurements found a range of fractional releases of Ag-110m and small fractional releases of many fission products (Cs-134, Cs-137, Ce-144, Sr-90, Eu-154) in addition to elevated Cs in two capsules indicating compacts containing suspected defective SiC fuel particles. One particle with SiC defect was identified in post burn leach. Fractional release in AGR-1 is similar to releases seen in other TRISO fuel irradiations (SL-P1 experiment, HFR-K3, HFR- EU1bis). The PARFUME code, which seems to over-predict fission product (Ag, Sr, Cs) release and predict maximum Pd penetration much less than the SiC thickness (safety test conditions), needs further development.

Ongoing compact ceramography showed no significant spatial trends in particle behavior. It appears that variability in buffer properties and subsequent irradiation behavior was much more significant than particle irradiation history in determining particle end-state morphologies. No correlation between damage and release has been established. Results of limited (six compacts taken from the AGR-1 irradiated inventory) deconsolidation[1] and particle gamma analysis to assess in-pile fuel performance show Ag release from particles to be significant, and little Ag was found to be retained in the compact matrix. The behavior of Pd is less clear. Pd was found in three compacts upon deconsolidation. Although electron microscopic characterization of a limited number of samples did not find significant “Pd corrosion” of SiC, Pd-rich precipitates were randomly distributed on SiC fingers and in SiC and IPyC in regions of SiC/IPyC interlayer. Pd rich precipitates occurred at grain boundaries of SiC. However, similar examinations that were performed at ORNL by a PhD student from the University of Wisconsin, Madison, observed Pd-U (with some Pd) fission product clusters in SiC with depth not specifically confined to near IPyC/SiC (in some particles throughout SiC). AGR-1 safety testing indicated no additional particle failure at 1600°C.

AGR-2 contains both UO_2 and UCO fuel and one capsule at peak irradiation temperature (1400°C) higher than AGR-1. The NGNP program has been focusing on the UCO fuel because of its potential for higher burn-up than the UO_2 fuel that has previously been used in HTGRs. AGR-2 (capsule design similar to AGR-1 with mirror image placement in ATR) will complete irradiation in June 2013. Several thermocouples (TCs) have failed, but no confirmed fuel particle failures have been observed up to 389 EFPDs (May 2012). PIE is scheduled for 2014-2015. To optimize the budget and schedule, the AGR program is occupying the NE flux trap (for both fuel and graphite irradiation, starting with AGR-3/4), and the E-flux trap has been abandoned. Although the E-flux trap offers more volume for sample placement, its use would require more funds and increased time to prepare for its use. The fuel fabrication campaign for AGR-5/6/7 will commence in late 2012, with AGR-7 for margin testing and the formal fuel qualification irradiation scheduled for 2015. Safety testing is critical to demonstrate robustness of TRISO fuel for HTGR use. Regarding source term qualification, irradiation is underway for AGR-3/4, with 80 designed to fail (DTF) fuel particles in each capsule (DTF particles are failing)

[1] Deconsolidation-leach-burn-leach (DLBL) - electrolytic deconsolidation of matrix in nitric acid to liberate particles, followed by: (1) leaching of fission products in matrix; (2) burning of particle and matrix debris to oxidize carbon and expose kernels with defective SiC; and (3) post-burn leach of remaining fission products from matrix or OPyC and leach kernel and fission products inside particles with defective SiC. Techniques used at INL and ORNL varied somewhat.

and will provide data on fission product release and retention from failed fuel. Further work is needed in the area of distinguishing signals from the onset of fuel failure versus already failed fuel. Follow-on PIE and safety testing will occur in 2014-2015. Developing automated compacting capability (for eventual industrial fuel fabrication) is the focus of 2012 fuel R&D, and the technology for a pilot line is being developed at B&W. Fabrication of qualification fuel is expected to start in 2013 after selection of a vendor.

In pile failure of TCs has been a concern that continues in AGR-2. The NRC needs to carefully review the use of commercial Type N TCs in AGR-2 and AGR-3/4 and the use of analytical techniques to predict missing data given the large uncertainty involved in analytical techniques.

Hans D. Gougar, INL, provided the status of the design methods and validation work, while Richard Schultz, INL, focused on providing an overview of the experimental V&V of CFD/System Codes. Dr. Gougar discussed the limitations of current methods (e.g., LWR lattice physics codes yielding large errors on power peaking, limitations of modeling stratified flow), and NGNP unique features (longer neutron travel across fuel blocks, large neutron leakage leading to increasing effects of neighboring material surrounding fuel). The most significant challenge to this effort is the lack of a final design. Other challenges include the lack of burn-up data, and the fact that legacy computational tools are not designed for HTGR physics. Regarding the development of core/plant simulation tools, PEBBED (the multi-physics code system for the pebble bed reactor) is being validated against critical experiments (HTR-10, PROTEUS). After a late start, a full coupled-core simulation is being tested for the prismatic core. A 3-phase computational sequence is designed to exercise prismatic core neutronics, thermal fluids, and lattice physics (PHISICS-RELAP5 for burn-up and transients). One of the test cases being used by INL is the OECD numerical benchmark (being sponsored by the OECD). Questions from participants emphasized the need of computational methods for predicting fission product transport and a mechanistic source term. In addition, the program is seeking input from vendors regarding test needs for validating their codes.

Experimental V&V will use plant data, integral and separate experiments, basic standard problem tests at universities, and complementary R&D by international partners for benchmarking the simulation tools. The Oregon State University (OSU) High Temperature Test Facility (HTTF) final design is being completed with installation and shakedown tests planned for 2012. It will investigate core behavior during loss of forced circulation (LOFC). Regarding ex-vessel experiments, refurbishment is progressing at the Argonne National Laboratory (ANL) Natural Circulation Shutdown Test Facility (NSTF). NSTF will investigate the reactor cavity cooling system (RCCS) performance with both air-cooled and water-cooled RCCS. Data from the first run of the isothermal bypass flow (matched-index-of-refraction (MIR)) testing at INL for CFD validation are being processed. Dr. Schultz presented data from the air ingress test at INL the objective of which is to study effects of density-driven, stratified flow on air ingress into the reactor core and develop experimental data for CFD code V&V. See his slides at the May 24 Methods breakout session that listed the data needs and work which is either underway or yet to be started. NQA1 level QA is applied to all NGNP work (NRC reviewed QA program).

Richard Wright, INL provided an overview of the high temperature metals (Subsection NH) program, which is focused on characterizing key properties of steam generator, heat exchanger, and pressure vessel alloys. The R&D program consists of coordinated activities at INL, ORNL, ANL, and universities. He discussed the work with Alloy 617 and A508/533 steel, and some results. In addition, validation of crack growth testing systems in helium with impurity levels is ongoing. He also mentioned the work that supported extension of Alloy 800H Code limits to 850°C and 500,000 hours. Some challenges being faced by the program include availability of

test equipment, extrapolation of lab data to complex design applications and long term service behavior, and need for close cooperation with ASME on Code Case development. Presentation slides for the High Temperature Materials Breakout sessions provide more detail.

William Windes, INL, provided an overview of developments in the area of graphite R&D. Work on characterizing the baseline as-formed properties of new graphite types (NBG-18[2], PCEA, IG-110, and 2114) show consistent graphite with very little variability across types and between billets (density 1.82 to 1.86 g/cc). Regarding irradiation testing, the AGC-1 irradiation was completed at 700°C and 6.5 dpa. Dr. Windes presented some of the preliminary results that show different "delta L over L" behavior against estimated dose between extruded and isomolded graphite. Creep samples were shipped to ORNL, and PIE data are being evaluated. AGC-2, which is being irradiated at 700°C and up to 5.5 dpa with a more even temperature profile, is to be completed in summer 2012. AGC-3 irradiation will begin in late summer 2012. AGC-4 is expected to be inserted in ATR in the fall of 2013. One goal of the graphite program is the development of validated analytical models to define the safe operative envelope of the graphite core to avoid expensive testing programs.

Mark Holbrook, INL, discussed the pre-license application activities. Eleven white papers developed by INL to address policy issues (e.g. source term, containment, defense-in-depth (DID), use of PRA in licensing) have been submitted. An NRC working group generated two assessment reports on five of the white papers (fuel qualification/ source term, and DID/licensing basis event/SSC classification). The HTGR-compatible version of the format and content guide (Regulatory Guide 1.206) is needed for future NGNP combined license applicants. It should incorporate the findings of the regulatory gap analysis (INL/EXT-11-23216). The NRC staff will develop position papers[3] on key HTGR policy and technical issues, with future ACRS briefings, if requested. The current NGNP licensing schedule shows a briefing of the ACRS on licensing issues during October-November 2012. Beyond the staff work to support these activities, I was told that NRO management is not planning much work on NGNP in 2013, unless something changes.

Kazuhiko Kunitomi of Japan Atomic Energy Agency (JAEA) provided an overview of their research activities behind the "naturally safe" HTGR concept as a response to Fukushima accident. For public acceptance, the use of deterministic analysis is being emphasized over probabilistic methods due to the apparent failure of the probabilistic arguments in consideration of the worst case natural disaster. He noted that the CO concentration in the core is to be kept low enough to avoid explosions (concern of water ingress producing combustible CO and H_2 as steam reacts with graphite). The R&D demonstration includes core design with excess reactivity, decay heat removal without engineered features during LOFC, formation of a stable oxide layer (SiO_2) on the surface of the TRISO fuel, and oxidation-resistant graphite for core components to maintain fuel geometry during air ingress. Some of these demonstrations will use the HTTR. Dr. Kunitomi discussed the status and schedule of the HTTR and noted that confirmation tests at cold conditions did not find any degradation after the 2011 earthquake. Possible collaboration between JAEA and INL was discussed.

FUEL BREAKOUT SESSIONS - MAY 23 AND 24

AGR-1 PIE and Safety Testing

[2] Slide 7 error: First bullet NBG-18 not 19
[3] NRC staff intends to issue statements on key technical and policy issues in lieu of draft SECY papers. An ACRS Future Plant Design Subcommittee briefing is scheduled for early 2013.

Paul Demkowicz, INL provided an overview of AGR-1 PIE, which is expected to be completed in September 2013. The objective of the PIE is to shake down the methods, characterize fuel performance, and support selection of a reference fuel for AGR-5/6/7. AGR-1 PIE is about half complete in that the fission product measurements of capsule components are complete, destructive analysis of compacts (ceramography, deconsolidation-leach-burn-leach (DLBL), mass spectroscopy, irradiated microsphere gamma analyzer (IMGA), electron microscope and microanalysis of particles) is in progress, and safety testing is underway. PIE is being done at both INL and ORNL. Dr. Demkowicz mentioned funding was limiting the work scope.

James Sterbentz, INL, discussed the methodology for AGR-1 burn-up and inventory analysis. INL developed and applied a detailed Monte Carlo depletion methodology (evolving over 5 calculations, from homogenized to particle models, to improve accuracy) in order to estimate AGR-1 compact burn-up characteristics and other physics parameters. Calculated vs. measured (C/E) ratios were derived for burn-up, fast fluence, and nuclide inventory (measurements discussed by Dr. Harp below) for homogenized and particle model calculations. Four compacts were selected over a range of parameters for burn-up comparison between the two models (homogenized and particle) and measurement techniques. Dr. Sterbentz noted that due to self-shielding, the homogenized model over-predicts Pu, which may over-predict some fission products. Calculated results so far show generally good agreement with PIE data.

Jason Harp, INL, presented the status of the AGR-1 compact burn-up evaluation that is based upon fission product inventory measurements. One of the AGR-1 PIE objectives is to assess overall fuel performance to verify simulations. Precision gamma spectrometry (PGS) of 72 compacts (in 0.1 inch slices) has been completed for a non-destructive burn-up profile evaluation. Several isotopes of interest were present in the PGS scans. Burn-up predictions from measured total compact Cs-137 activity and the Cs-134 to Cs-137 activity ratio were found to be optimum indicators. Measured burn-up profile compared well to detailed depletion simulations and mass spectroscopy (ICP-MS-destructive) burn-up analyses. Measured fission product inventories were compared to the predicted fission product inventories in the simulations. The calculated to experimental (C/E) ratio for many isotopes (Cs-137, Cs-134, Ce-144) was very near to 1.0 over the entire test train. The simulation did over-predict some isotopes such as Eu-154 and Sb-125. Results from ICP-MS are available for two compacts and forthcoming for two additional compacts.

Dr. Harp also presented the results of the AGR-1 fission product inventory measurements in capsule components. One of the AGR-1 PIE objectives is to evaluate fission product retention. Various capsule components were examined for condensable fission products Ag, Cs, Eu, Ce, and Sr. The spatial distribution of Cs and Ag was studied. Elevated Cs inventory in graphite shells and holders was considered to be from defective SiC in two capsules, one confirmed by INL gamma scan and the other sent to ORNL for IMGA and identification of defective SiC layer TRISO for study. End capsules had the majority of Ag in shells (probably due to the increased graphite-capsule gap) and middle capsules had Ag in graphite holders. Selected compacts were PGS rescanned for longer time per slice to quantify Ag-110m in the compact. Ag-110m mass balance in five capsules indicated reasonable agreement with predicted Ag-110m inventories. Regarding Ag inventory, no clear trend was observed with fuel type or with capsule average temperatures. Individual compact Ag release/retention exhibited a huge range. Large and varied fractional releases of Ag-110m, and small fractional releases of many fission products (Cs-134, Cs-137, Ce-144, Sr-90, and Eu-154) were found. Fractional release in AGR-1 is similar to releases seen in other TRISO fuel irradiations (SL-P1 experiment, HFR-K3, HFR-

EU1bis). The lack of Iodine in their measurements probably means it was released with fission gases.

Paul Demkowicz, INL, presented the optical microscopy of irradiated AGR-1 compact cross-sections and micrograph measurements of particles to better understand irradiation effects on kernel and coating. Techniques were used to characterize: kernel swelling and porosity; buffer densification and fracture; layers bonding, damage and fractures; OPyC to matrix interactions; and spatial variations in particle behavior. A total of 830 particles in five compacts have been classified so far for particle types based on buffer/ IPyC bonding and kernel-buffer behavior (fracture, densification, kernel swelling). Buffer areas and thicknesses were reduced by ~1/3 during irradiation. For all three compacts examined for kernel swelling, similar amounts of swelling and more porosity were observed in particles with still bonded buffer and IPyC (least constraint on kernels). A very few (~5% of total) particles had buffer and IPyC still bonded all around. Most of the particles (~95%) had buffer and IPyC completely or partially de-bonded. Less than ¼ of particles had fractured buffers (tangential and radial). No obvious correlation between buffer fracture and burn-up, fast fluence, or temperature has been found. Through wall IPyC fractures were found in particles from some compacts, while none in others. IPyC and SiC may delaminate at IPyC fracture tips, and SiC cracks were often associated with long IPyC-SiC delaminations. Through wall radial extension of tangential SiC cracks seen in one particle was explained away as the result of grinding (sample preparation). Possible foreign material (soot) inclusion between IPyC and SiC was suspected to cause SiC cracks. No significant OPyC/matrix interactions have been observed. In general, no significant spatial trends in particle behavior have been observed. It appears that variability in buffer properties and subsequent irradiation behavior was much more significant than particle irradiation history in determining particle end-state morphologies. Limitations resulting from working with 2-D views of 3-D structures and geometric errors were mentioned as some of the challenges. Upon questioning, Dr. Demkowicz noted that no correlation between damage and release has been established yet. Results will be documented in the INL report INL/EXT-12-25301, "Ceramographic Examinations of Irradiated AGR-1 FY12 Fuel Compacts," which is expected to be issued in June 2012.

Dr. Demkowicz presented the results of deconsolidation and particle gamma counting/analysis (including IMGA) to assess in-pile fuel performance by examining fission product release from compacts and particles post AGR-1 PIE. Six compacts were shared between INL (4) and ORNL (2) for this analysis with slightly different techniques. The DLBL process generated loose particles for measurement of fission product inventory outside the SiC layer and retained inside the particle (detect defective SiC). Results show Ag release from particles to be significant, albeit very non-uniform among individual particles. Although large variability was found within a compact, little Ag was found to be retained in the compact matrix. Eu release from particles could be as high as ~1.3%, mostly retained in the compact matrix. Ce and Sr release appears to be correlated with Eu but is 1 to 3 orders of magnitude lower. About 1% Pd was found in the matrix of three compacts. The feasibility of counting all ~4100 particles in a compact to screen for defective SiC was demonstrated (one particle with SiC defect identified in post burn leach). Insufficient data were obtained to determine if variant fuel types (TRISO manufactured with different SiC and IPyC deposition temperatures, etc) generated better retention. Challenges included hot cell contamination among others. Basic PIE on 5 compacts at INL and 5 compacts at ORNL are to be completed in 2012.

Isabella vanRooyen presented electron microscopic characterization of AGR-1 particles at INL. Her samples included an additional compact over the four in the INL deconsolidation inventory discussed in Dr. Demkowicz's presentation above. These compacts included variant fuel types

in addition to the baseline fuel. Unirradiated TRISO was used as a benchmark for characterization of irradiated particles (e.g., for SiC behavior). Scanning electron microscopy (SEM), transmission electron microscopy (TEM), energy-dispersive x-ray spectroscopy (EDS) and wavelength-dispersive x-ray spectroscopy (WDS) were used to examine samples from the kernel/buffer and IPyC/SiC interlayer. Technical highlights are as follows:

- Although significant "Pd corrosion" of SiC has not been identified, Pd-rich precipitates were randomly distributed on SiC fingers and in SiC and IPyC in regions of SiC/IPyC interlayer (not at IPyC/SiC interface)
- Pd rich precipitates occurred at grain boundaries of SiC layer
- Pd and U in precipitates with the possible presence of Ag and possibly Zr and Pu (UPd_2Si_2 or possibly $U(Ag,Pd)_2Si_2$) were found
- No significant difference in SiC microstructure observed between low and high 110m Ag particles - still under investigation in more particles
- At least one Cs-rich precipitate in the SiC layer has been identified. No SiC phase transformation due to irradiation was observed.

Work continues to identify other precipitates (a wormlike stringer containing Cs precipitates cross-cutting multiple grains, nano-sized precipitates inside grains); to confirm and understand possible crystallographic relationships between precipitates and SiC, and the preferred orientation of precipitates; and to understand irradiation effects on SiC microstructure and fuel kernel microstructure. Dr. vanRooyen mentioned the challenges and deliverables planned.

Tyler Gerczak, PhD Student at University of Wisconsin, Madison, presented interim results of the continued microanalysis of deconsolidated particles from AGR-1 compacts provided to ORNL. SEM was performed on selected particles from two compacts analyzed with IMGA, with a protocol for SEM analysis being developed. The results were somewhat interesting. Fission product clusters, primarily Pd-U (with some Pd), were observed in SiC with depth not confined to near IPyC/SiC (in some particles throughout SiC). Large fission product clusters were segregated to the IPyC/SiC interface, and Cs-U fission products were found in IPyC of particles from one compact.

Robert Morris, ORNL, presented results of ongoing AGR-1 safety testing. Fuel performance is being tested at elevated temperature to simulate a depressurized inert atmosphere conduction cool-down event. Irradiated compacts are heated at 1600-1800°C for 300-400 hours with monitoring of release. The purpose of the safety test is to understand the phenomena of release of fission products from the matrix, fission product transport through SiC, corrosion of SiC, and failure of individual particle coatings. Post-test analysis is performed to further characterize fission product release (Kr, Ag, Sr, Eu, and Cs) and study microstructural changes in coated particles. Furnace test results indicate, fast release of Ag and trace Cs upon initial temperature ramp up and no increase afterwards, and continued slow releases of Sr and Eu. Significant releases from the compact were Ag and Eu, with amounts comparable to those found during DLBL of as-irradiated compacts. Thus, fission products released at 1600°C appear to be from the matrix (due to long term in-pile releases) rather than from particles during the furnace test interval. Cs was released from one particle with defective SiC during the furnace test. Unusual Ag release was observed in conjunction with thermal cycling. Challenges include equipment issues and radiochemical analysis. Work continues in this area.

<u>Status of AGR-2, and 3/4</u>

Blaine Grover, INL, presented the status of the AGR-2 irradiation (June 2010 to April 2013). The AGR-2 capsule design is similar to AGR-1, with six capsules containing 72 fuel compacts. Accounting for two proprietary capsules from CEA and PBMR, AGR-2 has 48 compacts of NGNP fuel. It includes UO_2 and UCO (9.6% and 14% enrichment) fuel. ATR West Large B center vertical positioning provides uniform flux spectrum similar to NGNP (AGR-1 was in the East Large B) and modest acceleration of the irradiation time. A time average peak temperature of 1400°C for the highest temperature capsule, 10% FIMA burn-up and a fast fluence of $2x10^{25}$ is the goal. The current status indicates that several of the Type N TCs have failed, but no confirmed fuel particle failures have occurred up to 389 EFPDs (May 2012).

Mr. Grover also presented the AGR-3/4 irradiation status. It includes 12 capsules with 4 stacked compacts in each. AGR-3/4 includes 20 designed-to-fail particles (UCO 19.8% enriched) in each fuel compact positioned in the ATR Northeast Flux Trap. With this relocation of AGR irradiation experiments, accelerated irradiation, power level control, use of the full height of ATR and modified neutron spectrum will be achieved. In some of the 12 capsules in the test train, the matrix material has been replaced with nuclear graphite. Commercial Type N TCs are located at lower temperature locations in the capsule. Irradiation started in December 2011 and DTF particles started to fail as planned. The irradiation is scheduled to be completed in November 2013.

Dawn Scates, INL, presented a summary of the ongoing AGR-3/4 fission product monitoring data collection. She discussed the NaI shield design upgrade, software update, Iodine-131 testing, and how several encountered glitches were fixed. Particle failures are being reviewed to differentiate between failures and releases from previously failed particles, especially in capsules with high counts. A software update is being evaluated to automate particle failure counts.

<u>Fuel Methods and Prediction</u>

William F. Skerjanc, INL, discussed the status of the update to the coated particle fuel performance code (PARFUME) at INL for fuel particle failure prediction. This integrated mechanistic code evaluates the thermal, mechanical, and physico-chemical behavior of TRISO fuel particles, and is capable of evaluating fuel particle failure under both irradiation and accident conditions and fission product transport. Recent development has added the capability to capture the multidimensional behavior of different particle types and sizes over a broad range of normal and accident conditions. Verification of new models to represent cylindrical fuel geometry and an initially defective SiC layer is being pursued in addition to AGR-1 safety test predictions, AGR-3/4 pre-test predictions, and AGR-5/6/7 planning.

Blaise Collin, INL, discussed modeling of the PARFUME code for AGR-1 safety test predictions. Eighteen fuel compacts were selected based on a distribution of burn-up and irradiation temperature. Objectives of the AGR-1 safety testing included verification of estimated differences in performance between some variants and baseline fuel types, the effect of irradiation/accident safety test temperatures and burn-up on performance, and the random variation in fuel performance during safety tests. Predictions were developed for SiC failure probability, fractional release of Ag/Cs/Sr/Kr fission products, and Pd penetration (for consideration of Pd attack of the SiC layer) against irradiation/safety test temperatures. For the study, not a single particle failure was predicted by PARFUME. Maximum Pd penetration was found to be much less than the SiC thickness, and the maximum release predicted for Ag was 16% during irradiation and 92% during safety testing. In comparison with ORNL safety test data for four AGR-1 compacts (see Robert Morris presentation above); PARFUME seemed to over-

predict the release of Ag, Cs, and Sr. Dr. Collin noted that the predicted values of fission product release at temperatures higher than 1600°C were not as accurate for several reasons: it would be physically impossible to have all the fuel at that temperature for any period of time; calculations did not represent a scale model of the core; and the code overestimated diffusion effects (use of IAEA Tec. Doc. 978 diffusion coefficients were too conservative). Further work continues. The report INL/EXT-12-26014, "AGR-1 Safety Test Predictions Using the PARFUME Code," May 2012 provides details of this analysis.

David Hanson, GA (General Atomics), presented the predictions for AGR-1 fuel performance (fission gas R/B (release to birth) ratio) and fission product transport during irradiation using GA codes. They used the GA fuel design data manual (FDDM) Issue F for fuel failure models, materials property data, and FP transport correlation. Both FRG (German) Tec. Doc. 978 and FDDM diffusivities were used for comparison purposes. Predicted noble gas R/B from contamination was in good agreement with the measured R/B, but the measured R/Bs fell short of the predicted "total" noble gas R/Bs from exposed kernels + contamination. Dr. Hanson concluded that the FDDM/F OPyC failure model was inappropriate for a thermosetting resin matrix and over-predicted OPyC Failure (exposed kernels).

Regarding fission product transport, fractional release of Sr and Cs were computed using both FRG and FDDM diffusivities. Sr release is strongly dependent upon assumed SiC diffusivity (FRG diffusivities increased Sr release by >>10x compared to FDDM because of the predicted diffusive release through an intact SiC layer). Cs release is largely determined by the SiC failure fraction, but FRG diffusivities increase Cs release by ~2x compared to FDDM. They used three SiC Corrosion models (FDDM/E and FDDM/F and INL). Predicted particle SiC corrosion failure was found to be highly model dependent. INL and FDDM/E models predict no failure, but FDDM/F model predicts failure in the hottest capsule. The models are evidently very conservative, and uncertainties were a concern. Fission metal release predictions were strongly dependent upon material property data. Ag release was dominated by diffusive release from intact particles, and comparisons of predicted vs. preliminary PIE results appear to be favorable (no conclusions were reached due to preliminary nature). Future AGR-3/4 results will validate the source term and clarify some of the predictions. AGR-1 data imply fuel particle SiC corrosion may have been overestimated. Models need improvement.

Jeff Einerson, INL, presented the status of uncertainty calculations of the predicted AGR-1 temperatures, identification of parameters that affect it, and potential sources of uncertainties. Based on sensitivity and uncertainty considerations, the following parameters were found to be important: control gas gap width; Neon fraction; heat rate in fuel compacts; and graphite and fuel conductivity. INL performed regression analysis in ABAQUS, and second order effects were found to be negligible. The dominant factors in uncertainty of the TC measurement were determined. Overall uncertainty results for various temperature measurements vary between 10 to 79°C (see viewgraphs). Use of the uncertainty information in future capsule design is being contemplated.

Fuel Fabrication

Scott E. Niedzialek presented the commercial scale compacting equipment demonstration test at B&W. ORNL provided confirmatory analysis of fuel compacted by B&W. Measured broken particle levels in compacts were originally much higher than the specified $1x10^{-5}$ defect fraction of TRISO particles in the starting material. Round robin testing with ORNL and a systematic review helped determine the causes and to identify a window of operation to prevent particle damage (see paragraph below). Regarding packing fraction, [%] was noted as the process

limit (higher nos. provide more flexibility to core developers). 1200 NUCO compacts were produced using conditions within the processing window. The heavy metal contamination rate and SiC failure rate due to compacting were verified. The resulting process met all dimensional limits and process parameters for achieving high packing fractions and matrix density compacts. The process also resulted in very consistent uranium loading. Valuable process knowledge was achieved for limiting damage from the compacting process.

Douglas Marshall, INL, further discussed the results of the round-robin testing between B&W and ORNL to evaluate the analytical process at B&W and the lessons learned. The round-robin testing indicated the burn-back method used in analysis of compacts (faster process for exposing particles) induced substantial particle damage. In addition to a need for exposed U defect free TRISO particles, a thorough review of the analytical procedures, improved sample size, and the use of 95% confidence interval in decision making were deemed necessary.

Other Tests & Experiments

Paul Humrickhouse, INL, presented the Tritium permeation tests completed in FY11 and FY12 (confirmatory). The final report INL/EXT-11-23265, "Tritium Permeability of Incoloy 800H and Inconel 617," has been issued in July 2012. He discussed validation with available data (Alloy 800H), first-of-a-kind data for Alloy 617 and 230, expanding of the temperature and partial pressure range into NGNP conditions, and challenges encountered. Permeability of tritium was found to be much lower than hydrogen. Permeation in Alloys 800H/617 is decreased at low tritium pressures probably due to surface limited, rather than diffusion limited, transport, necessitating a new model as Sievert's law would not apply. Ideas explored included surface oxidation state and concentration versus isotope effects.

Richard Hobbins, RRH Consulting, presented the plan for moisture and air ingress experiments. For moisture ingress, key phenomena to be verified include the integrity of the SiC layer in TRISO surrogate fuel particles, the hypothesis that hydrolysis of UCO fuel only affects particles with exposed kernels, the rate of oxidation of graphite, and the hypothesis that the fractional release of fission gas by hydrolysis saturates at a water vapor partial pressure of about 0.1 atm. Air ingress experiments would measure oxidation of the fuel element graphite and compact matrix as a function of temperature, oxygen concentration, and exposure time. In addition to verifying previous key results that rate of oxidation of graphite saturates at temperatures of about 1200°C, it would measure the extent of attack and degradation of the SiC layer in the TRISO surrogate fuel particles and fission product release under accident heat up conditions as a function of oxygen partial pressure using irradiated fuel compacts. AGR-5/6 was mentioned as a vehicle for more testing. It appeared that DOE was looking for university involvement.