SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

NEDE-32906P, "TRACG APPLICATION FOR ANTICIPATED OPERATIONAL

OCCURRENCES (AOO) TRANSIENT ANALYSES"

GE NUCLEAR ENERGY

PROJECT NO. 710

1.0 INTRODUCTION

General Electric Nuclear Energy (GENE) and its subsidiary Global Nuclear Fuel (GNF) submitted TRACG02A (referred to hereafter as TRACG) for NRC review for application to anticipated operational occurrence (AOO) transient events on January 25, 2000 (Reference 1). The submittal includes the code model documents related to the TRACG code (Reference 2). The TRACG code is a thermal/hydraulic analysis code intended to be used in a realistic analysis mode. The approach taken by GENE in the proposed application is to qualify the code under the code scaling, applicability, and uncertainty (CSAU) evaluation methodology (References 3 and 4), rather than the conservative approach of the past.

The TRAC family of codes began as a pressurized water reactor analysis code developed for the NRC at Los Alamos National Laboratory. A boiling water reactor (BWR) version of the code was developed jointly by the NRC and GENE at the Idaho National Engineering Laboratory (INEL) as TRAC-BD1/MOD1 (Reference 5). GENE developed a proprietary version of the code designated as TRACG. The objective of the proprietary code development was to have a code capable of realistic analysis of transient, stability, and anticipated transients without scram (ATWS) events. The code was modified to include a three-dimensional kinetics capability in addition to the multi-dimensional, two-fluid thermal-hydraulics modeling.

The plant types for which the TRACG code is to be applied include the BWR/2s, BWR/3s, BWR/4s, BWR/5s, and BWR/6s. The code has not been submitted for review for application to any other plant design.

2.0 CODE APPLICABILITY

TRACG is a multi-dimensional, two-fluid reactor thermal-hydraulics analysis code with three-dimensional neutron kinetics capability. The code is designed to perform in a realistic manner with conservatism added, where appropriate, via the input specifications.

Table 1 - Applicable Standard Review Plan (SRP) Chapter 15 Events

Event	SRP No.
15.1 - Increase in Heat Removal by the Secondary System	
Decrease in Feedwater Flow	15.1.1
Increase in Feedwater Flow	15.1.2
Increase in Steam Flow	15.1.3
Inadvertent Opening of Steam Generator Relief/Safety Valve	15.1.4
15.2 - Decrease in Heat Removal by Secondary System	
Loss of External Load (LOEL)	15.2.1
Turbine Trip (TT)	15.2.2
Loss of Condenser Vacuum	15.2.3
Closure of Main Steam Isolation Valve (BWR)	15.2.4
Steam Pressure Regulator Failure (closed)	15.2.5
Loss of Non-Emergency AC Power to the Station Auxiliaries	15.2.6
Loss of Normal Feedwater Flow	15.2.7
15.3 - Decrease in Reactor Coolant Flow Rate	
Loss of Forced Reactor Coolant Flow (LOCF)	15.3.1
Flow Controller Malfunction	15.3.2
15.4 - Reactivity and Power Distribution Anomalies	
Startup of an Inactive, or Recirculation, Loop at an Incorrect Temperature	15.4.4
Flow Controller Malfunction Causing an Increase in BWR Core Flow Rate	15.4.5
15.5 - Increase in Reactor Coolant Inventory	
Inadvertent Operation of Emergency Core Cooling System (ECCS) that Increases Reactor Coolant Inventory	15.5.1
Chemical Volume Control System (CVCS) Malfunction that Increases Reactor Coolant Inventory	15.5.2
15.6 - Decrease in Reactor Coolant Inventory	
Inadvertent Opening of a PWR Pressurizer Relief Valve or a BWR Pressure Relief Valve	15.6.1

The current application of the TRACG code does not include transients involving stability analysis.

3.0 STAFF APPROACH TO REVIEW

The staff performed an extensive review of the TRACG code for application to the loss-of-coolant accident (LOCA) during the course of the simplified boiling water reactor (SBWR) review. At that time the code was examined carefully with regards to the thermal-hydraulic construction of the code. For the application to the AOO transients, the staff has built upon the previous review. The most intense review for the AOO transients was performed in the areas of kinetics and statistical analysis. The staff does note that a significant addition has been made to the thermal-hydraulic field equations in the addition of kinetic energy to the equations.

In the early stages of the review, the staff issued two draft documents (References 6 and 7) for public comment. The draft Regulatory Guide and draft Standard Review Plan outline the approach and guidance the staff is using in the review of thermal-hydraulic analysis codes. In addition, the staff has stated its guidance for code uncertainty analysis in References 3 and 4. These four documents provide the basis under which the TRACG review has been conducted. In the course of the review, the staff developed a number of requests for additional information (Reference 8) and received responses from GENE (Reference 9).

As the review progressed, GENE and the staff held several meetings to discuss the application.

May 25, 1999 - preliminary information meeting
July 15, 1999 - preliminary information meeting
March 16, 2000 - detailed presentation of code methodology
September 11, 2000 - staff review concerns
November 13/14, 2000 - ACRS T/H Subcommittee
August 22, 2001 - ACRS T/H Subcommittee
September 6, 2001 - ACRS

4.0 CODE ASSESSMENT

Assessment of computer codes is normally performed by comparison of code results with data from appropriate test facilities. The assessment process involves comparisons with data obtained via phenomenological experiments, separate effects tests, component tests, integral system tests, and plant tests. Assessment of code capability should also include sensitivity studies of time step size and nodalization. Nodalization of test facilities is expected to be done in a manner consistent with the nodalization to be used in a full scale plant analysis.

The TRACG documentation (Reference 2) provides extensive description of the code assessment that has been performed. Each of the phenomena identified in the Phenomena Identification and Ranking Table (PIRT) is correlated against the tests, separate effects tests, component tests, integral system tests, and plant tests and plant data, for which there has been quantitative assessment performed. The assessment descriptions cover the test facility, where applicable, the test results, TRACG sensitivity studies and nodalization studies, where applicable. All medium and high ranked phenomena have been assessed.

The assessment that has been performed to support the intended application of TRACG to AOO transients is appropriate in that it includes assessment of phenomenological models with data from separate effects tests, the entire code with systems tests, and the entire code versus full scale operating plant data. The assessment program has shown the capability of the code to represent the experimental and operating data.

5.0 STAFF EVALUATION OF TRACG

5.1 Thermal-Hydraulics

TRACG uses a two-fluid model, with six conservation equations for both the liquid and gas phases along with phasic constituitive relations for closure. A boron transport equation and a noncondensible gas mass equation are also solved. The spatially discretized equations are solved by donor-cell differencing in staggered meshes in one, two, or three dimensions. A unified flow regime map is also used.

The two-phase level tracking model invokes some approximations for the void fraction above and below the mixture level that may not be accurate if significant voiding occurs below the mixture level. In addition, the model uses an arbitrary cutpoint, α_{cut}, for level detection. This is significant for LOCAs, rather than the current application of TRACG, AOO transients, since they are not expected to result in significant void formation beyond that which is normal for BWR operation. Should significant voiding occur, such as in the case of a LOCA, the two-phase level tracking model will be reevaluated by the staff.

The TRAC-B code from which TRACG was derived had eliminated the kinetic energy term from the energy equations by algebraic manipulations. The kinetic energy term has been retained in TRACG to avoid the energy balance errors that occurred in the TRAC-B codes due to nonconservation of energy.

The two-fluid conservation equations contain a mixing term to account for turbulent mixing and molecular diffusion. This is a good addition which the staff accepts due to the acceptable qualitative results, but notes that the mixing model is qualitative and lacks experimental data necessary for validation. While there is a lack of direct experimental data for assessment, the overall performance of the model versus the more global data which do exist is acceptable.

TRACG solves the heat conduction equation for the fuel rods in cylindrical geometry and for structural materials in slab geometry. The latter case uses either a lumped slab model or a one-dimensional slab model. A strength of the TRACG heat conduction model is the sophisticated gap conductance model and the implicit solution method that couples implicitly the heat transfer between the fuel rod and the coolant by iteration. Although TRACG solves the heat conduction equations in only one-dimension, it does account for axial conduction by means of a correlation developed from two-dimensional (r,z) parametric calculations of the heat conduction in a fuel element. This is only important in modeling quenching or reflood in the core in a LOCA.

The TRACG code has had the GEXL heat transfer correlation installed. The GEXL correlation development is independent of the TRACG development. During the week of March 26, 2001, the NRC staff visited the GENE facility at Wilmington, North Carolina, as part of the review of the power uprate for Duane Arnold to audit material pertinent to the licensee’s power uprate.

Material reviewed included the data base used for the development of the GEXL14 correlation for the GE14 fuel, analyses of ATWS event, and LOCA related analyses. In the early stages of the audit, the staff discovered that GENE was using data generated by the computer code COBRAG, instead of experimental data obtained from their CHF test facility in San Jose, California. The use of artificial data instead of raw data called into question the validity of the statistical results obtained from this methodology. The statistical results are important because they are used to establish the validity of the minimum critical power ratio (MCPR) safety limit. GENE has proposed to resolve this issue by agreeing to remove the COBRAG reliance and recalculating the uncertainty associated with the development of GEXL14 correlation. GENE will then submit this re-calculation of the correlation uncertainty for staff review. GENE has not indicated whether it will submit the COBRAG code for staff review, nor has GENE indicated whether it intends to obtain additional data to complete their data base for the GE14 fuel in the future. Based on this ongoing review of the correlation, the staff concludes that it is acceptable to use the GEXL14 correlation in TRACG, provided that when the NRC approves the critical boiling length correlation uncertainty, that same uncertainty is also applied in use of TRACG.

The thermal-hydraulic models are acceptable for the intended application to AOO transients.

5.2 Component Models

TRACG uses basic component models as building blocks to construct physical models for intended applications. This provides a general and flexible tool to simulate a wide variety of systems. The components modeled include the pipe, pump, valve, tee, channel, jet pump, steam separator, steam dryer, vessel, upper plenum, heat exchanger, and break and fill as boundary conditions. The code is limited in that the heat exchanger contains simplifying approximations which may not be appropriate for simulating the isolation condenser or the condenser in the balance of plant. Should the code be applied to transients requiring a condenser, a separate model will be needed or the ability to adequately model the condenser must be demonstrated.

TRACG uses a first-principle mechanistic model for the steam separator. The model has been validated against full-scale performance test data for two-stage and three-stage steam separators. The important parameters that have been assessed are the pressure drop, carryunder and carryover which match the test data by means of correlation constants. The data base covers the applicable range for the intended AOO transients and the model is therefore acceptable.

5.3 Control Systems

TRACG uses control systems constructed by the user from 63 basic control block types. The types of control blocks available are sufficient to represent any control system. This allows both a flexible tool and flexible interface with the hydraulic component models. A wide variety of possible dynamic processes can be simulated with the control system models.

5.4 Numerics

The TRACG numerics represent a significant improvement over its predecessor, TRAC-BD1/MOD1. By default, TRACG uses a fully implicit integration for hydraulic equations and heat conduction equations, accomplished by a predictor-corrector iterative technique. The heat transfer coupling between the heat conduction and coolant hydraulics is also treated implicitly by an iterative technique. This implicit coupling is an improvement over explicit coupling since it is less prone to an error on the phase shift and amplitude in a thermally-induced oscillation. The coolant hydraulic solution has the option of an explicit integration for time-domain stability analyses where implicit integration may suppress real physical oscillations. The staff notes, however, that the current application of the code does not include stability analyses. TRACG was accepted in a limited way by the staff (Reference 10) as part of the detect and suppress solutions licensing basis methodology to define setpoints. Should the applicant want to apply the code to stability analyses beyond that limited approval, the staff will review the methodology for that purpose.

The control system equations are solved sequentially based on the order in which the control blocks are specified in the input. This makes it a potentially explicit integration scheme. If a feedback loop exists in the control system, an implicit solution of the control system equations is impossible. To make sure that the control system will be stable, TRACG uses a sufficiently small time step size (always less than or equal to the hydraulic time step size) to integrate the control system equations.

5.5 Neutron Kinetics

5.5.1 Model Description

The TRACG kinetics review focused on evaluating the derivation of the equations, their implementation in the code and using the code to predict several test problems. The derivation of the equations is discussed in chapter 9 of the Models and Correlations document (Reference 2). Starting with three group theory for the neutron flux, the model is simplified to a one group representation of the neutron flux. Delayed neutrons are modeled with a six group model and a five group model is available for decay heat. The flux model is then further simplified by imposing a quasi-static assumption which allows for the space and time dependence to be decoupled. This decomposition leads to an amplitude equation which is analogous to the point reactor kinetics equations and an equation for the shape function which is equivalent to the three-dimensional flux distribution.

Several auxiliary models are used to account for the affects of direct moderator heating, energy deposition in structural materials, and gamma smearing. Direct moderator heating accounts for prompt energy deposition in the fluid from neutron moderation and prompt gamma heating. This energy is then further subdivided into an in-channel and a bypass component. The in-channel component refers to energy deposited into the voided region inside the fuel channel and the bypass component is the energy deposited into the regions between the fuel channel. This model accounts for void effects for which the uncertainty and bias was quantified using the Monte Carlo Code for Neutron, Photon and Electron Transport (MCNP). Similarly, the uncertainty and bias in the fuel structure and gamma smearing modes were quantified using MCNP calculations.

The kinetics equations are solved using standard finite differencing techniques. Typically they are solved on a rectangular grid six inches square which is equivalent to the mean free path of a fast neutron. The calculation uses two governing time intervals; one in which only the amplitude equation is solved and one in which the shape function is updated. The shape function update is synchronized to the thermal-hydraulic time step and the amplitude function time step is deduced by applying extrapolation techniques and using a user input convergence criterion. The thermal-hydraulic time step is governed by the rate of change of many variables, one of which is the total power. If the system is changing too rapidly within a time step, the entire solution is returned to the previous time step value, the thermal-hydraulic time step is reduced and the procedure is repeated.

Lattice-averaged neutron cross sections in three energy groups are generated using GENE lattice physics methods. This information is fed into TRACG via the GENE three-dimensional steady state design code PANACEA which is used to define the TRACG initial condition. Cross sections are represented by functional fits over the expected range of density, square root of fuel temperature and boron concentration. The functional fits also account for the historical impacts due to water density and exposure. The density used in the fitting procedure is the "effective" nodal value which is a weighted average of the in-channel, water rod and bypass density. This model imposes the assumption that all neutrons behave similarly whether they slow down in the fuel or bypass region. The "effective" density model has no effect on the proposed application under review because for AOO analyses no significant water rod or bypass voiding (or density change) is expected. Therefore, the staff has not reviewed this model. This model would need to be re-considered and reviewed by the staff before TRACG was applied to ATWS analyses beyond previously accepted use for bench marking ODYN (Reference 11).

5.5.2 <u>Review of GNF Submittal</u>

The staff reviewed the TRACG kinetics model in three ways: first, the staff judged the written material presented in the Models and Correlations document, the Assessment Manual and responses to staff's RAIs; second, the staff reviewed the results from the assessments against experimental data; and, third, the staff completed a performance-based assessment of the code by evaluating its predictions to another set of results to a sample problem. The model was well developed from the three group diffusion theory model which was the assumed starting point. Although not currently widely used, the use of the factored one group diffusion theory model is well established and has been successfully applied in the past (Reference 12). The GNF factorization method is an extension of traditional quasi-static methods because the shape function is also a function of time. The cross-section formulation captures all of the relevant physics, and formulations such as those used in TRACG have been demonstrated by the Peach Bottom turbine trip benchmark study discussed in the Assessment Manual to be accurate enough to successfully model the small perturbations expected for AOO analyses. The auxiliary models for direct moderator heating, energy deposition in the structure and gamma smearing capture all of the relevant physics. It is difficult to assess each contribution separately because they will have a small effect on the predictions. However, based on the integral benchmarks presented in the Qualification document, these models are appropriate. One model which is not documented in the Models and Correlations manual, but is discussed in References 1 and 9, attempts to modify the lattice physics prediction of void reactivity based

upon MCNP calculations. Discussion of this model is contained in the next section where the performance-based review is discussed.

The decay heat model is predicated on the assumption that delayed neutron decay is exponential in nature. The fission precursors are grouped into five distinct bins each with a representative decay constant and fission fraction. The model for decay power for each "group" is then integrated using an exponential integrating factor. The model has a set of default or "built in" decay constants and fission fractions based on the May-Witt decay heat curves. This model used in its default mode has the ability to model decay power either as an average of different fuel types similar to the ANS 5.1 model or it can capture the detailed spectral effects on decay heat by overriding the default values and using fuel specific decay constants and fission fractions. The default parameters have been shown to be acceptable for AOO analyses by comparing the results to the latest ANS 5.1 standard.

The solution procedure leverages the factorization concept by solving the amplitude and shape function equations on a different temporal grid. Each governing time step is chosen by the code based on logic which is controlled by user input convergence criteria. This model is best reviewed by evaluating its ability to model experimental data representative of the expected application and sensitivity studies. Time step and sensitivity studies discussed in Reference 1 demonstrate that this model is acceptable because the chosen convergence criteria are shown to be insensitive to further reductions.

All of these models are combined into a code which will be applied by GNF to model AOO transients. AOO analysis is designed to evaluate whether or not specified acceptable fuel design limits (SAFDLs) are exceeded. The figure of merit for these types of analyses is the MCPR. Kinetics codes are needed to predict the direct heating of the coolant via gamma absorption and the energy deposited in the fuel. The energy deposited in the fuel is the dominant parameter. Energy deposition in the fuel is important because for a correlation such as the one used by GNF one must know the boiling length in order to predict the critical power. The boiling length is directly proportional to the fuel heat flux which is dependent on the fuel temperature. The fuel temperature is derived from the energy deposition. For convenience the fission power is often used as the metric for energy deposition. In this study, both energy deposition and power are considered.

5.5.3 Review of Experimental Benchmarks

GNF assessed TRACG against the Peach Bottom turbine trip tests. Three turbine trips were performed at the Peach Bottom Nuclear Power Plant to generate data for code assessment. These tests were initiated at three different power and flow conditions during the coastdown following Cycle 2 operation in 1977. The core consisted of initial load 7x7 fuel and retrofit 8x8 fuel. The 7x7 fuel was the dominant fuel type. These results show that TRACG correctly predicts the Peach Bottom test's fission power data to within an acceptable error.

Another kinetics assessment which is presented in the topical report is a prediction of one of the cold SPERT III E-Core experiments. The SPERT III E-Core is a challenging experiment to model and of limited usefulness when considering applications to AOO transients given the differences between the test parameters and the conditions expected during an AOO. The SPERT tests were initiated by ejecting a control rod and were intended to develop data for code

assessment for reactivity insertion accidents (RIA). This being said, it is evident from a cursory review of the results presented by GNF in the TRACG assessment manual that TRACG overpredicts the flux peak by 40 percent, but predicts the total energy with an error in the integrated energy of 10 percent. As the staff learned when it demonstrated the capability of our methods to predict the SPERT III E-core, the SPERT reactor is difficult to predict. The staff has not attempted to identify the reason for the discrepancy between the TRACG results and the SPERT data. The GNF results are mentioned to reinforce the point that due to the differences between the test conditions and the conditions expected during AOO events, the staff has not considered the TRACG SPERT calculations in our assessment.

5.5.4 Independent Analyses of TRACG

As is its current practice, the staff ran many TRACG cases on NRC computers at headquarters. The VMS operating system was installed on a staff DEC Alpha system and TRACG was installed on the machine. GNF personnel assisted the staff in this initial installation and with subsequent software issues. A test problem provided by GNF was run to check the installation. This case confirmed that the installation was successful and that the code predicted answers equivalent to those calculated at GNF.

The staff and GNF defined a problem intended to reduce the variability of the generated cross sections which would allow the focus to be on the differences in the kinetics modeling. The staff carefully defined this model because it was expected that there would be some variability in lattice physics inputs. In addition, due to the GNF kinetics solver and its use of three-group cross-sections with neutron energy spectrums characteristic of BWR lattices, the staff was unable to provide GNF with physics input to ensure that the lattice physics was not influencing the kinetics results. The initial core consisted of five different modern GNF fuel types at zero exposure. The model contained no components other than the channels and a vessel used to model the core bypass and the upper and lower plenum. Core inlet and exit conditions were modeled with velocity and pressure boundary conditions, respectively. Even with all of the care put into the model definition, unacceptably large differences in predicted lattice void reactivity were evident based on an assessment of the first transient analyses of the test core. Based on differences in input void reactivity, this model was further simplified to two fuel types. This void reactivity effect was caused by differences in the input cross sections because the staff and GNF lattice physics methods predicted different trends in the infinite eigenvalue as a function of void reactivity for certain GNF fuel lattices. Although the cause of this difference has not been identified and the staff is still considering this problem, it was appropriate to define a simpler core based on fuel types that did agree well to allow the TRACG review to proceed because the lattice physics analysis is not part of this review.

The staff and GNF predictions of the two fuel type core are compared in Figures 1 and 2. Figure 1 shows a three-dimensional view of the initial steady state power distribution and Figure 2 shows the infinite eigenvalue as a function of time for the two fuel types used in the core. One difference between the two predictions in Figure 1 is the fact that the staff results are not as smooth as the GNF analyses. This difference is typical when comparing modern nodal methods to finite difference methods, possibly because nodal methods attempt to more accurately account for inter-assembly gradients. Otherwise, Figure 1 demonstrates that the two methods quantitatively agree well with one another. Figure 2 shows that the void reactivity input into the two respective kinetics codes is equivalent.

Both TRACG and staff models were used to evaluate three transient problems: first, a slow pressure increase was modeled; second, an inlet flow decrease was modeled; and, finally, a main steam isolation valve (MSIV) closure transient was simulated. The first two transients were run to evaluate TRACG's ability to predict changes in total reactivity. The figure of merit for a test such as this is total power. In Figures 3 and 4, the two codes compare well with one another with regard to the change in reactivity from the imposed transient. The final transient is intended to assess TRACG's ability to predict prompt critical power changes similar to those expected during limiting AOO transients.

The MSIV closure simulation is modeled by imposing changes to the inlet and outlet boundary conditions. These changes were predicted from another TRAC model which modeled the entire reactor system and the balance of plant. Conditions as a function of time in the upper and lower plenum were extracted from this case, scaled to the test problem, and entered into the velocity and pressure boundary conditions. The staff compared the affects of many of the TRACG models on the results of this problem and many different cases were run. Only one model was found to significantly alter the results from the base case. The staff will refer to this model as the PIRT18 model. This model was previously mentioned in Section 5.5.2 of this safety evaluation. This model uses a set of precalculated MCNP results for various GNF fuel types as a function of void fraction and exposure to adjust the results from the standard GNF lattice physics methods. This adjustment is accomplished by modifying the reference density used in the TRACG fitting algorithm.

The staff independently assessed this model because the TRACG results are sensitive to it. The staff ran many MCNP calculations of a GNF fuel lattice using different modeling assumptions and different cross sections based on ENDF/B-V and ENDF/B-VI data. The results of the assessment identified a weakness in the GNF model. The GNF model uses the MCNP code, which is a Monte Carlo solver, to predict point values. Monte Carlo methods do not yield point answers; rather, they provide statistically significant ranges of answers. As the staff results in Figure 6 show, a wide range of different, but statistically equivalent answers, can be attained by using different cross section formulations and different (but equivalent) modeling assumptions. The differences presented in Figure 6 would not typically be of concern if it were not for the fact that BWRs are sensitive to void reactivity changes on the order of magnitude of the 95th percentile confidence intervals of the MCNP results.

Based on the results of the three review efforts, the staff considers that the TRACG kinetics code can adequately model AOO transients. The written material allowed the staff to conclude that there is reasonable assurance that the model captures all of the relevant phenomena and that the equations are appropriately derived. The method of solution has been used in other methods and the description provided in Reference 2 allows the informed reader to conclude that the mathematical formulations are adequate. Although the staff discounted the SPERT experimental validation, the results of the Peach Bottom assessment provide enough experimental evidence for the staff to make a finding that there is reasonable assurance that TRACG can predict AOO transients. The Peach Bottom benchmarking presented by GNF is a valuable result when one considers whether a code can adequately model the phenomena relevant to pressurization AOO transients. These results demonstrate that the TRACG kinetics model is capable of predicting the reactor power during a pressurization transient.

As one can see from the previous section, the staff spent considerable effort attempting to reconcile the differences between the TRACG and the TRAC/NESTLE independent assessment results. In the end this work focused on understanding the PIRT18 model. As one can see from Figure 5, it does significantly affect the peak power. However, after considering that the proposed application of TRACG is to AOO analyses, the staff concluded that this effect on peak power is not significant because when the peak is under-predicted, the global reactivity balance will force the tail to be over-predicted and TRACG has been shown to adequately predict the global reactivity balance. This has the affect of compensating for the effect that the PIRT18 model has on the key parameter of interest from the kinetics solver in AOO analyses, which is energy. Energy, not power, drives changes in critical power ratio. As one can see from Figures 7 and 8 both codes predict similar energy deposition. Figure 7 shows the energy as a function of time and Figure 8 shows the relative difference in energy as function of time between TRACG and TRAC/NESTLE. The staff has, therefore, determined that although the basis for this model has not been well established, its effect on AOO transient results will be minimal as demonstrated in Reference 9. In this evaluation, the affect of the PIRT18 model on the ΔCPR/ICPR results has been shown to be insignificant. This model will have to be reassessed and better justified should GNF desire to use it for RIA analyses.

Returning to the discussion of Figure 5, the staff results and the TRACG results are in reasonable agreement. Although the TRACG results without the PIRT18 model agree better with the staff results, the results with the PIRT18 model are acceptable when one considers the following:

1. TRACG compares well with the Peach Bottom turbine trip tests. Although these tests were not as limiting as the transient considered in the test problem and the Peach Bottom core used older BWR fuel that was easier to analyze, the results do provide evidence that TRACG adequately simulates pressurization transients; and

2. The TRACG results, when compared to the staff's results, do not differ significantly enough to affect predictions of ΔCPR/ICPR values. This is true because as mentioned earlier critical power is a function of energy deposition, not power.

5.5.5 <u>Summary of Findings</u>

In summary, the staff has reviewed the theoretical development of the TRACG code, the validation presented by GNF, and the information generated during our own analytical assessment of TRACG. The staff finds that the information presented on the theoretical development of the kinetics solver and its associated models is adequate to support the conclusion that these models are correctly derived and account for the important phenomena involved in AOO analyses. The benchmarking presented by GNF, most notably the comparisons to the Peach Bottom turbine trip experiments, demonstrate that for a core loaded with older BWR fuel under conditions similar to those expected during AOO analyses, TRACG adequately predicts the key parameters. In addition, assessments are also presented using plant data from Hatch MSIV closure, Nine Mile Point 2 pump upshift test, and the Leibstadt loss of feedwater event. Thus, a range of fuel generations have been included in the assessment cases. Finally, the independent assessment efforts of the staff focused on evaluating TRACG's ability to predict modern fuel for limiting transients, while not showing exact agreement with diverse methods, provides the staff with enough confidence in TRACG to conclude that it is

acceptable for AOO analyses. Issues discovered with the PIRT18 model do not significantly affect these conclusions because it has been shown that this model does not impact the primary result (ΔCPR/ICPR) of AOO analyses. Should GNF wish to apply TRACG to RIA analyses using this PIRT18 model, further justification will need to be provided. Most importantly, GNF will be required to demonstrate how the MCNP code can reliably predict point estimates for BWR lattice k-infinity values.

5.6 Statistical Methodology

In the subject report GENE requests review and approval by the NRC of:

1. The uncertainties documented in Section 5.0.

2. The statistical methodology for analyzing AOOs described in Section 7.0.

This evaluation is limited to these two sections.

The general overall analysis approach in the subject report follows the code, scaling applicability and uncertainty (CSAU) analysis methodology (Reference 3). This methodology consists of 14 steps that are addressed in the TRACG application in the subject report. The first few steps in the CSAU methodology identify and rank the physical phenomena important to judging the performance of the safety systems and margins in the design. The phenomena are compared to the modeling capability of the code to assess whether the code has the necessary models to simulate the phenomena. Most importantly, the range of the identified phenomena covered in experiments is compared to the corresponding range of the intended application to assure that the code has been qualified for the highly ranked phenomena over the appropriate range.

5.6.1 Model Uncertainties and Biases

This section quantifies the overall biases and uncertainties of the individual models associated with each high and medium ranked phenomenon in TRACG. The biases and uncertainties are computed and evaluated by comparing calculated results to: (1) separate effects test facility test data, (2) integral test facility data, (3) component qualification test data, and (4) BWR plant data. The sensitivity of ΔCPR/ICPR, the basic figure of merit for AOO transients, to the estimated magnitude of the uncertainty of each phenomenon is quantified for a typical BWR/4 plant for a turbine trip without bypass transient.

For each applicable phenomenon, Table 5-5 of Reference 1 summarizes quantitatively the bias and uncertainty associated with the parameters. For those parameters where there is sufficient and appropriate test data to compare to calculation, a statistical estimate is made of the bias and variance of the distribution. The distributions are tested for normality via the Anderson-Darling statistic and accepted as normal at the 5 percent level. For those phenomena where the descriptive statistics are explicitly shown, all distributions met this acceptance criterion except for some of the TRACG comparisons with respect to jet pump characteristics (Figures 5-19 and 5-21 of Reference 1). This non-normality appears, to some extent, to be most likely due to the relative small sample size with respect to the other phenomena.

For phenomena where data are not available, code comparisons are used to estimate the biases and variances. A parameter of particular importance for BWR AOO analysis and which falls into this category is the void coefficient. In the context of the TRACG three-dimensional transient neutron diffusion equations using one neutron energy group and up to six delayed neutron precursor groups, the nodal reactivity is computed in terms of the infinite multiplication factor, migration area, the fast group removal cross-section and fast group diffusion coefficient. These parameters are correlated to the void coefficient in terms of the moderator density. The infinite multiplication factor's dependence is also related to a history-weighted moderator density and nodal exposure.

The dominant component in the biases and uncertainties in the void coefficient is attributed to the biases and uncertainties in the infinite lattice eigenvalues calculated with the lattice physics code TGBLA. The TGBLA code is used to generate the cross section fits that are evaluated in TRACG. The biases and uncertainties associated with the TGBLA computed infinite multiplication factors are estimated by comparing the TGBLA results to those computed with the continuous energy Monte Carlo code MCNP (Reference 13).

GENE has evaluated the performance of MCNP against a set of critical experiments spanning a range of temperatures and fuel types; in particular Babcock and Wilcox UO_2 experiments. The results indicate that the code performs very well in comparison to the experiments (Reference 14). Thus, the results of the Monte Carlo calculations are taken as the "true" value of k-infinity in estimating bias and uncertainty of the void coefficient.

The bias and uncertainty in the void coefficient are computed based on k-infinity calculations by TGBLA and MCNP. The void coefficient at each lattice - exposure - in-channel void fraction can be computed for both the TGBLA and MCNP generated k-infinity values. The bias at a lattice-exposure-in-channel void point in the TGBLA void coefficient is defined as the difference at that point between the void coefficient computed by TGBLA and MCNP. In the analysis of an AOO, the initial spatial distribution of composition and void fraction are fixed within each node. The value of the bias and the uncertainty at that node are defined as the average of the biases associated with the lattices. The uncertainty is then the root-mean-square deviation of the biases from the mean bias at each exposure - in-channel void point. To implement these in TRACG requires a transformation from in-channel void fraction to relative water density for application to the number densities in the nodal neutronic calculation and the normalization of the TGBLA - MCNP differences in k-effective.

The claim is made that the lattices are a random sample from "literally thousands that are available" (Reference 8). In principle, the sample size is too small to characterize such a large population, unless the variation in the parameters of interest is well represented and/or does not have a large span. The latter appears to be the case, since the GENE 8x8, 9x9 and 10x10 geometric designs are included, and the differences between product lines is less important than the isotopic composition and concentrations as specified by the exposure. Table 5-1 of Reference 1 gives the p-values for the Andersen-Darling statistic and demonstrates the normality at the 5 percent level at each exposure - in-channel void fraction point.

GENE has assessed the sensitivity of ΔCRP/ICPR to an individual perturbation of each of the phenomena under consideration, and has demonstrated the effect to be small.

5.6.2 Combination of Uncertainties

Estimation of Design Limits

GENE has assessed the different basic methods for combining uncertainties, such as propagation of errors, Monte Carlo sampling methods in conjunction with the response surface technique and the evaluation of one-sided upper tolerance limits based on order statistics, or normal theory where applicable. Due to the limitation of the linearity assumption in the case of the propagation of errors, and the prohibitively large number of TRACG runs in the case of the response surface technique, GENE has chosen the estimation of one-sided upper tolerance intervals based on normal theory, when appropriate, and otherwise on order statistics. It is recognized that, especially in the case of order statistics, this results in more conservative design limits than one would obtain on the average from the other methods.

The methodology for combining the individual biases and uncertainties in the TRACG model and plant parameters in order to generate a probability density function of the code output of primary safety criteria parameters is based on Monte Carlo sampling. That is, the distributions given in Table 5-5 (Reference 1) are sampled at random; and for each sample of parameters an AOO transient is computed with TRACG. The histogram of the code output of primary safety criteria parameters forms the estimate of the probability density function and forms the basis for the design limits.

A histogram of at least 59 TRACG outputs is tested for normality. If normal, the 95/95 upper tolerance quantile value can be computed from normal theory. The interval is interpreted as containing 95 percent of all possible TRACG outcomes for the particular AOO with 95 percent confidence. If the normality test fails at 59 outcomes, the nonparametric method of order statistics is applied. The computation of a 95/95 upper tolerance quantile value in nonparametric statistical theory requires a sample size of at least 59 observations. Operationally the sample is ordered by value, from lowest to highest; and the 59th value becomes the upper 95/95 tolerance limit. The interpretation of the interval is that 95 percent of all possible TRACG outcomes for the particular AOO lie below the 59th outcome with 95 percent confidence. The interval based on normal theory is likely to be much more narrow than the one computed with nonparametric methods.

Determination of Operating Limit Minimum Critical Power Ratio (OLMCPR)

The approach to deriving an OLMCPR is to impose an uncertainty on the models and plant parameters judged of high importance in determining the progression of the transient computed with the TRACG code and based on the variation in the transient due to the uncertainties compute the probability of avoiding the boiling transition.

The general approach to accounting for statistical uncertainty in thermal-hydraulic test data and measurements of the core operating state is to evaluate an MCPR. The safety limit minimum critical power ratio ($SLMCPR_{99.9}$) is determined so that less than 0.1 percent of the rods in the core are expected to experience boiling transition at this value (i.e., 99.9 percent of the rods in the core are expected to avoid boiling transition if the limiting MCPR is greater than the $SLMCPR_{99.9}$).

The concept of an OLMCPR is introduced to assure that the safety limit is not exceeded during a transient. In principle, the OLMCPR can be computed for the limiting AOO by running a large number of TRACG transient calculations and randomly varying in each calculation the initial conditions, model parameters and plant parameter based on the distributions established in Section 5.0. These computations can, in principle, generate histograms of rod critical power ratios (CPRs) for a core under transient conditions.

Central to evaluating $SLMCPR_{99.9}$ is the computation of the number of rods subject to boiling transition (NRSBT) which is based on the experimental critical power ratio (ECPR) distribution from data obtained at GENE's ATLAS test facility. Operationally, the probability that some rod "i" operating at $MCPR_i$ is in boiling transition is given by the integral of the ECPR distribution from MCPRi to $+\infty$. It should be noted that the distribution of the random variable ECPR is based on experimentally measured values, while MCPR is computed at thermal-hydraulic conditions based on TRACG calculations. Strictly speaking, only if ECPR and MCPR have the same distribution can a probability based on an observation of MCPR be computed with the probability density function of ECPR. For the analysis at hand, this discrepancy in the numerical value of the probability that a rod is in boiling transition is likely to be very small. GENE has done extensive sensitivity analysis of ΔCPR/ICPR to variations in the parameters deemed important and demonstrated very low sensitivity. Furthermore, the standard deviation of these parameters is generally on the order of a few percent, thus indicating that the difference in the distributions is small. In addition, the MCPR values of interest lie in the tail of the normal distribution and the small differences between MCPR and ECPR contribute little to the probability that a rod is in boiling transition.

The expected number of rods subject to boiling transition can be computed by summing the probability that a rod is subject to boiling transition for all the rods in the core. The OLMCPR is then determined from the limiting MCPR value in the core when the NRSBT equals 0.1 percent.

The drawback to the above approach is the large number of TRACG transient calculations required for a sufficiently high confidence in the results. The currently approved approach to determining OLMCPR is divided into two distinct steps. First the $SLMCPR_{99.9}$ is determined. The OLMCPR is then established by adding to $SLMCPR_{99.9}$ the maximum change in MCPR ($\Delta CPR_{95/95}$) expected for the most limiting transient event. The transient uncertainty in ΔCPR for computing $\Delta CPR_{95/95}$ is obtained by Monte Carlo trials combining model uncertainty with uncertainties in the plant parameters such as core power and scram speed.

The proposed approach uses TRACG for computing the thermal-hydraulic conditions during a transient and builds on the currently approved methodology for establishing the OLMCPR. The approach is based on the following computations. For <u>each type</u> of AOO and for <u>each class</u> of BWR plant type and <u>each fuel type</u> the "generic" transient bias and uncertainty in ΔCPR/ICPR is determined based on TRACG runs using nominal initial conditions, random variations in the models and plant parameters. Since an OLMCPR is to be established for a specific plant/cycle/event, a TRACG transient calculation is performed for such a specific plant/cycle/event starting from nominal initial conditions. This results in a nominal ΔCPR/ICPR for this specific event. Based on these (i.e., "specific" nominal ΔCPR/ICPR and a "generic" ΔCPR/ICPR uncertainty), a MCPR can be computed for each rod in the specific core. As in the previous described methodologies, the value of NRSBT for each rod is computed as an integral from the rod MCPR to infinity over the ECPR probability density distribution. The initial

minimum CPR value corresponds to the OLMCPR when the mean value of NRSBT is equal to 0.1 percent.

5.6.3 Summary of Findings

In the subject report, GNF has documented the quantification of uncertainties as applied to realistic nominal results of TRACG analyses such that less than 0.1 percent of the fuel rods are expected to experience a boiling transition for the most severe AOO. The approach follows the accepted CSAU analysis methodology by which the physical phenomena important to judging the performance of the safety systems and margins in the design are elicited by the Delphi Method. GNF has quantified the uncertainties and biases in models associated with these identified and highly ranked phenomena based on experimental data and computation with validated codes. The process is acceptable and the quantities are reasonable. These together with the computed sensitivity estimates of ΔCPR/ICPR with respect to variation in the model parameters indicate smoothness and stability in the solution to TRACG transient computations within the uncertainties in the models. Moreover, random sampling from the estimated uncertainty distributions in the model parameters is likely to be adequate in light of "the curse of dimensionality."

The objective of estimating the uncertainties associated with the TRACG models is to determine the OLMCPR so as to demonstrate acceptable margins to design limits. The proposed methodology groups the TRACG statistical studies by event/BWR type/fuel type; thereby establishing a generic bias and uncertainty. Subsequently, any, for example, BWR/4 type plant loading GENE14 fuel can utilize the generic bias and uncertainty of the group for a specific transient event. The separation of analysis of the transient behavior under uncertainty into a generic transient bias and uncertainty in ΔCPR/ICPR and a nominal ΔCPR/ICPR for the specific plant/cycle/event under consideration is reasonable and avoids running on the order of 100 TRACG transient calculations for each AOO.

5.7 Code User Experience

The TRACG code uses an input deck which closely emulates the input deck of the original TRAC base code it grew out of. Therefore, a knowledgeable user of TRAC can readily understand the structure and design of the TRACG input decks. An appendix to the model description document facilitates the transfer between codes by outlining the major changes between the TRAC-BF1 and TRACG codes. The user’s manual for TRACG contains less guidance than the original TRAC base code user’s manual. Significant changes to the input deck design are in the areas where GENE has expanded or refined the original code to more easily model BWR systems or components or to include proprietary modeling in the code.

TRACG maintains the execution structure for control blocks of the original TRAC code. This structure will only allow the execution of the control blocks in the numerical order they are entered into the code. This limitation requires the renumbering of control blocks if additional control blocks are needed after the original deck is created. Renumbering the control blocks and changing the associated variables in the blocks can be a source of user error. Additionally, this limitation can introduce difficulty if a feedback loop exists in the control system. To reduce the impact of this limitation, a small time step size must be used. While the user manual gives some general guidance on the maximum time step size, it is not very clear on this issue.

Instead, it mentions that the automatic control algorithm will respond to the numerical instability caused by reducing the time step size. Additional guidance on this issue would be very helpful to the user.

In TRACG the user creates an initial input deck which is then run under the steady state option of the code until steady state conditions are achieved. During this steady state calculation procedure, the code will determine the correct flow regimes for the components and use the constitutive relations for these flow regimes. This prevents the user from using options to change the relations. Steady state conditions are determined by the user through inspection of the time rates of change of the thermal and fluid variables. This can be a source of error if the user identifies a state which may not be changing significantly at the time step chosen but is not the actual steady state condition.

GENE has developed standard input for the classes of BWR systems this code will be used to analyze. This standard input was developed after sensitivity studies to ensure that the modeling parameters chosen would not bias the analysis results. These standard input sets will reduce the user introduced error in the code results.

6.0 CONDITIONS AND LIMITATIONS

The following are conditions and limitations on use of the TRACG code for analysis of AOO events.

1. Use of the GEXL14 correlation is acceptable provided that when the NRC approves the critical boiling length correlation uncertainty it is applied in TRACG.

2. Should the applicant want to apply TRACG to stability analyses beyond the limited application discussed in Reference 13, the methodology is to be submitted for staff review for that purpose.

3. TRACG is not acceptable for application to ATWS analyses without specific staff review for that purpose, beyond previously accepted use for bench marking ODYN (Reference 14).

4. The PIRT18 model will have to be reassessed and better justified before TRACG can be applied to RIA analyses. Most importantly, GNF will be required to demonstrate how the MCNP code can reliably predict point estimates for BWR lattice k-infinity values.

5. Should the code be applied to transients requiring a condenser, a separate model will be needed or the ability to adequately model the condenser must be demonstrated.

7.0 CONCLUSIONS

The staff supports the efforts of applicants to integrate codes for analysis of accidents and transients rather than manual transfer of information between the codes. Integrating the thermal-hydraulic, fuel rod performance, and other codes, permits a smoother and more accurate prediction of the performance of the system under accident conditions.

The TRACG code has had the GEXL heat transfer correlation installed. Based on reviews of that correlation, the staff has concluded that it is acceptable provided the NRC approved critical boiling length correlation uncertainty is applied.

The staff has reviewed the theoretical development of the TRACG code, validation presented by GNF, and information generated during our own analytical assessment of TRACG. The staff finds that the information presented on the theoretical development of the kinetics solver and its associated models is adequate to support the conclusion that these models are correctly derived and account for the important phenomena involved in AOO analyses. The bench marking presented by GNF, most notably the comparisons to the Peach Bottom turbine trip experiments, demonstrate that for a core loaded with older BWR fuel under conditions similar to those expected during AOO analyses, TRACG adequately predicts results. Finally, the independent assessment efforts of the staff, which focused on evaluating TRACG's ability to predict fuel behavior for limiting transients, while not showing exact agreement with diverse methods, provides the staff with enough confidence in TRACG to conclude that it is acceptable for AOO analyses. Issues discovered with the so-called PIRT18 model do not significantly affect these conclusions because it has been shown that this model does not impact the primary result (ΔCPR/ICPR) of AOO analyses. Should GNF wish to apply TRACG to RIA analyses using this PIRT18 model, further justification will need to be provided. Most important, GNF will need to demonstrate that a Monte Carlo code can reliably predict point answers.

GNF has documented the quantification of uncertainties as applied to realistic nominal results of TRACG analyses such that less than 0.1 percent of the fuel rods are expected to experience a boiling transition for the most severe AOO. The approach follows the accepted CSAU analysis methodology by which the physical phenomena important to judging the performance of the safety systems and margins in the design are elicited by the Delphi Method. GNF has quantified the uncertainties and biases in models associated with these identified and highly ranked phenomena based on experimental data and computation with validated codes. The process is acceptable and the quantities are reasonable. These together with the computed sensitivity estimates of ΔCPR/ICPR with respect to variation in the model parameters indicate smoothness and stability in the solution to TRACG transient computations within the uncertainties in the models.

GENE has developed standard input for the classes of BWR systems this code will be used to analyze. This standard input was developed after sensitivity studies to ensure that the modeling parameters chosen would not bias the analysis results. These standard input sets will reduce the user introduced error in the code results.

8.0 REFERENCES

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Attachments: Figure 1 through Figure 8

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Date: October 22, 2001

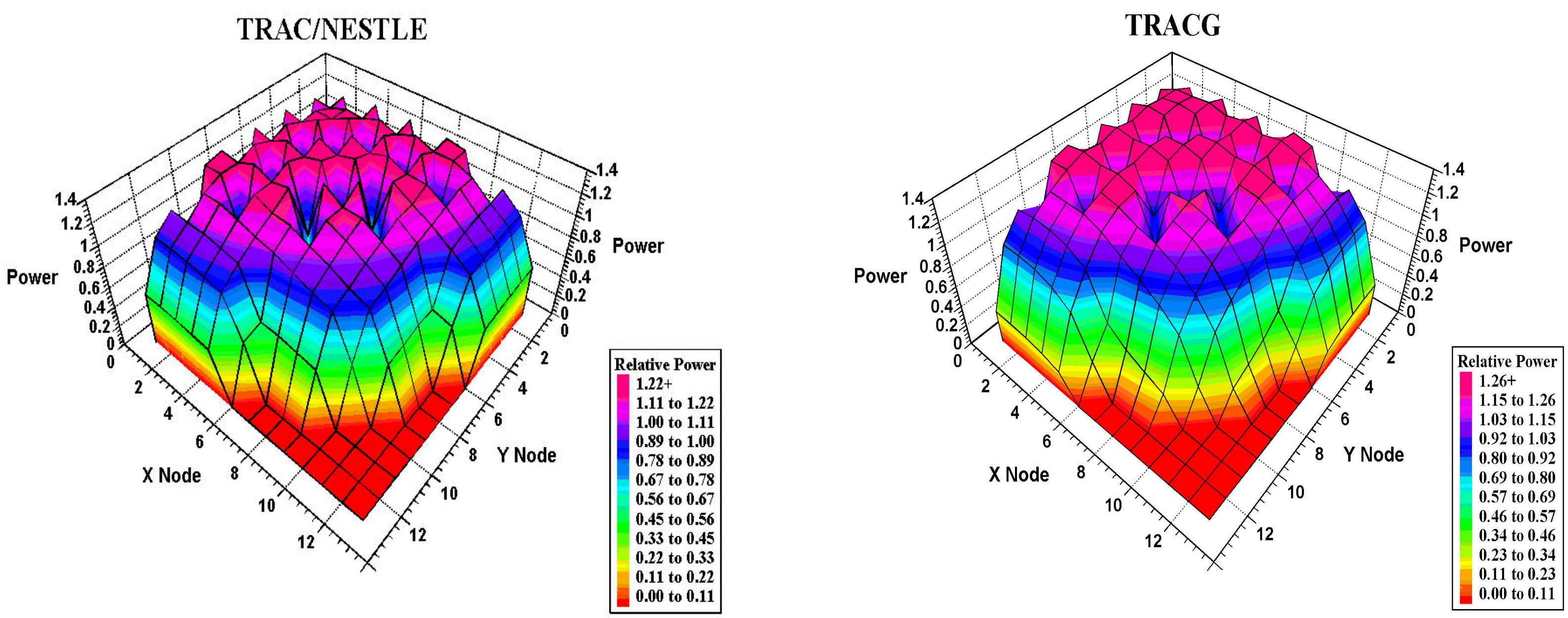

Figure 1 Comparison of Radial Power Distributions for two Methods used in the Analysis

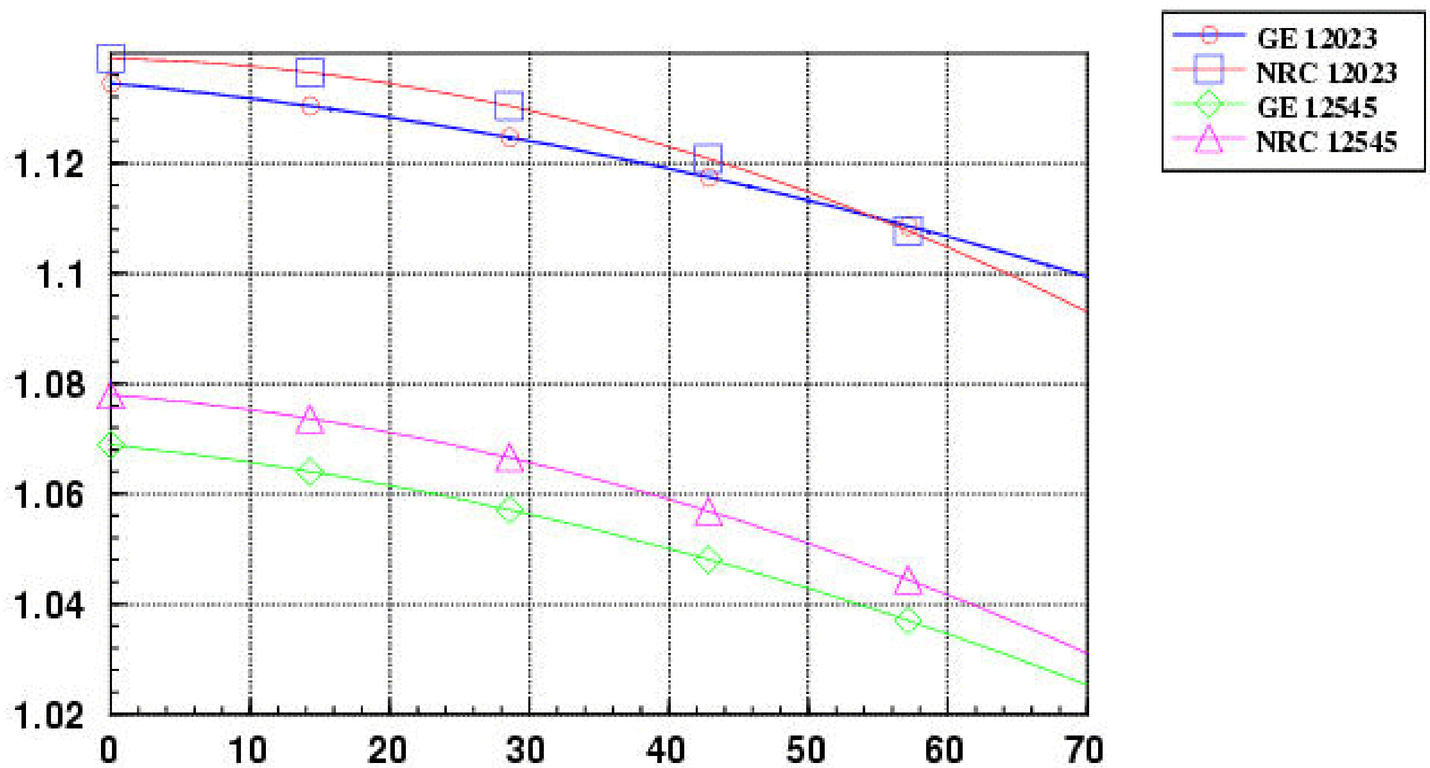

Figure 2 Comparison of Void Reactivity between NRC and GENE Methods for Sample Core

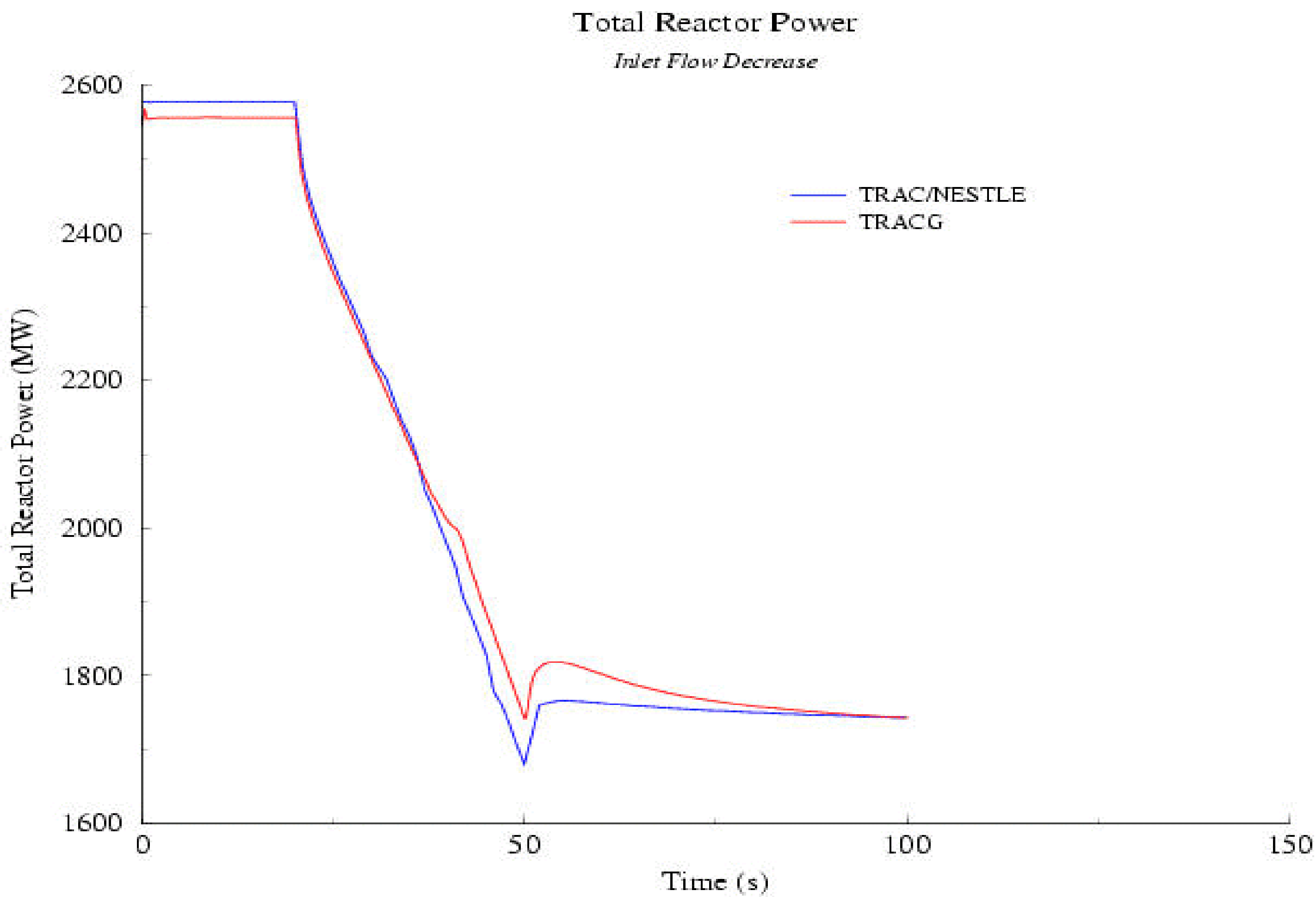

Figure 3 Total Power for a Inlet Flow Ramp

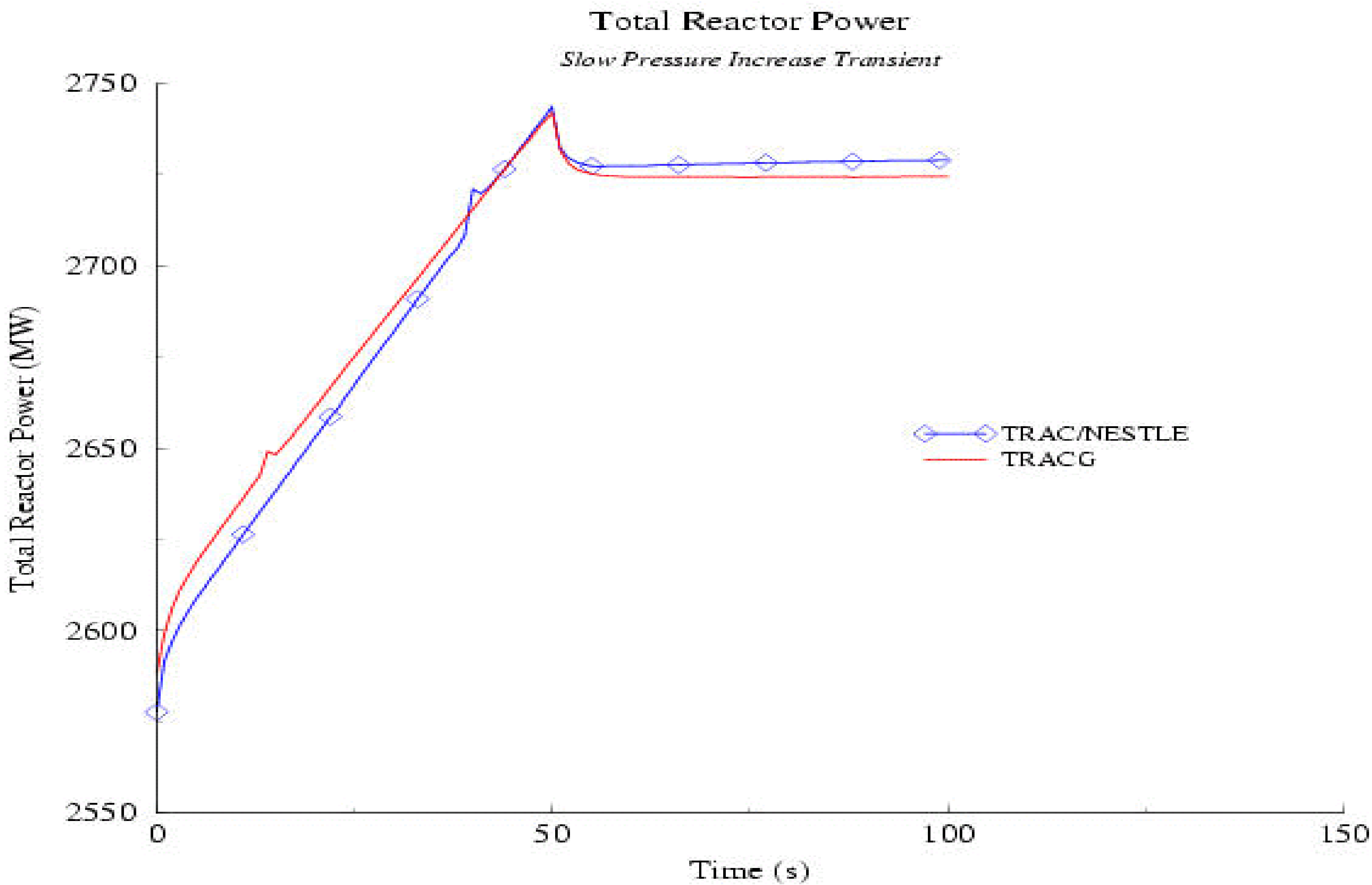

Figure 4 Total Reactor Power for Slow Pressure Increase Transient

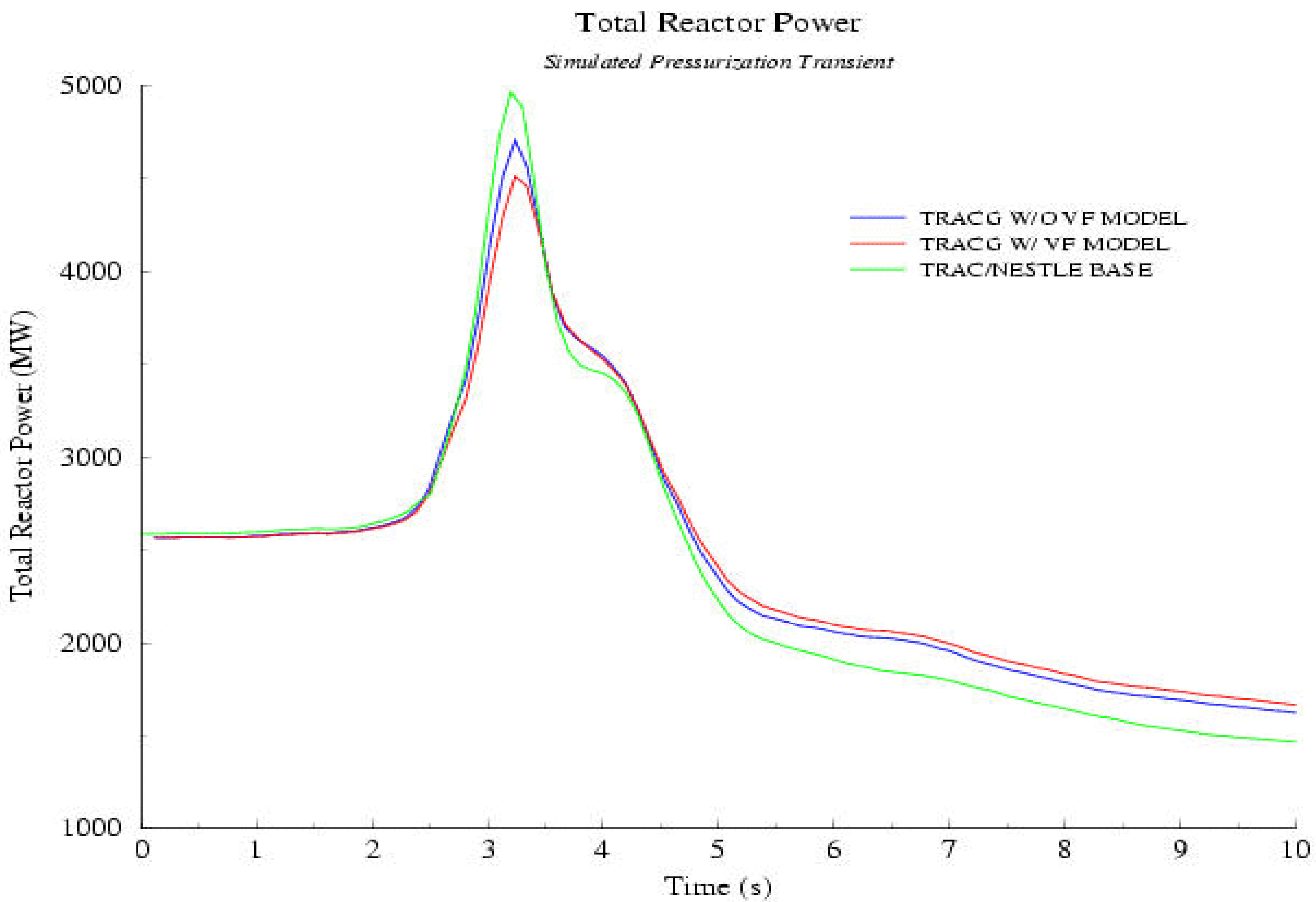

Figure 5 Total Reactor Power for Simulated Pressurization Transient

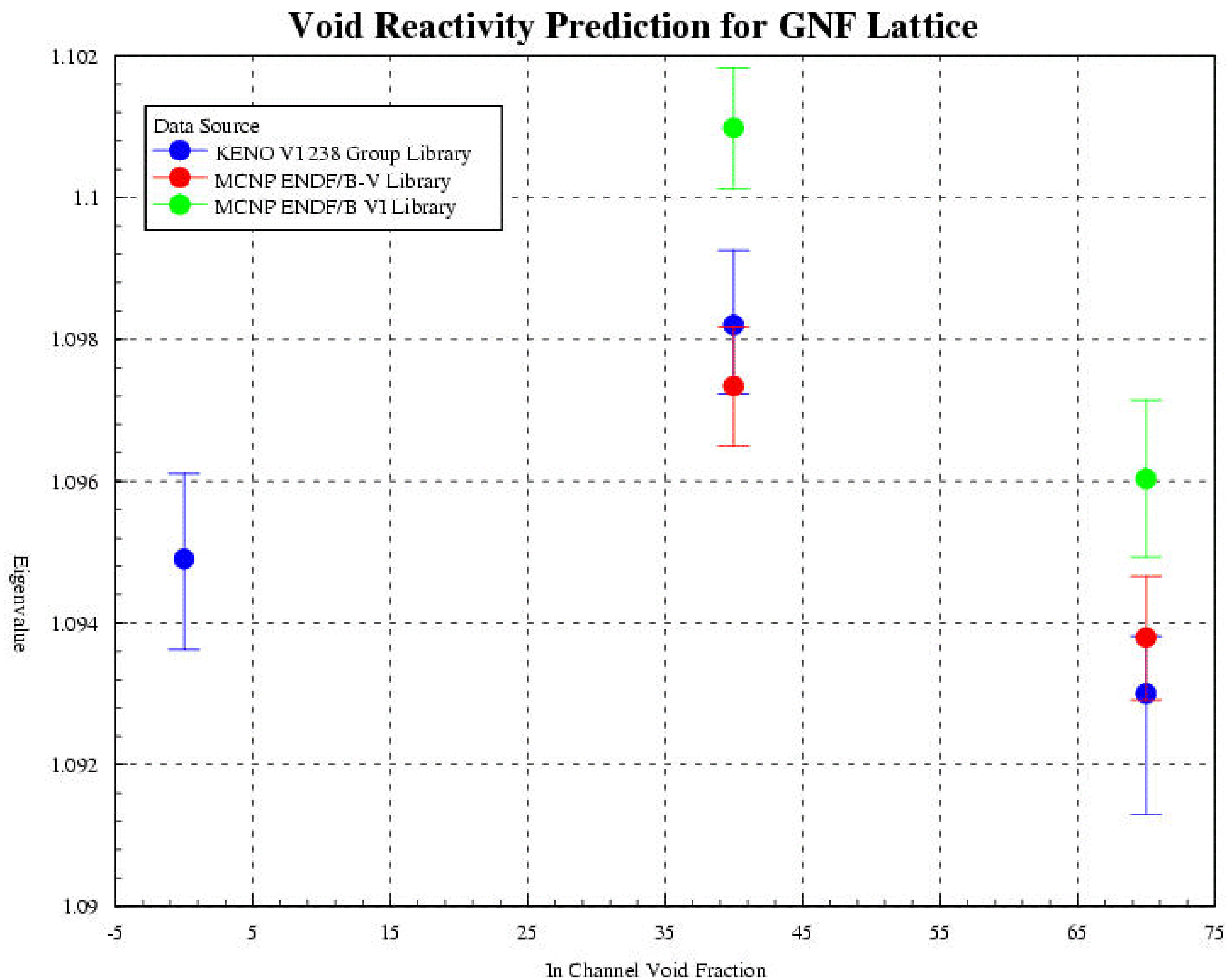

Figure 6 Comparison of Different Monte Carlo Evaluations of the Same GNF Lattice

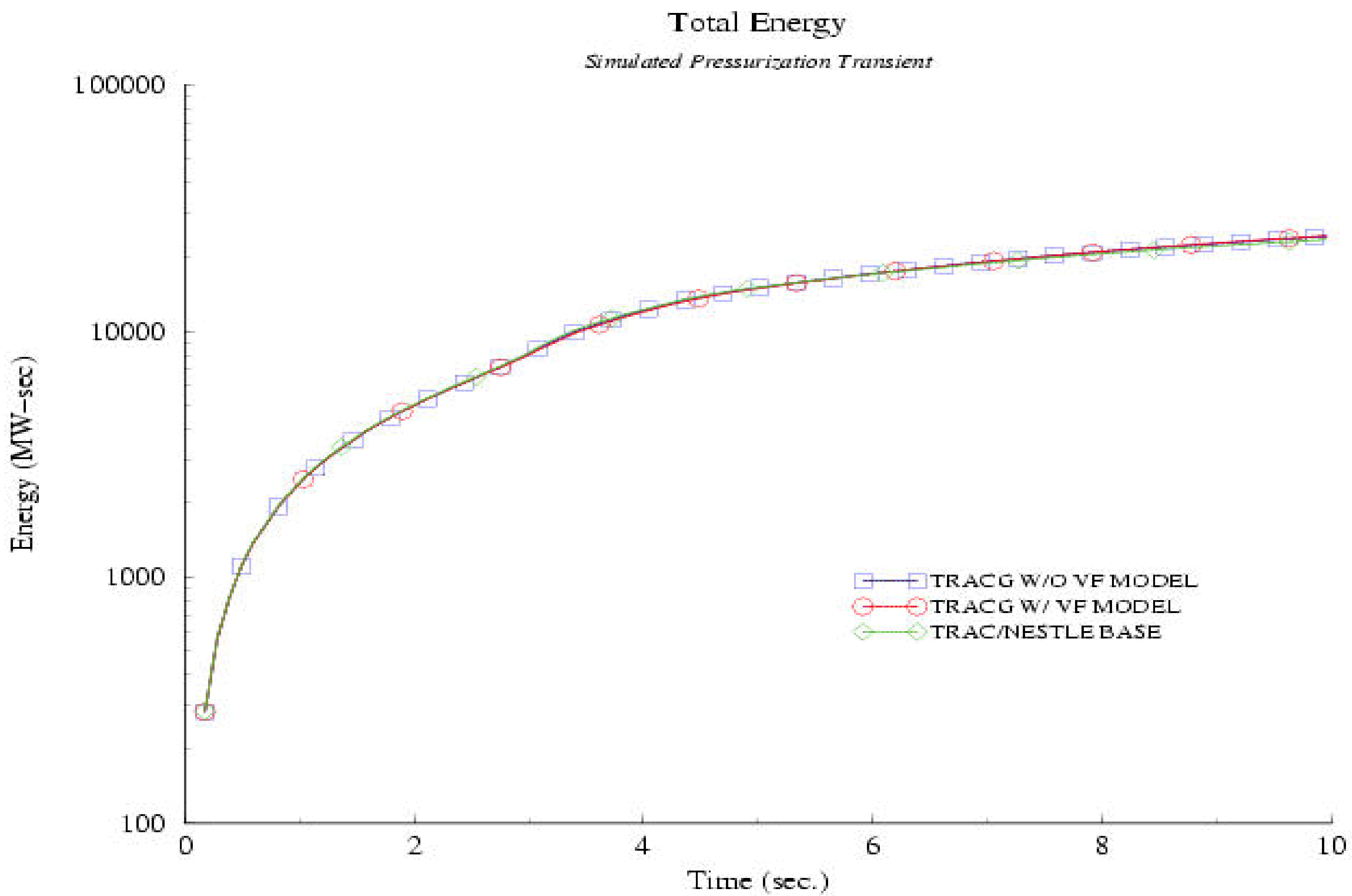

Figure 7 Energy released during simulated MSIV closure event.

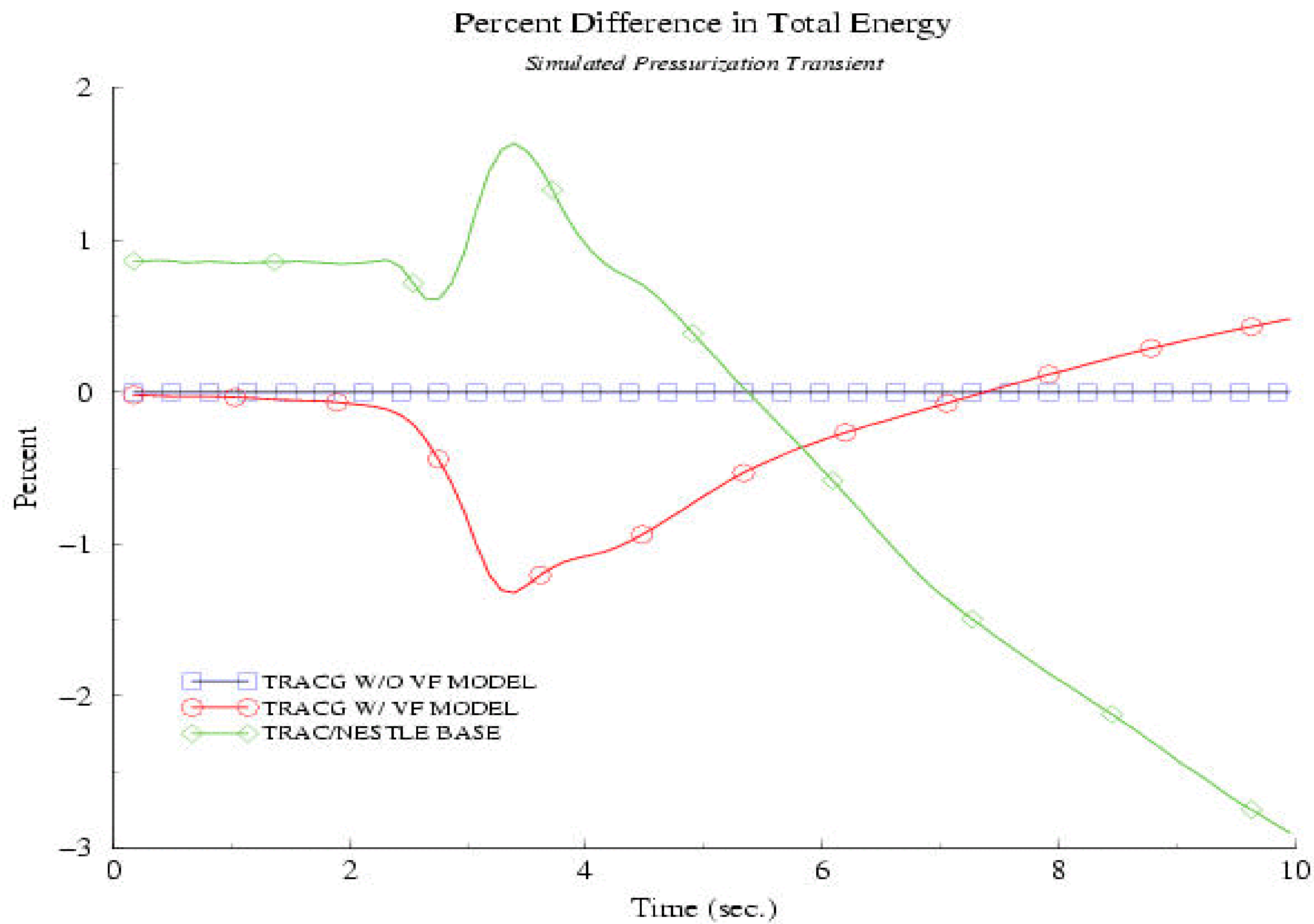

Figure 8 Relative differences between TRACG and TRAC/NESTLE results for MSIV closure simulation.