THE REACTOR KINETICS CODE TANK:

A VALIDATION AGAINST SELECTED SPERT-1B EXPERIMENTS

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The two-dimensional space-time transient analysis code TANK is being developed for the simulation of transient behaviour in the MAPLE class of research reactors. MAPLE research reactor cores are compact, light-water-cooled and -moderated, with a high degree of forced subcooling. The SPERT-1B(24/32) reactor core had many similarities to MAPLE-X10, and the results of the SPERT transient experiments are well documented. As a validation of TANK, a series of simulations of certain SPERT reactor transients was undertaken. Special features were added to the TANK code to model reactors with plate-type fuel and to allow for the simulation of rapid void production. The results of a series of super-prompt-critical reactivity step-insertion transient simulations are presented. The selected SPERT transients were all initiated from low power, at ambient temperatures, and with negligible coolant flow. The results of the TANK simulations are in good agreement with the trends in the experimental SPERT data.

1. INTRODUCTION

TANK [1-4] (Transient Analysis with Neutron Kinetics) is a two-dimensional space-time reactor kinetics computer code being developed for the simulation of reactivity transients in the Atomic Energy of Canada Limited (AECL) MAPLE class of research reactors. The coding makes use of some of the features of the earlier AECL steady-state neutronics code, VARIHEX [5]. Some of the methods and techniques for solving the neutronics of a reactor simulation are similar to those used in the kinetics code HEXKIN [6]. To assess the validity of the methods and correlations used in TANK, a series of validation computer simulations was made of well-documented SPERT [7-11] (Special Power Excursion Reactor Tests) transient experiments.

Modifications were made to the original TANK code to allow for the optional modelling of reactors (such as the SPERT-1B) with plate-type fuel. The thermalhydraulics considerations and temperature distribution solutions are quite different from those for the fuel pin arrangement for which TANK was first intended. Rapid void formation in near-stagnant water is difficult to model and is not directly applicable to the forced coolant situation expected in most postulated MAPLE transient scenarios. Nevertheless, voiding features have been added to TANK to model the onset of void in SPERT transients.

2. MODELLING TECHNIQUES USED IN CODE TANK

TANK is used for simulating the kinetic behaviour of a nuclear reactor on a two-dimensional mesh of hexagonal cells. The TANK model of a nuclear reactor usually contains up to 900 hexagonal cells, representing the neutronic and physical properties of the reactor materials. Two neutron-energy groups are considered in the TANK algorithms: (i) fast neutrons, with kinetic energy $\geq$ 0.625 eV, and (ii) thermal neutrons, with kinetic energy $<$ 0.625 eV. Considerations are included for effects in the third (axial) dimension, for example: coolant void distributions along a fuel channel, axial power distribution, and control and shutdown rod positions.

During a transient simulation, the temperature-dependent thermal properties of the fuel, cladding and coolant are calculated for each fuel cell, at each time step. Subroutines in TANK are used to determine the transient fuel, cladding, and coolant temperature distributions, for each of the fuelled sites. The heat transfer package of the thermalhydraulics code SPORTS-M [12] is linked to TANK, providing important heat flow information. These subroutines provide values for the cladding/coolant heat transfer coefficients, the heated cladding surface heat flux, water properties, and predict the inception of void formation at any site in the core.

Each hexagonal cell in the TANK model is characterized by a set of nine kinetic parameters: fast- and thermal-neutron macroscopic absorption and fission cross sections, fast-to-thermal macroscopic removal (down scatter) cross sections, fast and thermal axial diffusion coefficients, and the cell-averaged fast- and thermal-neutron velocities. These parameters are obtained from computations using the multigroup neutron transport code, WIMS [13,14], for models representing appropriate cell compositions.

The kinetic parameters for the fuelled cells are updated each simulation time step, through parameterized equations, for changes in fuel temperature and density and coolant density/void. Using this method, the various reactivity feedback mechanisms are modelled.

A flux factorization approach is used in TANK to separate the total neutron flux level into the product of a space-dependent function and an amplitude function. The kinetic calculations in TANK generally account for six delayed-neutron precursor groups, in addition to the prompt fission neutrons. The space-time reactor kinetics equations for the two energy groups are coupled with delayed-neutron precursor concentration equations to form a set of differential equations that describes the fast- and thermal-neutron flux levels during transients. Numerical methods are employed to solve these equations. For the SPERT benchmarking simulations, a finite-difference approach was used with time steps as small as 0.1 ms. At each time step during a transient simulation, TANK generates much information describing reactor conditions, for example: cell power levels, neutron flux levels, temperature distributions, dynamic reactivity, and instantaneous inverse period.

3. THE SPERT REACTOR TRANSIENT PROGRAM

A major objective of the SPERT project was a comprehensive understanding of the properties responsible for the self-limitation of power under "runaway" conditions. The SPERT experimental transient program was initiated in 1955 to extend and enhance the results of the earlier (1952-1954) BORAX [15] tests.

A variety of reactor core configurations and materials were studied during the SPERT program. Four SPERT facilities were constructed and tested at the NRTS (National Reactor Testing Site, Idaho) between 1955 and 1963. The SPERT-1 reactors were unpressurized, coolant pressure being adjusted by the height of the water head, while the SPERT-II, III, and IV reactors were operated with increased coolant pressure and forced convection [16]. These latter were used to study the behaviour of pressurized water reactors and boiling water reactors. The SPERT-1 reactors were operated under conditions representative of many research reactors.

3.1. The SPERT-1B(24/32) Core

The naming of the various SPERT cores (e.g., SPERT-1B(24/32)) involves the use of four indicators: (i) SPERT reactor facility (e.g., **1**); (ii) the core type (e.g., **B**); (iii) the number of fuel plates per assembly (e.g., **24**); and (iv) the number of assemblies in the core (e.g., **32**). The SPERT-1B reactor cores were fuelled with highly enriched uranium-aluminum plates clad with aluminum and moderated and reflected by light water. These SPERT reactors had prompt neutron generation times, Λ, of approximately 50 to 80 μs, depending on the degree of moderation, and so were representative of thermal reactors. The SPERT-1B(24/32) cores had many similarities to the proposed MAPLE-X10 reactor. Both are slightly under-moderated, the amount of ^{235}U in both reactors is comparable, and the fuel-to-moderator volume ratios are similar.

Some of the physical details and reactivity parameters of the SPERT-1B(24/32) reactor are presented in Table I [7,17]. This material information was used in devising the models for the computer simulations. Table I also shows some of the reactivity data applicable to the specific SPERT-1B(24/32) reactor tests.

4. SIMULATIONS OF SPERT TRANSIENTS USING TANK

The SPERT-1B(24/32) reactor core is represented in the TANK model by an array of hexagonal cells, with a flat-to-flat lattice pitch of 2.73 cm. Each of the cells represents the material and neutronic properties of that part of the reactor. For instance, each of the 32 fuel assemblies in the SPERT core is modelled by nine fuel cells. Models describing appropriate cells were used with the multigroup transport code WIMS [14]. An extensive study of the static neutronic characteristics of the reactor model was made using the diffusion code 3DDT [18], with up to 10 energy groups. The findings indicate good agreement with the statics evaluation of the reactor, and will be published elsewhere. With these models, WIMS was used in generating two-group parameters for the various cells in the TANK model.

The temperature and void/coolant density dependencies of the parameters were determined and incorporated into TANK subroutines, as mentioned above.

Table I. Details and Characteristics of the SPERT-1B(24/32) Test Reactor.

Fuel	93.5 w/o ^{235}U in U-Al alloy (88.3% Al, 10.9% ^{235}U, 0.8% ^{238}U)
Cladding	Al (Type 6061) (97.9% Al, 1% Mg, 0.6% Si, 0.25% Cu, 0.25% Cr)
Number of fuel assemblies	32
Number of plates/assembly	24
^{235}U per plate	7.0 g
Fuel thickness	0.051 cm
Clad thickness	0.051 cm
Inter-plate water gap	0.165 cm
Total core volume	1.11×10^5 cm^3
Total core mass of Al	1.58×10^5 g
Total core mass of H_2O	5.25×10^4 g
Calculated critical mass	4.79 kg
Total loaded fuel mass	5.38 kg
Metal/water in assemblies	1.14
Excess reactivity	46 mk
Total effective delayed fraction, β_{eff}	7.0 mk
Prompt neutron generation time, Λ	50 ± 5 μs

Prior to the actual SPERT-1B experimental series, the neutron flux detectors were calibrated using calorimetric methods [7]. The procedure was repeated periodically during the program. The technique basically involved the determination of reactor power by measurement of the temperature increase of the entire reactor system. The total reactor power level and accumulated energy was then compared to the measured neutron flux data.

In the SPERT-1B program, reactivity step-insertion transient tests were carried out [7,8] in the following manner: The position of four ganged control absorbers was adjusted so as to insert a predetermined amount of reactivity into the core, once a transient rod was removed. The transient rod could be forced out of the reactor core using pneumatic pressure in approximately 80 μs. The resulting rapid reactivity insertion ramp can be considered a near step insertion, particularly from an initial low power.

Shortly after the insertion, the reactor power will increase exponentially with time at a natural exponent period of τ_o. Step-insertion transients in the SPERT-1B(24/32) reactor, initially at a near-zero power level and with nearly stagnant moderator at 20°C, were categorized by the asymptotic inverse reactor period, α_o ($\alpha_o = \tau_o^{-1}$). These latter values

were calculated during SPERT using an Inhour relation (e.g., similar to Equation 1) with the calibrated amount of reactivity to be step-inserted:

$$\alpha_o = \frac{\rho - \beta_{eff}}{\Lambda} + \sum_i \frac{\beta_i \lambda_i}{\alpha_o + \lambda_i} \qquad \text{(Eq. 1)}$$

where ρ is the inserted reactivity, β_{eff} is the total effective delayed-neutron fraction, β_i are the delayed fractions for each of six delayed-neutron precursor groups, λ_i are the decay constants of these groups, and Λ is the prompt neutron generation time. For the prompt critical situation ($\rho > \beta_{eff}$), a plot of α_o vs ρ approaches a straight line, as the first term in Eq. 1 is dominant. The value of Λ has a large effect on the determination of α_o as α_o becomes large, i.e., as the transients become more severe.

Uncertainty in the determination of the asymptotic inverse period results from the uncertainty in the values of Λ and ρ. In the SPERT-1B experiments, each inch of ganged control rod withdrawal near the mid-plane of the reactor was calculated to add 5.6 mk of reactivity [19]. So if the position of the control rods had been known with a possible error of ±0.01 in, the uncertainty in ρ would have been about ±0.06 mk. A variational error analysis technique using the Inhour equation (with Λ = 50 μs) was used to determine reasonable uncertainties for the values of α_o quoted in the SPERT literature.

Two power burst parameters will be used to evaluate the SPERT transient simulations: (i) peak power, P_{max}, and (ii) accumulated energy at time of peak power, E_{tm}. The maximum cladding surface temperature at time of peak power would also have been a useful variable to compare to SPERT experimental data. However, the temperatures presented in the SPERT literature were measured at a variety of locations during the different tests. Presumably, the results were from surviving thermocouples and represent the highest clad temperature measurement available, not necessarily the actual highest temperature. Thus, the peak cladding temperatures predicted by TANK will not be compared to the experimental results. An example of the time behaviour of the temperature during a SPERT simulation is presented later.

A 10% error is allowed for non-linearities in the flux/power relationship, particularly near the time of peak transient power, based on the estimate of SPERT personnel [8]. A further 5% uncertainty is allowed for instrumentation and data acquisition and reduction [7]. A net uncertainty for SPERT peak power and energy data is therefore assumed to be ±15%. This is consistent with the error assignment by Obenchain [20] and by Clancy et al. [21]. Table II lists the SPERT-1B(24/32) transient power burst data for the range of reactivity insertions considered in the TANK benchmarking project. The values of α_o and τ_o with their estimated uncertainties are presented in Table II. The experimental results for P_{max} and E_{tm} are shown with their estimated 15% uncertainty.

Table II. SPERT-1B(24/32) EXPERIMENTAL DATA, WITH ESTIMATED ERRORS.

α_o (s^{-1})	τ_o (ms)	P_{max} (MW)	E_{tm} (MJ)
92.6 ± 1.2	10.8 ± 0.14	849 ±127	13.6 ± 2.0
86.2 ± 1.2	11.6 ± 0.16	635 ± 95	12.3 ± 1.8
62.5 ± 1.2	16.0 ± 0.30	429 ± 64	10.3 ± 1.5
52.6 ± 1.2	19.0 ± 0.43	292 ± 44	9.88 ± 1.48
45.5 ± 1.2	22.0 ± 0.57	210 ± 31	9.98 ± 1.50
42.6 ± 1.2	23.5 ± 0.64	207 ± 31	8.59 ± 1.29
27.8 ± 1.1	36.0 ± 1.45	131 ± 20	7.46 ± 1.12
26.7 ± 1.1	37.4 ± 1.6	85.6 ± 12.8	6.02 ± 0.90
21.4 ± 1.1	46.7 ± 2.3	72.3 ± 10.8	5.40 ± 0.81

In TANK simulations, as in the actual SPERT experiments, the reactivity change is accomplished by withdrawing the control rods a predetermined distance. The transient rod is then modelled to be drawn into the core to reduce k_{eff} to 1. Once the transient is under way, the prompt neutron lifetime is dependent to some extent on the set position of the control rods. In the TANK simulations, Λ is determined to be 51.9 μs with the control rods in their critical position, and with the transient rod completely out of the core. For step insertions of ~12 mk, Λ increases to about 53.1 μs. The values for α_o used to describe TANK simulations were determined with Eq. 1 using the value for Λ determined with TANK.

The main shut-down mechanism terminating the SPERT-1B transients was originally thought to be large-scale void formation. However, it is now believed that most of the void production occurs after the first power peak, as the energy stored in the fuel plates is transported to the coolant. The rapid production of void by a sudden large surface heat flux was studied in a series of water expulsion tests conducted at Argonne National Laboratory [22]. The actual voiding mechanism is still not fully understood, but several different approaches have been made in computer codes for modelling rapid void formation [see references 21, 23].

In TANK, the onset and rapid spread of void in the hot regions of the fuel assemblies is modelled by partitioning the high-power section of each of the 288 fuel cells into 60 axial segments. In TANK, the void formation modelling technique is basically the same as that used for the code PARET [23]. Void formation and collapse contributions are calculated for each location, based on surface heat flux, bubble lifetime, and coolant enthalpy considerations.

5. TANK SIMULATION RESULTS AND DISCUSSION

In TANK simulations, the power generation in each fuelled cell of the reactor model is calculated. Most of the fission energy remains in the fuel plates and some is deposited directly into the light-water moderator. Some energy, though, is deposited in the reflector region outside the core. As mentioned earlier in this paper, the SPERT instrumentation was calibrated in terms of the total energy deposition to the reactor system, including prompt and delayed energy within and outside the core. It is the

power generation within the fuel cells that leads to temperature rise in the fuel plates and moderator and is important to the reactivity feedback effects. The energy deposited to the reflector does not appreciably increase the temperature by virtue of the bulk mass of the extra-core water.

To correctly compare the TANK simulation results to the SPERT experimental data, a determination of the total system power during power bursts is required. Following the method of Stephan et al. [24], the total available energy per fission is divided as follows: prompt energy deposited within the core, 181.2 MeV; prompt energy outside the core, 7.8 MeV; and total delayed energy, 12.8 MeV. No delayed energy is assumed to manifest itself during the brief power burst. Thus, 89.71% of the total available fission energy remains in the core during a rapid transient. A conversion to the SPERT scale for total system energy and power involves multiplying the TANK simulation values for core power and energy by a factor of 0.8971^{-1}.

Many super-prompt-critical transient simulations with the SPERT-1B(24/32) model were run using TANK. These simulation cases span the range of asymptotic inverse periods from actual SPERT transients shown in Table II (i.e., from 20 to 93 s^{-1}).

As an example of a SPERT-1B(24/32) transient simulation with TANK, a power burst analysis is presented in Figs. 2 and 3 and summarized in Table III. This particular transient is the highest α_o case simulated with TANK.

Table III. Description of a TANK simulation of a SPERT-1B(24/32) transient.

Inserted reactivity, $\Delta\rho$	11.85 mk
Prompt-neutron generation time calculated in TANK, Λ	53.09 μs
Asymptotic reactor period, τ_o	10.77 ms
Inverse asymptotic reactor period, α_o	92.89 s^{-1}
Total reactor power peak, P_{max}	850.3 MW
Energy release to power peak, E_{tm}	11.35 MJ

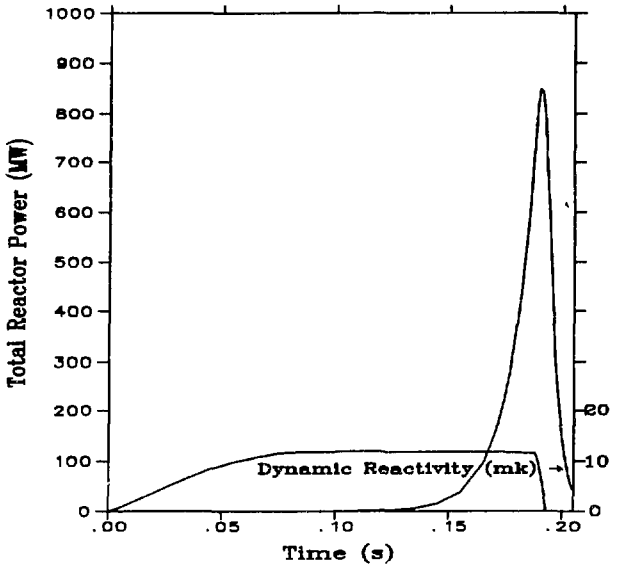

Fig. 1. TANK simulation of a SPERT-1B(24/32) transient with α_o = 93 s^{-1}. Power level and dynamic reactivity are shown.

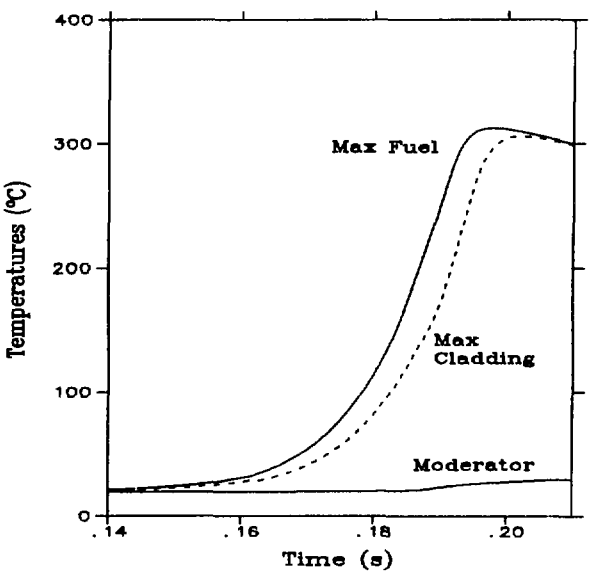

Fig. 2. TANK simulation of peak fuel, cladding surface and bulk moderator temperatures during the 93 s^{-1} power burst.

Figure 1 presents the behaviour of the dynamic reactivity and the total reactor power history for a step reactivity-insertion scenario with α_o = 93 s^{-1}. This transient is assumed to begin at a low initial power level of 500 W. (Note: transient simulations starting from 5 W or 500 W showed negligible differences). The reactivity insertion is seen to take 80 ms, the time needed to eject the transient absorber rod. The total power is seen to peak at 850 MW; by comparison, the actual SPERT experimental value for the peak power for a transient with this value of α_o is 849 MW (see Table II).

Figure 2 shows the corresponding peak fuel centre-line, peak cladding surface, and bulk coolant/moderator temperature for the hottest plate in the core model. These are the predicted temperatures at the hottest axial position in the fuel plate. The peak cladding surface temperatures mentioned in the SPERT data [7] were measured at a variety of locations and do not necessarily indicate the hottest position. For instance, TANK predicts 305°C as the maximum cladding surface temperature, while SPERT data have 228°C. The fuel centre-line temperature is seen in Fig. 2 to peak at 311°C. The cladding temperature peaks shortly afterwards because of heat transfer considerations. After the power peak, the maximum fuel centre-line and cladding surface temperatures are nearly equal: void formation has reduced the heat flow to the coolant. The coolant/moderator temperature is seen to rise slightly during the power burst.

None of the transient simulation cases in this study indicated any fuel or cladding damage. None of the materials exceeded their melting point. For even the high α_o cases, void production was just beginning at the time of the power peak, with void fractions of the order of 0.01 to 0.02. This agrees with the SPERT observation that steam generation in rapid transients became large-scale only after the power peaked. Also, for all of the SPERT transient simulations with TANK, the axial velocity of the light-water moderator/coolant was assumed to be a near-stagnant 0.3 cm/s, the value used also by Woodruff et al. [23].

Figure 3 summarizes the results of the TANK simulations of SPERT-1B(24/32) step-insertion transients for total transient reactor power levels. The results from TANK are fit to a smooth curve for comparison purposes. The SPERT experimental data are indicated by the points with the error bars. These data are also fit to a smooth curve indicated by the dashed line. The internal scatter of the SPERT experimental data is apparent. The TANK results agree well within the error bounds of the SPERT data: recall that the SPERT data are accurate to ±15%; a reproducibility error of ±7% has been assigned [21] to the SPERT peak-power values.

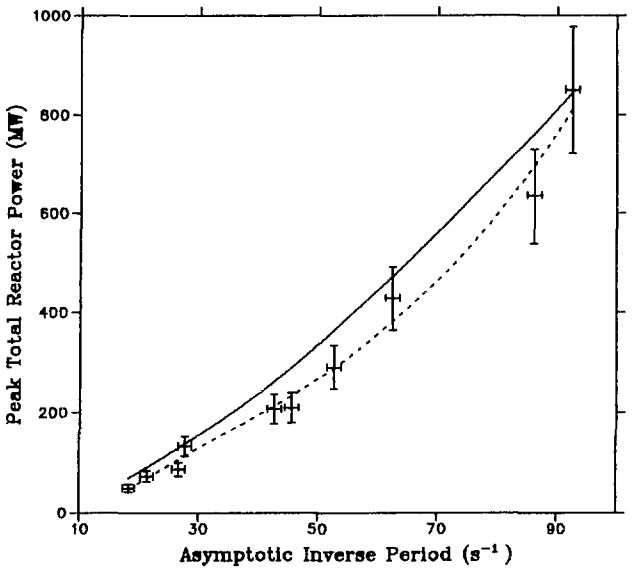

Fig. 3. Comparison of TANK simulation results (solid curve) for peak power levels to SPERT-1B(24/32) experimental data (error bars, fit to the dashed curve).

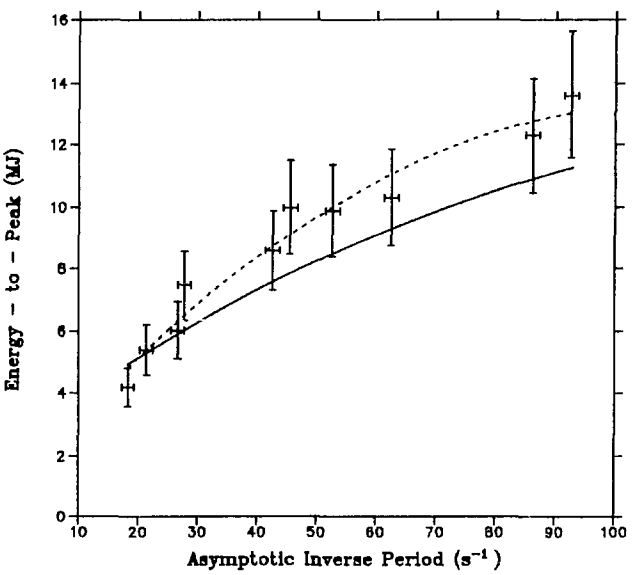

Fig. 4. Comparison of TANK simulation results (solid curve) for energy release at peak power to SPERT-1B(24/32) experimental data (error bars, fit to the dashed curve).

Figure 4 displays the agreement between SPERT data and the TANK simulation determinations for the energy accumulated in the total reactor system up to the time of peak power. The solid curve drawn through the TANK simulation results is within the uncertainty of the SPERT data, fit by the dashed curve. Again, the scatter in the experimental data is evident, a reproducibility error of ±10% has been suggested [21] for the SPERT energy release data. The experimental data also has a measurement uncertainty of ±15%.

The TANK validation study is comparable to the simulations by two other groups: (i) Clancy et al. with the code ZAPP, and (ii) Woodruff et al. with the code PARET. ZAPP is a point kinetics code with special heat transfer routines and correlations developed to apply to plate-type fuel. It models void formation as the constant formation of steam once the cladding temperature has exceeded a threshold. The PARET code provides a coupled thermalhydraulic and point kinetic capability with continuous reactivity feedback and an optional model for estimating voiding during subcooled boiling. PARET was originally created to analyze the SPERT-III experiments for pin- and plate-type cores under power reactor conditions using measured heat transfer information for SPERT. To improve the agreement with the experimental SPERT-1B data, the selection of suitable heat transfer correlations and thermal properties [23] was required.

Figure 5 compares the peak power determinations of each of TANK, ZAPP, and PARET with the SPERT-1B(24/32) data. Bearing in mind the uncertainties of the experimental data, the agreement of all three codes is quite reasonable, particularly for $\alpha_o > 60\ s^{-1}$. At lower values of α_o, PARET and ZAPP tend to underestimate P_{max}, whereas TANK overpredicts P_{max}. The overall scatter in the ratio of calculated-to-experimental peak-power level is less for the TANK simulation than for ZAPP and PARET.

Figure 6 shows the relative agreement of ratios of calculated-to-experimental energy release at time of peak power for TANK, ZAPP, and PARET. All three codes agree reasonably well to the SPERT data. TANK seems to underpredict the energy release by about 14% for large values of α_o. Again, the scatter in the TANK results is smaller than for ZAPP and PARET.

The correlations for heat transfer used in TANK (from SPORTS-M [12]) were originally developed for, or applied to, situations in MAPLE research reactors. No modifications have been made to the heat transfer correlations for the SPERT validation of TANK. That is, the correlations were not revised to reflect actual SPERT plate-type fuel assembly experimental heat transfer data. Also, the void bubble lifetime considered in all the TANK simulations was set at 1 ms, and the residual velocity of the near-stagnant moderator/coolant was set at 0.3 cm/s [23]. The TANK results are somewhat sensitive to these two variables; however, no adjustments were made to improve the agreement with experimental data.

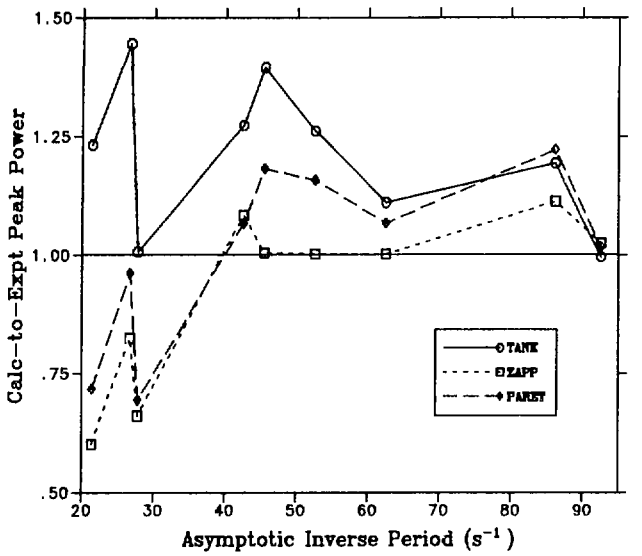

Fig. 5. Comparison of calculated-to-experimental ratios for peak power for computer simulations with TANK, ZAPP, and PARET.

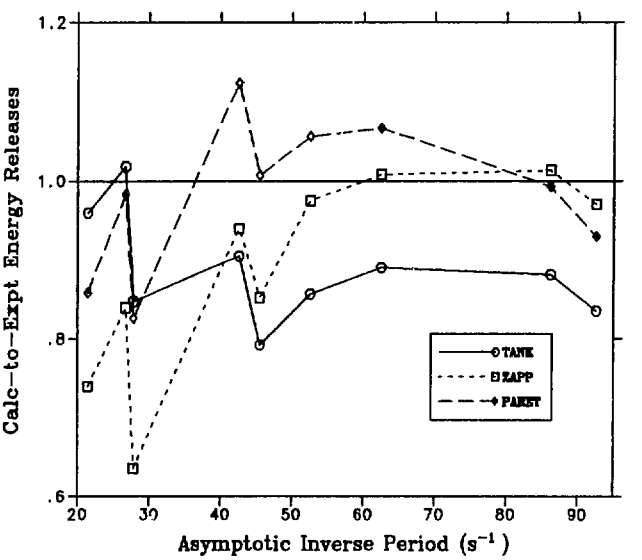

Fig. 6. Comparison of calculated-to-experimental ratios for energy release at time of peak power for computer simulations with TANK, ZAPP, and PARET.

6. CONCLUSIONS

This report presents the results of a series of simulated step reactivity-insertions using the code TANK with a SPERT-1B(24/32) model. The agreement between the results of the TANK simulations and the actual SPERT experimental data is within the limits of uncertainty. The agreement of the TANK simulation with the experimental data is comparable with other computer code studies.

This series of simulations validates TANK for the important class of postulated accident scenarios characterized by super-prompt-critical step reactivity-insertions from low-power levels.

TANK does a good job of describing the SPERT-1B transients. It is therefore a reliable tool for describing similar postulated transients for MAPLE safety analyses.

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