Study on Improvement of Core Safety - Study on GEM (III)

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Project Hanford Management Contractor for the
U.S. Department of Energy under Contract DE-AC06-96RL13200

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T. M. Burke
B & W Hanford Company

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1.0 INTRODUCTION

This report provides a summary of activities associated with the technical exchange between representatives of the Japan Atomic Power Company (JAPC) and the United States Department of Energy (DOE) regarding the development and testing of Gas Expansion Modules (GEM) at the Fast Flux Test Facility (FFTF). Issuance of this report completes the scope of work defined in the original contract between JAPC and DOE titled "Study on Improvement of Core Safety - Study on GEM (III)." Negotiations related to potential modification of the contract are in progress. Under the proposed contract modification, DOE would provide an additional report documenting FFTF pump start tests with GEMs and answer additional JAPC questions related to core safety with and without GEMs.

2.0 BACKGROUND

The Demonstration Fast Breeder Reactor (DFBR) is a 1600 MWt three loop, Liquid Metal Fast Breeder Reactor (LMFBR) being designed in Japan for planned construction early in the next century. The designers, a group of Japanese companies led by the Japan Atomic Power Company (JAPC), wish to design the DFBR plant with enhanced safety characteristics. In particular, they are aware of the work done at the Fast Flux Test Facility (FFTF) in the mid 1980's to develop and test a device called the Gas Expansion Module (GEM) which provides inherent negative reactivity feedback in the event of a loss of flow to the reactor core. If the negative feedback insertion is of sufficient magnitude and occurs fast enough, then the reactor can withstand a loss of flow without scram (LOFWOS) event with no significant consequences (e.g., no core damage). In order to take advantage of the information and experience gained from the FFTF GEM development and testing program, JAPC entered into a contract with the United States Department of Energy. The contract lists four specific items to be performed by DOE:

- Provide three existing reports to JAPC. Two of these reports document the design of the GEMs tested at the FFTF and the third provides the FFTF LOFWOS with GEMs test results. These reports were transmitted from DOE to JAPC shortly after contract signing in August, 1996.

- Hold a "GEM Specialists Meeting" in the United States in October of 1996. The purpose of the meeting was to discuss the FFTF GEM development and testing program and review Japanese analyses of the FFTF tests. At the request of JAPC, the meeting was delayed until December 3-5, 1996. The report from the meeting was previously issued on December 31, 1996.

- Participate in a meeting with representatives of Japan's electric power companies in February of 1997. The purpose was to make a presentation summarizing the results of the FFTF development and testing program and the GEM Specialists Meeting. This meeting was held on February 3, 1997 in Tokyo, Japan.
Issue a report documenting the two meetings listed above.

In addition to the specific items listed above, during the performance of this contract JAPC requested additional information to assist in their analysis of the FFTF GEM design and testing. This additional information has been provided by DOE in several letters.

3.0 JAPC/FFTF GEM SPECIALISTS MEETING

The JAPC/FFTF GEM Specialists Meeting was held in Richland, Washington, on December 3-5, 1996. The meeting attendance is provided in Appendix A.

3.1 OVERVIEW OF GEM SPECIALISTS MEETING

The format of the first two days of the GEM Specialists Meeting was to provide a short presentation on each subject listed on the agenda. Included in the introductory session was an overview of the Hanford contractor organization and a brief history and current status of the FFTF. Each presentation was followed by an open discussion period. At appropriate times, the results, conclusions and action items from the discussions were summarized by the entire group, in writing, to ensure that all key items would be recorded and not forgotten. The third day consisted of a tour of the FFTF plant. This tour lasted approximately three hours and provided additional opportunity to discuss items of interest.

The Japanese representatives at the meeting indicated that the information presented (both at the meeting and in response to their previous written questions) was very helpful and provided the data they needed to develop and validate their analytical models. They were very appreciative of the efforts by the United States representatives to assist them in their endeavor. The U.S. representatives at the meeting were able to answer many questions and provide clarification of the information in many areas. A number of observations related to the Japanese analytical modelling approach were provided and other comments related to the overall Japanese program were offered. These are included in the presentation discussion sections of this report.

The United States representatives were impressed with the level of detail included in the Japanese modeling of the FFTF GEM tests. In general, the Japanese have put considerably more effort into the analytical modelling of the GEMs than the United States has. It was pointed out that development and testing of the GEMs at FFTF was accomplished over a very short time period and at a relatively low cost. This did not allow for a significant analytical effort. The design of the FFTF GEMs was based on a collection of scoping and bounding calculations. The FFTF test program was then conceived to utilize the results of initial low power testing to demonstrate the acceptability of performing the next (higher power) test. This "bootstrapping" approach eliminated the need for complete detailed understanding and analysis of the GEM performance and was completely acceptable and rational for a program intended to develop and demonstrate the GEM device. However, in the case where the design and licensing of a reactor system will be
dependent on work performed prior to operation and testing of that facility, the Japanese approach of extensive, detailed analytical modelling (and selected small scale feature testing) is required. The U.S. representatives were again impressed with how well the Japanese model matched the FFTF zero power test data, following slight adjustments to a few key parameters (these adjustments being within the estimated uncertainty of those parameters). This good agreement confirms the validity of the Japanese model of the FFTF GEMs. Obtaining such good agreement with the at-power LOFWOS test data will be much more difficult due to the presence of other complex aspects such as temperature changes in the assemblies surrounding the GEMs and the effects of other reactivity feedback mechanisms (e.g., Doppler).

It was agreed that the United States would send two representatives to Japan during the first week of February for two purposes:

- Review and discuss the Japanese analyses of the FFTF Loss of Flow Without Scram tests (these analyses were to be completed during the intervening weeks).
- Make a presentation to representatives of the Japanese electric power companies. This presentation was to summarize the FFTF GEM development and testing program as well as the GEM Specialists Meeting.

The next section of this report provides a summary of each of the presentations made during the GEM Specialists Meeting; each summary is followed by a synopsis of the comments, questions and actions resulting from the subsequent discussion. A copy of the presentation material used in the meeting is provided in the meeting report.

3.2 SUMMARY OF PRESENTATIONS AND DISCUSSIONS

3.2.1 Overview of GEM Development and Testing at FFTF

Summary

This presentation provided an overview of the FFTF GEM development and testing program. Included was a summary of the reasons for and goals of the program. The emphasis on inherent reactor safety in the United States in the mid 1980's was discussed. A general description of the GEM and the theory of its operation was provided. Limitations of the FFTF GEM design and testing program were described. For example, the GEMs were analyzed for only short term use (25 effective full power days) and peak temperatures were limited to those experienced during normal operation (in order minimize the impact on fuel lifetime).
Discussion

Since this was a high level overview, there was relatively little discussion related to it. However, the following items are noted:

- If GEMs are to be left in the core for a long period of time, swelling and bowing must be evaluated. It was suggested by the U.S. participants that it may be prudent to rotate them periodically (as FFTF did with reflectors). However, based upon information provided subsequent to the meeting, analyses of the effects of the neutron fluence in the DFBR have shown that the design of the GEMS (and other core assemblies) is sufficient for a five cycle lifetime (approximately five years). Furthermore, an assessment of the benefits of rotating the GEMS was performed and showed that with rotation, the lifetime would still be limited to six cycles. The DFBR fuel handling equipment does not accommodate assembly rotation. It was suggested that it may be appropriate to perform an analysis to evaluate the cost/benefit of using more expensive radiation resistant materials versus requiring more frequent GEM replacement. Long term GEM performance will need to be verified by long term irradiation testing.

- The GEM behavior is highly dependent on the core pressure drop. The DFBR core pressure drop is approximately one half of the FFTF value. Also, the DFBR fission gas plenum is at the bottom of the fuel pin while the FFTF's is at the top; this will have to be considered in the DFBR GEM design. The JAPC representatives said that they have been able to develop a suitable GEM design for the DFBR core.

- The FFTF GEMs utilized a round duct for cost reasons. A hexagonal duct should also work and may actually provide a slight reactivity worth benefit over a round duct due to the greater gas volume (cross sectional area).

3.2.2 GEM Mechanical/T&H Design and GEM Loading

Summary

The mechanical and thermal-hydraulic design and analysis of the FFTF GEMS was discussed in considerable detail in this session. Again the relatively short exposure time (but significant number of transient tests, about 30) was emphasized. However, it was stated that although the FFTF GEMS were analyzed for only short term exposure, there was no known reason why the design would not be acceptable for long term exposure. The major thermal hydraulic consideration was to achieve a sodium level above the core at full flow and below the core at zero flow in order to achieve maximum reactivity insertion. A full sodium flow level of about one foot above the core was selected to eliminate the possibility of power fluctuations (induced by GEM level fluctuations) while limiting the delay in reactivity insertion. The FFTF GEM loading process and resultant uncertainty in conditions (gas pressure, gas temperature and thus gas mass) was described. The basis for selection of the heat transfer coefficient used between the GEM duct and the
enclosed gas (3 BTU/hr/ft²/°F) was discussed. Finally, potential mechanisms for gas loss or accumulation in the GEMs were reviewed; it was pointed out that no change in reactivity was detected during the approximately 30 tests at FFTF.

Discussion

- The GEM temperature during initial insertion into sodium establishes the trapped gas mass and thus affects the GEM performance. At FFTF, this temperature could not be controlled precisely and is thus somewhat uncertain. The GEM loading process needs to be carefully developed for DFBR and any other plant using GEMs.

- Gas accumulation in the GEMs from gas bubbles entrained in the circulating sodium was felt to be the most credible mechanism for changing the GEM gas content at FFTF (gas is known to be entrained in the FFTF primary sodium). There was no evidence of the GEM gas content actually changing. The design of the DFBR (e.g., reactor inlet plenum and GEM inlet nozzle) should be reviewed to evaluate the possibility of gas entrainment in the sodium and possible release/accumulation in the GEMs.

- If the DFBR (or any other plant) is designed to rely on GEMs, then a method will have to be developed to periodically confirm the GEM reactivity (i.e., that the gas volume has not changed). At FFTF this was not a major consideration due to the short exposure time. However, FFTF did verify the GEM reactivity worth at zero power prior to every reactor startup. A periodic core flow reduction/reactivity measurement is probably the most reasonable approach for verification of GEM reactivity. However, the uncertainty in the measured GEM worth using this approach must be assessed.

3.2.3 Zero Power Calculation of GEM Reactivity Worth in FFTF

Summary

The three dimensional diffusion theory model used to predict the zero power GEM worth was described in detail. Two radial mesh sizes were studied due to concerns about potential effects of the GEMs being close to the model boundary; however, the results of the two models were very consistent. The calculated results were also quite consistent with measured values. Additional work with other models was less successful:

- A model using modified diffusion coefficients to account for the low density of the GEMs was initiated but not completed. There was a large discrepancy observed between initial calculations and measurements.

- Monte Carlo calculations were attempted but there was difficulty in obtaining sufficient numbers of neutron histories to get good statistics; this led to large uncertainties in the results.
Discussion

The major items of discussion from this presentation were:

- While the Monte Carlo method of GEM reactivity worth calculation was not completed for FFTF, the advent of more powerful and faster computers over the past ten years may now make this a viable technique.

- Based upon Japanese experience, diffusion theory yields about 30% higher GEM worth than transport theory.

- The GEM reactivity calculational model must have credibility with regulatory bodies. The FFTF measured GEM reactivity worth provides a set of data for benchmarking both simple diffusion theory and more sophisticated models. Additional testing of GEMs in another reactor would provide extremely valuable data for further validation of the calculational techniques.

3.2.4 Subcritical GEM Worth Measurements

Summary

This presentation described the various methods used to measure the FFTF GEM reactivity worth at zero power (isothermal) conditions. The three measurement methods were Modified Source Multiplication (MSM), inverse kinetics and initial critical rod position. All three agreed extremely well. Data was presented on the reactivity changes due to variations in flow rate and temperature. Data was also presented showing that the measured GEM reactivity worth was consistent over the entire duration of the test program (within the measurement uncertainty). The measured data was judged to validate the calculated GEM sodium levels although some minor deviations can be observed (e.g., timing of initial negative reactivity insertion).

Discussion

There was considerable discussion about the location of the neutron flux monitors (used to obtain data from which the measured GEM reactivity worth is calculated). In FFTF, the flux monitors are located at core midplane in three different circumferential locations (120° apart). The GEMs were located away from the flux monitors in order to minimize measurement problems caused by varying GEM sodium levels. In DFBR, the flux monitors will be located below the core; this should eliminate any concern about varying GEM sodium level affecting the readings. JAPC requested a detailed assessment of the GEM reactivity worth measurement uncertainty; this was provided later in the meeting and the information is provided in the Specialists Meeting report.
3.2.5 Analysis of Zero Power Test of FFTF with GEM

Summary

The Japanese modeling of the FFTF zero power GEM worth tests was described in this session. It should be noted that all of the analyses use the measured FFTF GEM reactivity data and apply them using the Japanese GEM thermal-hydraulic numerical model. The thermal-hydraulic model is generally consistent with but more detailed than the model used at FFTF and the calculated steady state GEM sodium levels appear to be essentially the same as those calculated at FFTF. In order to establish an appropriate heat transfer coefficient between the GEM duct and gas (for use in the transient calculations), both a literature search and a set of experiments were performed for JAPC by General Electric. Initial transient GEM calculations were performed using the "bounding correlation" developed from this work. However, in order to accurately match the measured FFTF data, the heat transfer coefficient had to be increased by about a factor of five over the bounding value (to a value of approximately 4 BTU/hr/ft²/°F). The remaining small differences between the measured and calculated reactivity responses could be virtually eliminated by a small adjustment in the GEM gas loading condition.

Discussion

As stated above, the Japanese and FFTF steady-state models appear to be consistent with one another. The Japanese transient model is much more detailed than the FFTF model in that it accounts for the temperature gradient through the sodium and duct walls surrounding the GEM and adjacent fuel assemblies. In FFTF, these gradients were expected to be very small and were assumed to be zero. The excellent match between the FFTF measurements and the Japanese model provide validation of the model. It should be noted that the parameter adjusted to achieve the final good agreement between the measurements and calculations was the gas pressure at the time of the GEM loading. However, it is more likely that uncertainty in the temperature at the time of GEM loading is the cause of the difference. The required adjustment is well within the estimated uncertainty.

3.2.6 Loss of Flow Without Scram Tests at FFTF

Summary

This session began with a review of the history of the inherent safety philosophy in the United States. Following this history review, a simple quasi-static reactivity model was described that can be used to provide an approximate assessment of the transient behavior of FFTF (or any other reactor if the overall feedback behaviors are known). The remainder of the presentation described in detail the entire series of Loss of Flow Without Scram (LOFWOS) tests performed at the FFTF in 1986. After again reviewing the overall test sequence and "bootstrapping" technique, the special instrumentation used to monitor the test was described. The key instruments were fast response thermocouples located above the hottest assembly in the core (Row 2) and above a "typical"
assembly in the outer fueled region of the core (Row 6). These thermocouple assemblies were called fast response Proximity Instrumented Open Test Assemblies (PIOTAs). Following a brief review of the zero power GEM reactivity measurement results, the series of LOFWOS tests to both pony motor and natural circulation flow were described.

In the pony motor tests, an initial temperature peak was observed approximately fifteen seconds after pump main motor trip. The initial temperature increase occurs due to the flow decay prior to insertion of significant negative reactivity. The duration of the temperature increase (beyond the few seconds required for the GEM gas level to enter the high reactivity worth region near the top of the core) is due to the transport time of the coolant to the fast response PIOTA thermocouples which are located approximately five feet above the top of the core. Once the GEM gas level reaches the top of the core, power decreases more rapidly than flow for approximately the next twenty seconds so temperatures decrease. Between approximately thirty and forty-five seconds, flow again decreases more rapidly than power and temperatures again rise. As the pump reaches pony motor speed (approximately 10% of full speed, 45 seconds after pump main motor trip) and flow stabilizes, the temperatures begin to drop as power continues to decrease. For the lower power tests the second temperature peak is lower than the first while for the higher power tests the second peak is higher. The peak measured temperature (in the Row 2 PIOTA) was approximately 915°F compared to the established test limit of 992°F (set to limit the impact of the tests on fuel lifetime) and the pre-test prediction of approximately 980°F. Both the first and second peaks were considerably lower than predicted.

As expected, the first temperature peak in the tests to natural circulation flow was virtually identical to that in the corresponding test to pony motor flow. The second peak occurs much later (1-1/2 to 3 minutes after pump trip) and is always higher than the first peak. This second peak is associated with the transition to natural circulation flow (pump coastdown from full speed to zero speed requires approximately 100 seconds). The variation in the timing of the second peak is primarily due to the varying natural circulation flow rate and the associated fluid transport time from the core to the monitoring thermocouples. The peak measured temperature (in the Row 2 PIOTA) was 944°F compared to the established test limit of 992°F and the pre-test prediction of 1136°F. It is believed that the main cause of the large discrepancy between measured and predicted values in the natural circulation tests is the lack of consideration of flow redistribution between assemblies in the single channel IANUS computer code that was used for the pre-test predictions.

A review of the measured power and flow for the tests shows that the calculated and measured flow rates agree quite well while the measured power is 10-20% lower than predicted at the time of peak temperature. For the test from 50% power to natural circulation, it is estimated that approximately one-third of the deviation between measured and predicted peak temperatures is due to the difference in powers while the other two-thirds is due to flow redistribution effects. The natural circulation test results also suggest that flow drops to essentially
zero in the outer row of fuel assemblies, perhaps because there is significant radial heat transfer to the relatively cool reflectors.

Extrapolation of the measured test results indicate that with nine GEMs in the FFTF, a LOFWOS event from full power to natural circulation would result in a peak temperature three to four hundred degrees Fahrenheit below sodium boiling. Without GEMs, the peak temperature is calculated to exceed sodium boiling within about twenty seconds of pump trip.

Discussion

The major conclusion and topic of discussion from this section was that the test results showed that the pre-test predictions were very conservative (measured peak temperatures were considerably lower than predicted). To a large extent, this is due to the lack of core flow redistribution effects in the pre-test (IANUS) predictions. However, the measured power level is also considerably lower than predicted. There has not been sufficient analysis of the test data to conclude whether this is due to under-predicting the GEM worth in these tests or whether it is due to variations between the calculated and actual magnitude of one or more of the other contributors to the total feedback. Doppler feedback is perhaps the most likely contributor because the others (e.g., radial expansion) may not be fast enough to contribute significantly (especially in the case of the first peak). Also, there appears to be positive feedback from one or more mechanism since the "maximum" negative reactivity observed (in the 50% test) is approximately $0.8$ compared to the zero power measured GEM worth of approximately $1.4$. It is expected that Doppler would be the main source of positive feedback in these tests. A question was raised about the possibility that the presence of GEMs could change the structural reactivity feedback characteristics. This is not considered likely in FFTF due to the small number of GEMs. However, this may need to be evaluated in the DFBR design which will have 60 GEMs.

3.2.7 Overview of Japanese Models (FFTF LOFWOS w/ GEM Test Analysis)

Summary

This presentation described the numerical model that is being developed by the JAPC representatives to analyze the FFTF Loss of Flow Without Scram tests. The setup of a typical model was described first. It included a primary/secondary heat transport loop model (to calculate loop flow rates and temperatures), a multi-channel reactor model (to calculate core temperatures and flow rates), and a reactor kinetics model (to calculate reactivity feedbacks and power level). Their model setup appears to be quite similar to the SASSYS model developed at FFTF to do post-test analyses of the LOFWOS tests. The Japanese model presented included five core channels, a GEM channel and a bypass channel (specific channels can be selected depending on the purpose of the model). The reactor and loop model details presented look reasonable. However, for analysis of the FFTF LOFWOS tests, modeling of the loop will not be performed. The core model will simply be driven with the measured loop flow rate and reactor inlet temperature. The plan presented was to analyze only the test from 50% power to pony motor
flow. Calculated results for the PIOTA outlet temperatures, reactor power and net reactivity will be compared to the measured values in order to validate the model. Additional information required to complete the model was requested from FFTF. This includes additional geometric data, the core inlet temperature and the reactor decay heat as a function of time. This data was provided by DOE in late December, 1996.

Discussion

The analytical model described, including the selection of core channels, appears to be appropriate. However, based upon a more detailed review of the information performed subsequent to the meeting, DOE representatives suggested that an unheated bypass channel be added. This will represent the flow through non-core regions of the reactor vessel such as the in-vessel storage modules and reactor vessel thermal liner. As provided in the data previously sent to JAPC, this flow is calculated to be approximately 7% of the total loop flow. The plan to drive the model with the measured loop flow rate and inlet temperature is also appropriate. As stated in the meeting, for all tests the reactor inlet temperature was essentially constant at 600°F, at least through the first several minutes of the test.

It was stated that the calculation would be carried out to only 50 seconds. However, following considerable discussion, it was agreed that the calculation should probably be carried out past the second temperature peak (approximately 60 seconds) since the flow (and thus GEM sodium level) continues to change until approximately this time and comparison of the measured and predicted second peaks may provide additional insights. JAPC also stated that radial expansion, bowing and control rod expansion reactivity effects would not be included due to the long (1-1/2 to 3 minute) time constants associated with them. However, it was pointed out that even with these relatively long time constants, these feedbacks could contribute to the core behavior (because they are first order time constants, not time delays). Furthermore, it was suggested that the time constant for radial expansion be varied between one and three minutes (the three minute time constant quoted is a conservative value, suggested for use in safety analyses).

It was also suggested that JAPC consider analyzing two additional cases, a zero power test and a 10% power LOFWOS test. The impact of other reactivity feedbacks will be much smaller in these tests than in the test from 50% power and thus it should be much easier to compare measured and predicted GEM reactivity effects.

3.2.8 Overview of LOFWOS Post-Test Analyses

Summary

The contents of the report describing the analysis of the Fast Flux Test Facility passive safety tests using the SASSYS code were reviewed briefly (this report is not included in the current contract between DOE and JAPC). This report documents the comparison of post-test analyses
performed with the SASSYS code to both the measured data and the pre-test IANUS analyses. The SASSYS code was being developed by the Argonne National Laboratory for use in the United States' national liquid metal reactor program. It incorporates a great deal of flexibility, allowing it to be applied to a variety of plant and core designs, and allows for modelling the core with multiple channels. Due to difficulties found in analyzing the FFTF LOFWOS tests, it was decided to bypass some of the SASSYS models and utilize FFTF data or models (for example, decay power calculations and reactivity feedback models). Other modelling changes were implemented to more accurately reproduce the FFTF characteristics (e.g., fuel temperatures and flow coastdown). The resulting analyses showed better agreement with the measured data than was found with the IANUS code. However, there are still some differences that could perhaps be reduced with further work.

Discussion

The information presented in this report provides additional understanding and interpretation of the test results and may be of value in the development of other models used to analyze the tests. It was pointed out that in addition to selected LOFWOS tests, the report also includes a discussion and analysis of the LOFWOS "precursor" tests: the Delayed Pony Motor Trip Test (transition to natural circulation from near-isothermal conditions) and the Steady State Natural Circulation Test (reactor operation at several percent power with natural circulation flow). JAPC has decided that they are not currently interested in obtaining this report.

3.2.9 Overview of Pump Restart Tests

Summary

The final presentation reviewed the report describing the FFTF pump start with GEMS test. Again, this report is not included in the current contract between DOE and JAPC. The pump restart tests were performed in 1991 in support of the design and licensing of the General Electric PRISM reactor. The purpose was to demonstrate the relatively benign behavior that would occur in response to a reactivity insertion event caused by an inadvertent start of the primary pumps with GEMS in the core. In order to avoid the necessity of reconfiguring the plant protection system for these tests, only three GEMS were included (compared to nine in the LOFWOS tests). The initial test was performed from a relatively low initial reactivity ($0.38 subcritical) and reached a final power level of approximately 3%. The final test was performed with an initial subcriticality of $0.21 and reached a final power level of approximately 9%. In all cases, the transient was well behaved and agreed well with pre-test predictions (performed with the SASSYS code).

Discussion

These test results are considered valuable for two reasons: they demonstrate the benign response to a potential accident initiator (a potential safety/licensing issue for a core utilizing GEMS) and they provide additional data (of a somewhat different nature than the LOFWOS
tests) that can be used for additional validation of analytical methods. JAPC and DOE are negotiating a modification to the existing contract to include providing this report.

4.0 SUMMARY MEETING HELD IN JAPAN

A summary of the JAPC/FFTF GEM technology exchange was presented by T.M. Burke (B&W Hanford Company) and D.M. Lucoff (Fluor Daniel Hanford, Inc.) at the offices of the Japan Atomic Power Company in Tokyo, Japan, on February 3, 1997. The meeting attendance is provided in Appendix B. The presentation material covered four main topics (the presentation material used is presented in Appendix C):

- Introductory information including the organization and responsibilities of the Hanford contractors, the history and status of the FFTF and the background of the JAPC/FFTF GEM technology exchange contract
- The development and design of the GEMs at the FFTF
- A summary of the GEM Specialists meeting held at Hanford in December of 1996

There were few questions asked during or following the presentations. The only two of significance were the following:

- What is the explanation for the 18 cent discrepancy between measured and predicted reactivity in the Loss of Flow Without Scram (LOFWOS) test from 50% power to natural circulation flow?

  Two possible contributions to the discrepancy were discussed. First, the GEM reactivity appears to increase as the initial power level is raised. This is perhaps due to the reduction in the zero flow GEM sodium level (to greater distances below the bottom of the core) at the increased temperatures; there is some GEM reactivity worth in this region. Secondly, the reactivity coefficients for other feedback mechanisms (e.g., Doppler and radial expansion) were developed from quasi-steady measurements but are applied to the transient calculations. There may be dynamic effects that are not accounted for.

- Are we sure that the fuel assembly under the Row 2 PIOTA was the hottest assembly?

  It was explained that the core loading was specifically developed to assure that the hottest assembly was indeed located under the Row 2 PIOTA (core location 3202). The assembly in this location during the GEM testing was a fresh fuel assembly. In addition, the presence of the PIOTA reduces the flow slightly relative to assemblies without the PIOTA. Although other assemblies near the center of the core are also quite hot, they will not be as hot as the fresh assembly located beneath the Row 2 PIOTA.
It was originally planned that a second meeting would be held during this trip in order to continue more detailed discussions on the JAPC efforts to perform calculations of the FFTF LOFWOS tests. However, this meeting was canceled because JAPC had not made as much progress as planned on these calculations since the time of their visit to Hanford in December. According to JAPC, there is no need to reschedule the second meeting.

5.0 ADDITIONAL INFORMATION PROVIDED TO JAPC BY DOE

Prior to and during the GEM Specialists Meeting, the JAPC representatives asked a number of questions related to the design and testing of the GEMs at FFTF. The subjects of these questions included more detailed description of the FFTF GEMS, details of the FFTF core design and clarification of information included in the GEM reports. Responses to these questions were provided in a series of letters from FFTF/DOE to JAPC. In addition to the responses documented in these letters, the following questions were answered during the GEM Specialists Meeting:

- How were the fuel-to-cladding gap contact resistances specified in the FFTF LOFWOS report obtained?

  They were derived from calculations performed with more detailed FFTF fuel performance codes (e.g., SIEX).

- Is the gap resistance for the core average?

  Yes.

- Was the same gap resistance employed for the evaluation of Doppler feedback and evaluation of coolant temperature?

  Yes (the IANUS code models only a single average channel and fuel pin).

- Was the same approach used in the post-test analysis?

  No. The post-test analyses were performed with the SASSYS code and the fuel pin performance models incorporated in the SASSYS code were used. However, the SASSYS model parameters were adjusted to achieve reasonable agreement with the predicted temperatures from the FFTF fuel performance codes.

- What temperature should be used in the calculation of control rod expansion (both control rod drive line and reactor vessel components)?

  The core average outlet temperature should be used for both components. Although this may not be the actual temperature experienced by the components, this is consistent with the development of the semi-empirical equations.
What is the flow rate in the gap between fuel assemblies and reflector assemblies?

The flow rate in the gaps between assemblies is essentially zero. It is also expected that even if there is a very small flow rate, it will have an insignificant effect on the calculated core behavior (this could be evaluated by varying the value in the model).

6.0 SUMMARY

The workscope identified in the original contract "Study on Improvement of Core Safety - Study on GEM(III)" between JAPC and DOE has been completed. This workscope consisted of the transmittal of three reports related to testing of GEMs at FFTF, holding a GEM Specialists Meeting at Hanford, participating in a summary meeting in Tokyo, providing additional information related to GEM development and testing at FFTF, and issuing this final report.

With the information provided by DOE, JAPC can develop and validate their models for predicting GEM performance in the DFRBR core. JAPC modelling efforts to date have been reviewed by DOE representatives and the models appear to be appropriate and in general more detailed than the models developed and used at FFTF. The DOE representatives were very impressed with the agreement achieved between the JAPC models and the FFTF data.

Negotiations related to the potential modification of the subject contract between DOE and JAPC are in progress. Under the proposed contract modification, DOE would provide an additional report documenting FFTF pump start tests with GEMs and answer additional JAPC questions related to core safety with and without GEMs.
APPENDIX C
PRESENTATION MATERIAL FROM SUMMARY MEETING
February 3, 1997
Summary of JAPC/FFTF GEM Technology Exchange Presented to Japanese Electric Power Companies

T. M. Burke
B&W Hanford Company

D. M. Lucoff
Fluor Daniel Hanford

Date Published
January 1997

To Be Presented at
JAPC/FFTF GEM Technology Exchange
Tokyo, Japan
February 3, 1997

Prepared for the U.S. Department of Energy
Office of Nuclear Energy, Science and Technology

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DISCLM-2.CHP (1-91)
SUMMARY OF JAPC/FFTF GEM TECHNOLOGY EXCHANGE PRESENTED TO JAPANESE ELECTRIC POWER COMPANIES

February 3, 1997

Thomas M. Burke - B&W Hanford Company
David M. Lucoff - Fluor Daniel Hanford, Inc.
PRESENTATION CONTENTS

- Introduction
  - Hanford organizations
  - FFTF history and status
  - JAPC/FFTF GEM technology contract
- GEM design at the FFTF
- GEM testing at the FFTF
- Summary of JAPC/FFTF GEM Specialists Meeting
INTRODUCTION
PROJECT HANFORD MANAGEMENT CONTRACTORS

PHMC Subcontractors

B&W HANFORD COMPANY
- Facility Stabilization
- Includes: Process Facilities and FFTF

DE&S HANFORD, INC.
- Spent Nuclear Fuel

LOCKHEED MARTIN HANFORD CORPORATION
- Tank Waste Remediation

NUMATEC HANFORD CORPORATION
- Technology Implementation
- Nuclear Engineering

RUST FEDERAL SERVICES OF HANFORD
- Waste Treatment/Disposal

DYNCORP TRI-CITIES SERVICES, INC.
- Site Infrastructure
- Emergency Preparedness

Enterprise Companies

FLUOR DANIEL HANFORD, INC.
- PHMC Prime Contractor
- Management and Integration
- Ultimate Responsibility

B&W PROTEC, INC.
- Safeguards and Security

DE&S NORTHWEST, INC.
- Quality Assurance Service

LOCKHEED MARTIN SERVICES, INC.
- Records Management
- Computer Support

SGN EURISYS SERVICES CORPORATION

RUST FEDERAL SERVICES, INC.
- Air and Groundwater Sampling and Modeling

FLUOR DANIEL NORTHEAST, INC.
- Engineering
- Construction
FAST FLUX TEST FACILITY - HISTORY & STATUS

- Originally designed & operated to develop LMFBR fuels and materials
- Design/construction completed in late 1970’s
- Initial criticality achieved in early 1980
- U.S. LMFBR program was de-emphasized in early 1980’s
- FFTF operation continues with multiple missions
  - International LMFBR development
  - U.S. LMR Safety
  - Fusion program support
  - Space power
  - Medical isotope production
FFTTF HISTORY & STATUS - CONTINUED


- Current FFTTF status:
  - All fuel removed from reactor vessel in 1994
  - Fuel washing and dry cask loading in progress
  - Ready to initiate drain of sodium in 1995 but placed on hold

- DOE evaluating potential future missions
  - Tritium production
  - Medical isotopes
JAPC/FFTF GEM TECHNOLOGY CONTRACT

- Provide three reports (GEM Test Design Descriptions and LOFWOS Test Report)
- GEM Specialists Meeting at Hanford (December 3-5, 1996) (including questions/answers and review of JAPC analyses)
- Summary presentations at Japanese utility meeting
- Issue reports documenting above meetings

Assist JAPC in developing/verifying ability to predict GEM (and core) behavior under Loss Of Flow Without Scram conditions
GEM DESIGN AT THE FFTF
INTRODUCTION

• FFTF was originally designed/constructed/operated to develop LMFBR fuels and materials

• Inherent safety became a major focus of the US nuclear industry in the mid 1980’s

• The inherent safety characteristics of LMFBRs were recognized but additional enhancement was desired
FFTF INHERENT SAFETY TESTING PROGRAM
FFTF UNPROTECTED PUMP COASTDOWN

INITIATED FROM FULL POWER

(100% POWER)

PEAK CHANNEL SODIUM TEMPERATURE (°F)

TIME FROM INITIATION OF EVENT (SECONDS)

SODIUM BOILING
W/O ENHANCEMENT DEVICE(S)

WITH ENHANCEMENT DEVICE(S)

SHUTDOWN REACTIVITY ASSOCIATED WITH ENHANCEMENT DEVICE(S)

1$
2$

1670
1100
GEM (Gas Expansion Module)
Assembly in First Radial Blanket Row

- Inert Gas
- Liquid Sodium

Neutron Core

Pumps On

Increased Neutron Loss → Shutdown

Pumps Off
FFTF GEM DESIGN GOALS

- Develop concept for reducing consequences of Loss of Flow Without Scram transient

- Design, fabricate, and test device in short time period at low cost

- Perform tests at significant power level (up to 50% power, 200 MWt)

- Limit sodium temperatures during tests to normal operating values
FFT F GEM DESIGN/TESTING SEQUENCE

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<thead>
<tr>
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<tbody>
<tr>
<td>Concept Proposed</td>
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<tr>
<td>Scoping Analyses</td>
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<td>Design/Fabrication</td>
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<td>Zero Power Tests</td>
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<tr>
<td>&quot;Precursor&quot; N.C. Tests</td>
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<td>LOFWOS Tests</td>
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<tr>
<td>Pump Restart Tests</td>
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</tr>
</tbody>
</table>
GEM PHYSICAL ARRANGEMENT

- Shield Plug
- Gas Space
- Standard Inlet Nozzle
- Handling Socket
- Top of Expansion Volume
- Lower Shield
- Flow Inlet Holes
GEM THERMAL-HYDRAULIC DESIGN CONSIDERATIONS

- Achieve maximum feedback effect
  - GEM sodium level above core @ full flow
  - GEM sodium level below core @ zero flow
- Avoid reactivity/power fluctuations
  - Full flow GEM sodium level ~1 foot above top of core
- Avoid loss of gas during normal operation
CALCULATED GEM SODIUM LEVEL vs. PLANT CONDITIONS

- **210°C, 100% FLOW = 233 cm**
- **316°C, 100% FLOW = 226 cm**
- **FULL POWER AND FLOW = 215 cm**
- **210°C, 10% FLOW (REFUELING) = 107 cm**
- **316°C, 10% FLOW = 74 cm**
- **10% FLOW, FULL POWER TEMPERATURE = 0 cm**

HEIGHT ABOVE INLET SLOTS, cm

SODIUM LEVEL
Calculated GEM Level Response Versus Heat Transfer Coefficient

Inches Above Bottom of Core

Top of Core

H=0

H=10

Bottom of Core

Seconds After Pump Trip

H=0

H=1

H=2

H=5

H=10

BTU/hr/ft²/F

(H=3 BTU/hr/ft²/F used in pre-test analyses)
GEM REACTIVITY WORTH

Predicted GEM Worth (9 Assemblies in Row 7)

3-D Diffusion Theory

12 Groups, ENDF/B-V2
Triangular Mesh, 6 Points Per Core Assembly
Structure and Sodium Homogenized

Worth/Assembly = -0.17 $

Monte Carlo

Fuel Assembly Detail
Worth/Assembly = -0.18 $
GEM TESTING AT THE FFTF
ZERO POWER PHYSICS TEST
GEM CONFIGURATION

FFTF

CORE REGION
REFLECTOR REGION
GEM GAS EXPANSION MODULE
CR CONTROL ROD
SR SAFETY ROD
LLFM LOW LEVEL FLUX MONITORS
(LOCATIONS NOT TO SCALE)
SUMMARY OF GEM REACTIVITY WORTH MEASUREMENTS

- PUMPS ON/PUMPS OFF WORTH
  - $-0.15$ per GEM @ 440°F
  - $-0.16$ per GEM @ 600°F

- REFLECTOR REPLACEMENT WORTH
  - $-0.13$ per GEM @ 440°F

- COMPARISON WITH PRE-MEASUREMENT CALCULATION
  - 3D DIFFUSION THEORY (400°F) $-0.17$ per GEM
  - MONTE CARLO (HOT) $-0.18$ to $-0.20$ per GEM

---

Graph showing FFTF Cycle S8B reactivity change over time from pump trip. The measured reactivity starts at $-1.35$ at 440°F and decreases over time.
# WORTH MEASUREMENTS

## REPEATABLE (NO GAS LOSS)

<table>
<thead>
<tr>
<th>Date</th>
<th>Worth ($)</th>
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<tbody>
<tr>
<td>6/30/86</td>
<td>1.40</td>
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<tr>
<td>7/02/86</td>
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<tr>
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<tr>
<td>7/17/86</td>
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</table>
LOF/WOS TO PONY MOTOR
ROW 2 ASSEMBLY OUTLET TEMPERATURE

TEST LIMIT - 992°F

TIME IN SECONDS

TEMPERATURE IN DEGREES F

50%
40%
30%
20%
10%
LOF/WOS TO NATURAL CIRCULATION
ROW 2 ASSEMBLY OUTLET TEMPERATURE

TEST LIMIT – 992°F
COMPUTER ANALYSIS CODES

- Pre-test analysis performed with IANUS
  - IANUS is a Westinghouse proprietary systems analysis code developed to specifically model the FFTF
  - Many models/correlations in IANUS were calibrated to component/system test results
  - IANUS uses a single channel model of the core with specified “Hot Channel Factors”
  - Hot Channel Factor to account for flow redistribution was not included in the pre-test analyses
Post-test analysis performed with SASSYS

- SASSYS developed by Argonne National Laboratory for the US National LMR Program
- SASSYS incorporates multi-channel modeling of core with flow redistribution between channels
- SASSYS includes many options to allow application to a wide range of plant/core designs
- SASSYS models required calibration to FFTF data (e.g., fuel temperatures and flow coastdown)
Fig. 7. Temperature at core location 3202 for LOFWOS from 50% power to natural circulation flow.
PRELIMINARY DATA EVALUATION 50% LOF/WOS TO NATURAL CIRCULATION WITH GEMs

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>EVALUATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Row 2 outlet temperature</td>
<td>Measured peak temperature approximately 944°F versus 1136°F predicted</td>
</tr>
<tr>
<td>Total reactor flow</td>
<td>Good agreement - no significant contribution to discrepancy in outlet temperature</td>
</tr>
<tr>
<td>Total reactor power</td>
<td>Measured value 10-20% less than predicted value near time of peak temperature. Results in 50-100°F reduction in row 2 outlet temperature. Most likely due to uncertainty in reactivity feedbacks during transient</td>
</tr>
<tr>
<td>Core flow redistribution</td>
<td>Predictions assumed no core flow redistribution. Hot channel factor curves would predict 20-30% (100-150°F) reduction in hot assembly ΔT. Preliminary multi-channel analyses indicate similar reduction</td>
</tr>
<tr>
<td>Radial heat transfer</td>
<td>Not included in predictions. Probably small direct effect for central assemblies. May be important at core periphery with resulting impact on core flow distribution</td>
</tr>
</tbody>
</table>
9 GEMS in FFTF will provide significant margin to boiling for LOFWOS event
LOSWOS WITH GEMs - CONCLUSIONS

- 13 tests conducted
  - Power level: 40 MW - 200 MW (10%-50%)
  - Cooling mode: pony motors and natural circulation
- Peak sodium temperatures were lower than predicted
  - For most aggressive test (50% power/100% flow to nat. circ.)
    Peak sodium temperature W/O GEM (predicted)... 1670°F (boiling)
    Peak sodium temperature W/GEM (predicted)... 1136°F
    Peak sodium temperature W/GEM (measured)... 944°F
- GEM functioned as predicted
  - Nine GEMs tested 30 times
- The GEM is a viable device for safely terminating a LOFWOS event in an LMR
SUMMARY OF JAPC/FFTF
GEM SPECIALISTS MEETING
OBJECTIVES

- Discuss FFTF GEM design/testing program
  - Provide additional information & understanding
- Review JAPC modeling of FFTF GEM tests

Assist JAPC in developing/verifying ability to predict GEM (and core) behavior under Loss Of Flow Without Scram conditions
GEM SPECIALISTS MEETING ATTENDEES

Japan

Mari Uematsu (Japan Atomic Power Company, Ltd.)
Yoshiyuki Okubo (Mitsubishi Heavy Industries, Ltd.)
Yoshiaki Sakashita (Toshiba, Ltd.)
Takanobu Kamei (FBR Engineering Company, Ltd.)
Hiroshi Hanaki (Hitachi, Ltd.)

United States

Rod Almquist (U.S. DOE)  Bob Beach (BWHC)
Tom Burke (BWHC)         Larry Campbell (DynCorp)
Eldon Cramer (LMHC)      Ken Dobbin (FDN)
Sandi Gilchrist (BWHC)   Fred Heard (LMHC)
Dick Harris (BWHC)       Dave Lucoff (FDH)
Joe Nelson (FDN)         Jim Waldo (BWHC)
AGENDA FOR JAPC/FFTF GEM SPECIALISTS MEETING
December 3-5, 1996

Tuesday, December 3:
- Welcome/Introduction/Agenda/Format  Burke
- Overview of GEM Development and Testing at FFTF  Burke
- GEM Mechanical/T&H Design and GEM Loading  Burke
- Zero Power Calculation of GEM Reactivity Worth in FFTF  Nelson
- Subcritical GEM Worth Measurements  Campbell

LUNCH

- Analysis of Zero Power Test of FFTF with GEM  Okubo
- Summarize Day 1 Discussions  All

DINNER

Wednesday, December 4:
- Overview of LOFWOS Tests  Lucoff
- Overview of Japanese Models  Sakashita
  (FFTF LOF/WOS with GEM Test Analysis)
- Discussion of JAPC Questions and Open Discussion  All

LUNCH

- Overview of LOFWOS Post-Test Analyses with SASSYS  Burke
- Overview of Pump start Transients with GEMs  Campbell
- Summarize Day 2 Discussions  All

Thursday, December 5:
- Tour of FFTF  Burke

Return Visitors to Hotel by Noon
**FFTF LOF/WOS with GEM Test Analysis (2)**

*This investigation was conducted as a part of the Japanese DFBR Development Project under the sponsorship of the nine Japanese electric power companies, the Electric Power Development Co. Ltd. and the Japan Atomic Power Company.*

**Momentum Equation**
\[
\text{gas} \uparrow \quad \text{plenum pressure} \quad \downarrow \quad \text{sodium}
\]

- **duct to gas heat transfer coefficient**
- **atmospheric GEM test result**
- **FFTF zero power test result**
- **inter-SA sodium to duct, and**
- **duct to sodium heat transfer coefficient**
- **Subbotin's equation**

**GEM Reactivity**
- determined by GEM sodium level
- GEM worth and axial profile by table input
Gas charging condition:
300°F, 14.9 psia

Reactivity vs Time  Case 1

Calculation
Experiment

440°F (227°C)  Reference

Reactivity vs Time  Case 2

Calculation
Experiment

440°F (227°C)  Ref. × 5
REVIEW OF JAPC MODEL OF FFTF ZERO POWER GEM TESTS

- JAPC steady-state model consistent with U.S. model
  - Perfect gas law
  - Calculated GEM levels appear consistent
- JAPC transient model much more detailed than FFTF model
- Heat transfer coefficient required to match test results is reasonable
  - Comparable to value estimated by FFTF
  - Consistent with General Electric feature tests
- Minor adjustment in GEM gas loading conditions gives excellent agreement with measurements
FFTF LOF/WOS with GEM Test Analysis (2)

calculation model (2) - multichannel model

Average Core PIOTA 1 PIOTA 2 Adjacent fuel SA GEM Adjacent Reflector

Input: measured core coolant flow Flow (t)

Primary loop is not considered for lack of plant data
Planned modeling of core only is appropriate
  - Model to be driven with measured flow rate
Selection of core channels is reasonable
  - Core bypass channels should be included
Other reactivity feedbacks should be included
Additional information was requested to complete the model
MEETING ACTION ITEMS

Provide additional information

- Calculated decay heat for LOFWOS tests
- Cycle 8C axial power distribution
- Fuel assembly, control rod and reflector design details
- Fuel thermal conductivity
- Components of GEM worth measurement uncertainty

Issue meeting report (completed 12/31/96)
GEM SPECIALISTS MEETING
RESULTS/CONCLUSIONS

- JAPC Technical Team found information/discussion very valuable
- JAPC Technical Team have developed excellent model of GEM thermal-hydraulic behavior
  - More detailed than FFTF model
  - Excellent agreement achieved with FFTF zero power tests
- JAPC Technical Team methods of GEM worth calculation consistent with FFTF modeling
- JAPC Technical Team multi-channel core model for LOFWOS analyses is appropriate
- Additional information required was identified and provided