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Coupled Three Dimensional Neutronics/Thermal-hydraulics Code STTA for SCWR Core Transient Analysis

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ABSTRACT

A coupled three dimensional neutronics/thermal-hydraulics code STTA (**S**CWR **T**hree dimensional **T**ransient **A**nalysis code) is developed for SCWR core transient analysis. Nodal Green's Function Method based on the second boundary condition (NGFMN_K) is used for solving transient neutron diffusion equation. The SCWR sub-channel code ATHAS is integrated into NGFMN_K through the serial integration coupling approach. The NEACRP-L-335 PWR benchmark problem and SCWR rod ejection problems are studied to verify STTA. Numerical results show that the PWR solution of STTA agrees well with reference solutions and the SCWR solution is reasonable. The coupled code can be well applied to the core transients and accidents analysis with 3-D core model during both subcritical pressure and supercritical pressure operation.

1 Introduction

In supercritical water cooled reactor (SCWR), the density of inlet coolant is about 800 kg/m^3 and the density of outlet coolant is about 100 kg/m^3. Hence, huge change of the coolant density changes the core slowing-down cross-section field and has an important influence on the power distribution, and forms the strongly coupling characteristic between neutronics and thermal-hydraulics in SCWR. The coupling between neutronics and thermal-hydraulics must be considered in core steady design, and also the spatial power distribution and its change must be considered for core transient and accident analysis. Only after that consideration, the feedback effect can be modeled rightly, the transient process can be simulated truly and core safety performance can be assessed soundly.

By coupling three dimensional neutronics and thermal-hydraulics code, STTA (**S**CWR **T**hree dimensional **T**ransient **A**nalysis code) is developed for SCWR core transient analysis. The reliability of STTA is preliminarily validated by the NEACRP-L-335 PWR benchmark problem and SCWR rod ejection problems.

2 Development of STTA

A coupled three dimensional neutronics/thermal-hydraulics code STTA is developed for SCWR core transient analysis. Nodal Green's Function Method based on the second boundary condition (NGFMN_K) [1] is used for solving transient neutron diffusion equation. The SCWR sub-channel code ATHAS is integrated into NGFMN_K through the serial integration coupling approach.

2.1 Neutron spatial kinetics code

The transient diffusion equation is given by,

$$\begin{cases} \frac{1}{v_g}\frac{\partial \phi_g(\vec{r},t)}{\partial t} - \nabla \bullet D_g \nabla \phi_g(\vec{r},t) + \Sigma_{r,g}\phi_g(\vec{r},t) = \sum_{g'\neq g}\Sigma_{s,g'\to g}\phi_{g'}(\vec{r},t) + \chi_g(1-\beta)\sum_{g'=1}^{G}\nu\Sigma_{f,g'}\phi_{g'}(\vec{r},t) \\ +\sum_{i=1}^{ND}\chi_{g,i}\lambda_i c_i(\vec{r},t) \quad , \quad g=1,\dots,G \\ \frac{\partial c_i(\vec{r},t)}{\partial t} = \beta_i\sum_{g'=1}^{G}\nu\Sigma_{f,g'}\phi_{g'}(\vec{r},t) - \lambda_i c_i(\vec{r},t), \ i=1,..,ND \end{cases} \tag{1}$$

where subscript g denotes energy group, G is number of the energy groups, subscript i denotes precursor group, ND is number of the precursor groups, $\phi_g(\vec{r},t)$ is the flux for group g, cm^{-2}·s^{-1}, $c_i(\vec{r},t)$ is the concentration of the i-th delayed neutron precursor, cm^{-3}, D_g is the diffusion coefficient for group g, cm, $\Sigma_{r,g}$ is the macroscopic removal cross-section for group g, $\Sigma_{f,g}$ is the macroscopic fission cross-section for group g, $\Sigma_{s,g'\to g}$ is the macroscopic scatter cross-section from group g' to group g, cm^{-1}, ν is the number of neutrons per fission, χ_g is the prompt fission spectrum in group g, $\chi_{g,I}$ is the delayed neutron spectrum for delayed neurons emitted by the i-th precursor in group g, λ_i is the decay constant in precursor group i, s^{-1}, β_i is delayed neutron fraction in precursor group i.

The A-stable Backward Euler scheme is used for temporal discretization written as

$$\frac{\partial\phi_g(\vec{r},t)}{\partial t}=\frac{\phi_g(\vec{r},t)-\phi_g(\vec{r},t_0)}{\Delta t} \tag{2}$$

$$\frac{\partial C_i(\vec{r},t)}{\partial t}=\frac{C_i(\vec{r},t)-C_i(\vec{r},t_0)}{\Delta t} \tag{3}$$

, where t is the current time point, t_0 is the previous time point, $\Delta t=t-t_0$ is the time step.

Substituting Eq (3) into precursor equation gives

$$c_i(\vec{r},t)=\frac{c_i(\vec{r},t_0)}{1+\lambda_i\Delta t}+\frac{\Delta t}{1+\lambda_i\Delta t}\beta_i\sum_{g'=1}^{G}\nu\Sigma_{f,g'}\phi_{g'}(\vec{r},t) \tag{4}$$

Substituting Eq (2) and Eq (4) into neutron equation leads

$$-\nabla\bullet D_g\nabla\phi_g(\vec{r},t)+\Sigma_{r,g}\phi_g(\vec{r},t)=-\frac{1}{v_g}\frac{\phi_g(\vec{r},t)}{\Delta t}+\hat{Q}_g(\vec{r},t)+S_g(\vec{r},t_0) \tag{5}$$

, with

$$\hat{Q}_g(\vec{r},t)=\sum_{g'=1}^{G}\Sigma_{S,g'\to g}(\vec{r},t)\phi_{g'}(\vec{r},t) \\ +(\chi_g(1-\beta)+\sum_{i=1}^{ND}\chi_{g,i}\frac{\lambda_i\beta_i\Delta t}{1+\lambda_i\Delta t})\times\sum_{g'=1}^{G}\upsilon\Sigma_{f,g'}(\vec{r},t)\phi_{g'}(\vec{r},t) \tag{6}$$

$$S_g(\vec{r},t_0)=\sum_{i=1}^{ND}\chi_{g,i}\frac{\lambda_i}{1+\lambda_i\Delta t}c_i(\vec{r},t_0)+\frac{1}{v_g}\frac{\phi_g(\vec{r},t_0)}{\Delta t_j} \tag{7}$$

Eq (5) is the fixed source problem (FSP). At every time step, the fixed source is updated by the result of the previous moment, then FSP is solved by NGFMN_K, and the concentration of the precursor at the current moment is updated by the latest flux. The computation at the next time step is repeated the process above.

2.2 Thermal-hydraulics code

The sub-channel thermal-hydraulics code ATHAS (Advanced Thermal-Hydraulics Analysis Sub-channel) [2] can be used to simulate the sub-channel flow distribution in the assemblies of PWR, BWR, SCWR or CANDU during both subcritical pressure and supercritical pressure operation. Especially in SWCR computation, heat is transferred between the moderator channel and the coolant channel, and ATHAS is able to compute the two cases in which the coolant and the moderator flow along the same or opposite direction. The calculation for supercritical water properties is based on a combined method of formulas and lookup table, improving the computation performance and accurate. The redevelopment of ATHAS is performed for coupling computation for SCWR multi-flow core transient analysis.

2.3 Coupling of neutronics and thermal-hydraulics

SCWR three dimensional transient analysis code STTA is developed by coupling three dimensional neutron spatial kinetics code NGFMN_K and sub-channel thermal-hydraulics code ATHAS. Firstly NGFMN_K calculates the core power distribution according to the initial distributions of coolant density, moderator density and fuel temperature. Secondly, ATHAS calculates the water density and fuel temperature distributions based on the core power distribution. Then the neutronics code calculates the power distribution again, using the new distributions of water density and fuel temperature. These evaluations are alternately repeated until the distributions of coolant density, moderator density and fuel temperature are converged.

The SCWR sub-channel code ATHAS is integrated into NGFMN_K through the serial integration coupling approach. Same time step size is adopted in both neutronics and thermal-hydraulics calculation. Implicit coupling method is adopted, i.e., neutronics and thermal-hydraulics evaluations are alternately repeated until power distribution is converged in each time step.

Each assembly is treated as a single channel, and the core is uniformly divided in axial direction for the core evaluation by ATHAS code. The mesh partitions in NGFMN_K and ATHAS usually are inconsistent, especially in axial direction. Volume weight method is used for mesh corresponding of subroutine data in the coupling code. Commonly, the core mesh partitions in axial direction and radial direction can be separated. The weight of each mesh can be gained by the multiplication of weight in axial direction and weight in radial direction.

Correspondence of radial mesh can be realized by prearranging the weight of neutronics and thermal-hydraulics mesh in the input file. But the preparation of input file is complex and inconvenient. Fine mesh covering method is adopted in STTA. The core is divided into series of fine mesh to ensure that every fine mesh only belongs to one subchannel and only one physics node. The transferred data will be firstly mapped to the fine mesh, and then mapped to the target mesh from the fine mesh.

Two-path coolant flow scheme is applied on CSR1000 (**C**hina **S**upercritical water-cooled **R**eactor with the rated electric power of **1000**MWe) thermal-hydraulics design [3]. Only one flow path can be solved per calling ATHAS solver. The inlet boundary conditions of the second flow path depend on the outlet boundary conditions of the first flow path. In addition for transient calculation, the previous data should be storage for both flow paths. However, many common blocks are used for data storage in ATHAS leading procedures and variables are tied together. Thus two ATHAS solvers are used in coupling. Both ATHAS solvers are compiled as the Dynamic Link Libraries (DLL), while only few shared procedures and variables need modification.

3 Verification of STTA

3.1 NEACRP rod ejection benchmark

Due to lack of transient benchmark for SCWR, PWR rod ejection benchmark problem NEACRP-L-335 [4] is chosen for the verification of 3-D transient analysis code STTA. NEACRP rod ejection problem at hot zero power (HZP) and hot full power (HFP) is calculated by STTA and obtained results were compared with the published reference and the revised reference solution. The benchmark core geometry is of the Westinghouse 3-loop core type, with 157 fuel assemblies. The transients are initiated by a rapid ejection of control rod (CR) at HZP or HFP condition. Calculated geometries and conditions of six cases are described as follows:

A1: Octant core geometry and Ejection of the central CR at HZP

A2: Octant core geometry and Ejection of the central CR at HFP

B1: Octant core geometry and Ejection of the peripheral CR at HZP

B2: Octant core geometry and Ejection of the peripheral CR at HFP

C1: Full core geometry and Ejection of one peripheral CR at HZP

C2: Full core geometry and Ejection of one peripheral CR at HFP

The normal power (NP) of the reactor is 2775MW, and the initial core power at HZP is 2775W. There are 157 fuel assemblies and 64 reflector elements, each of width 21.606cm. The detailed condition of six benchmark problems is described in the reference [4].

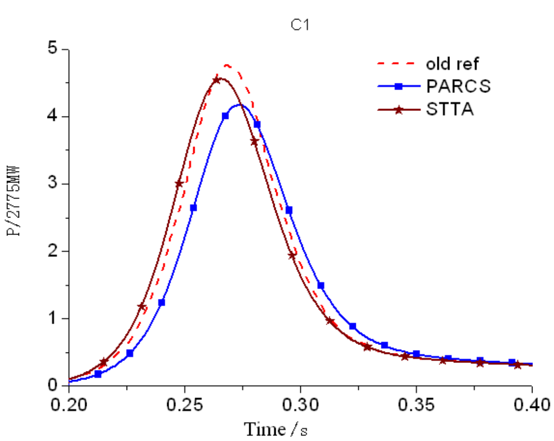
All of the six cases have been calculated by STTA and the results are shown in table 1 and table 2. The numerical results of STTA are in good agreement with the reference solution by PANTHER [5], and also agree well with solutions by PANBOX [6] and NLSANMT/COBRA-IV [7]. Of the six, problem C1, the HZP full core case, is most severe and challenging and is chosen for detailed results comparison. The detailed results of case C1 are shown in figure 1, where "old ref" means the early published results by PANTHER [6], and "PARCS" means the results calculated by stand-alone PARCS. The power curve by STTA is more close to old reference than PARCS, and the thermal-hydraulics curve by STTA is in good agreement with PARCS.

Table 1 Results of NEACRP-L-335 Rod Ejection Benchmark (A1, B1, and C1)

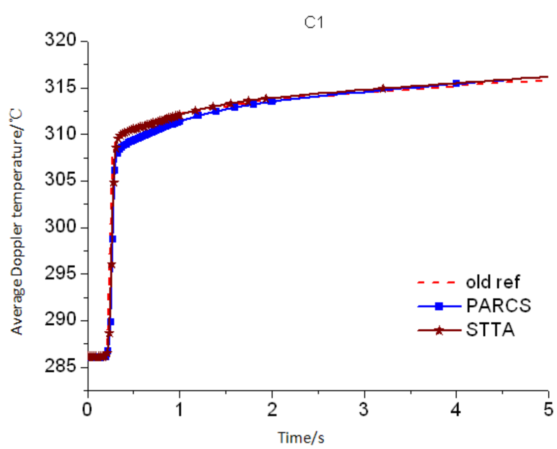
	Critical boron concentration/ppm			Power at peak (NP)			Time to the power peak (sec)			Power at 5 sec (NP)		
	A1	B1	C1	A1	B1	C1	A1	B1	C1	A1	B1	C1
Reference	561.20	1247.98	1128.29	1.2678	2.3151	4.4112	0.538	0.523	0.271	0.1969	0.3197	0.1460
PANBOX	564.80	1253.70	1133.40	1.0330	2.4000	4.7180	0.600	0.520	0.270	0.1970	0.3250	0.1500
NLSANMT/ COBRA-Ⅳ	533.39	1223.50	1101.50	1.5281	2.3110	4.5021	0.513	0.538	0.270	0.2009	0.3218	0.1484
STTA	561.15	1248.10	1128.30	1.2932	2.3638	4.5457	0.536	0.520	0.266	0.1957	0.3167	0.1446

Table 2 Results of NEACRP-L-335 Rod Ejection Benchmark (A2, B2, and C2)

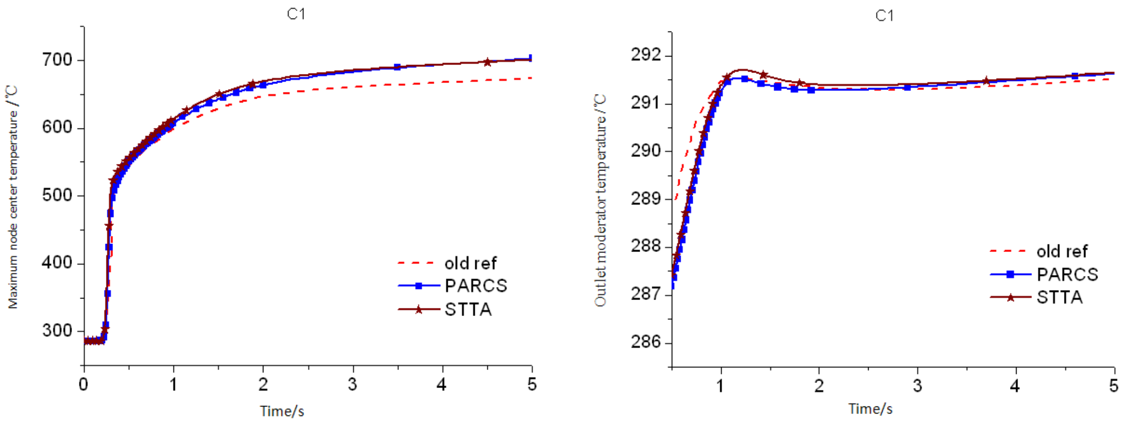
	Critical boron concentration/ppm			Power at peak (NP)			Time to the power peak (sec)			Power at 5 sec (NP)		
	A2	B2	C2	A2	B2	C2	A2	B2	C2	A2	B2	C2
Reference	1156.63	1183.83	1156.63	1.0830	1.0640	1.0734	0.095	0.100	0.095	1.0362	1.0394	1.0314
PANBOX	1162.60	1189.40	1162.70	1.0800	1.0690	1.0740	0.100	0.110	0.100	1.0360	1.0410	1.0320
NLSANMT/ COBRA-Ⅳ	1128.59	1157.19	1128.59	1.0894	1.0646	1.0809	0.098	0.103	0.100	1.0376	1.0392	1.0333
STTA	1151.90	1179.20	1151.90	1.0841	1.0656	1.0752	0.095	0.100	0.098	1.0362	1.0397	1.0315



a Core relative power（C1）



b Average Doppler temperature（C1）



c Maximum node center temperature（C1） d Outlet moderator temperature（C1）

Figure 1 Results Comparison of Case C1

3.2 SCWR rod ejection problems

Two rod ejection problems at HZP and HFP are calculated for SCWR. The core geometry is of the CSR1000 core type, with 157 fuel assemblies. The normal power of CSR1000 is 2300MW, and the initial core power at HZP is 2300W. The position of the ejected rod is E11 at the second flow path. For HZP rod ejection problem, the initial position of the lower ejected rod edge from the bottom of the active zone is 7.7 cm, while the final position is 420.0 cm in 0.1 s. For HFP rod ejection problem, the initial position of the lower ejected rod edge from the bottom of the active zone is 210.0 cm, while the final position is 420.0 cm in 0.1 s. The rod worth of HZP and HFP problems are \$0.899 and \$0.385 respectively.

The detailed results of HZP rod ejection problem and HFP rod ejection problem are shown in figure 3 and figure 4 respectively. The peaking power of HZP rod ejection problem is 0.68 NP, and the maximum cladding surface temperature is 440℃. The peaking power of HFP rod ejection problem is 1.74 NP, and the maximum cladding surface temperature is 1075℃.

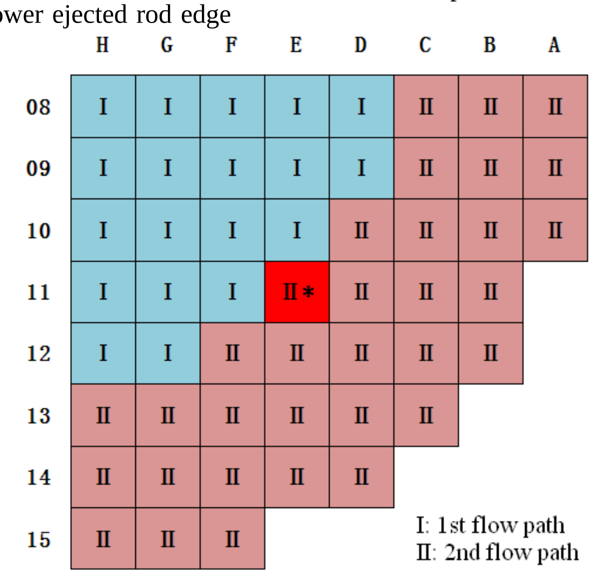
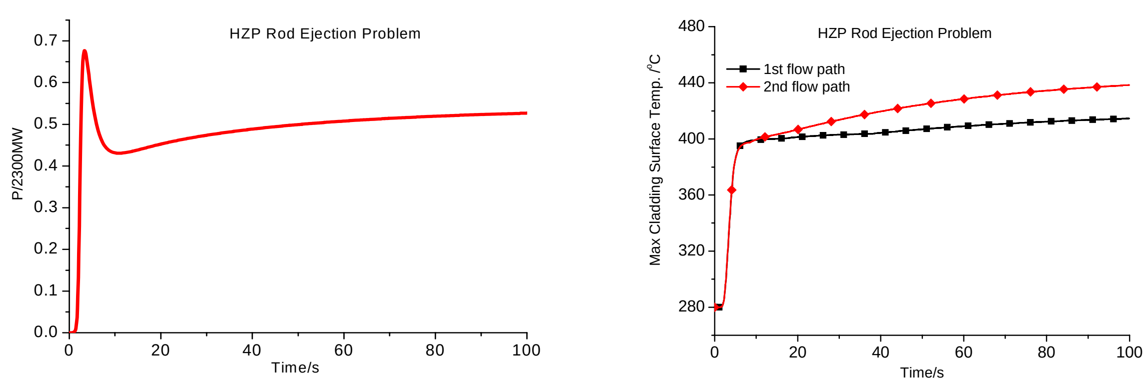
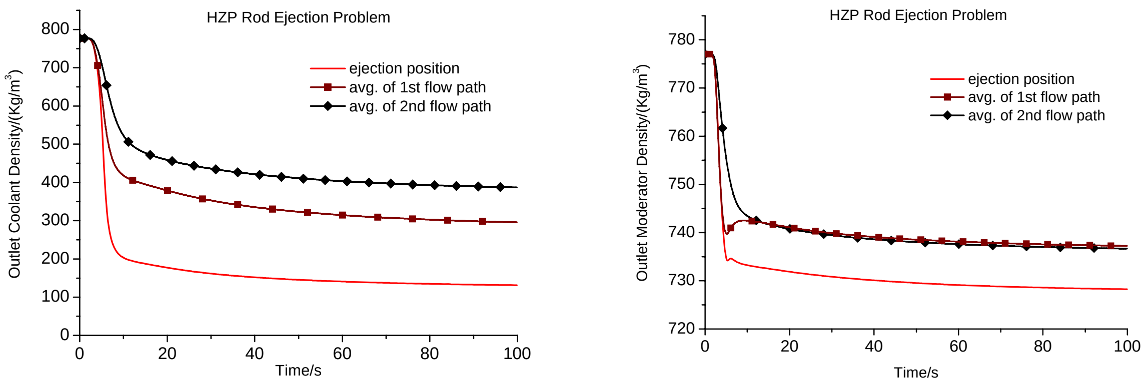


Figure 2 CSR1000 1/4 core and ejection rod position

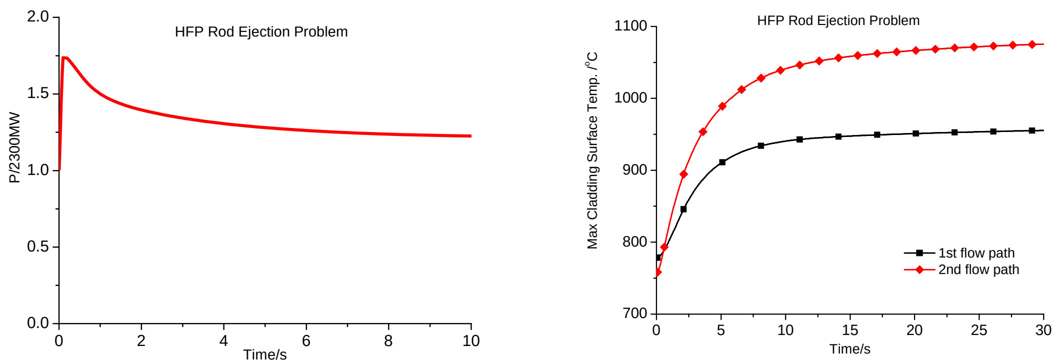


a Core relative power b Maximum cladding surface temperature

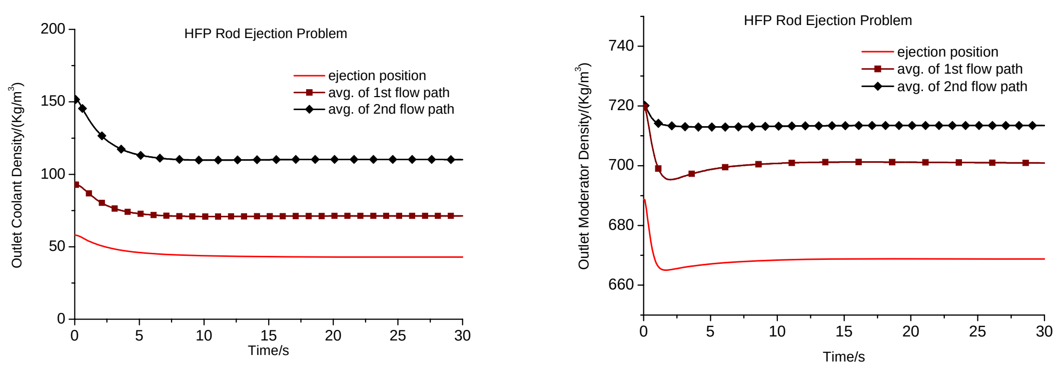


c Outlet coolant density d Outlet moderator density

Figure 3 Results of HZP rod ejection problem



a Core relative power b Maximum cladding surface temperature



c Outlet coolant density d Outlet moderator density

Figure 4 Results of HFP rod ejection problem

4 Conclusions

A SCWR three dimensional transient analysis code STTA is developed by coupling three dimensional neutron spatial kinetics code NGFMN_K and SCWR sub-channel thermal-hydraulics code ATHAS. The reliability of STTA is preliminarily validated by the NEACRP-L-335 PWR benchmark problem and SCWR rod ejection problems. The numerical results show that STTA meets the requisition of code for SCWR core 3-D transient analysis. The coupled code STTA can be well applied to the core transients and accidents analysis with 3-D core model during both subcritical pressure and supercritical pressure operation.

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