BENCHMARK CALCULATIONS FOR VVER-1000 FUEL ASSEMBLIES USING URANIUM OR MOX FUEL

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ABSTRACT

Burnup benchmark calculations are performed for VVER-1000 LEU and MOX fuel assemblies with the Monte-Carlo codes MCU-REA, CONKEMO, MCNP, KENO and with deterministic codes TVS-M, APOLLO-2 and CASMO. This benchmark serves for investigating the quality of design codes when used for calculating systems containing weapon grade plutonium. Various

states of the fuel assemblies are considered. Reactivities and power distributions are studied. The results obtained for the calculated cases are in very satisfactory agreement.

1. INTRODUCTION

There exist various international activities aiming at the reduction of plutonium from nuclear weapons by using it as fuel for nuclear power reactors. In the frame of the "French-German-Russian Trilateral Project on Civil Uses of Plutonium from Dismantled Russian Nuclear Weapons Subject to Arms Reduction", the qualification of nuclear design methods for such conditions is addressed. A series of benchmark problems were defined to compare results obtained with code systems of participating institutions. The main objectives are to determine the accuracy of analytical methods for calculating reactivity equivalents and power density distributions. The first step refers to steady state fuel assembly calculations of VVER-1000.

2. DESCRIPTION OF THE BENCHMARK

Four different VVER-1000 fuel assemblies were specified. These hexagonal assemblies consist of 312 fuel cells and 19 cells with tubes containing moderator or absorber rods. An uranium assembly (Variant 1) uniformly contains fuel pins with a ^{235}U enrichment of 3.7 %, a MOX assembly (Variant 2) contains fuel pins with weapon grade plutonium, with fissile Pu contents of 4.2%, 3.0% and 2.0%, arranged in three zones from the center to the edge of the fuel assembly. Additionally, a LEU (low enriched uranium) and a MOX assembly were defined with 12 regular fuel pins each replaced with LEU fuel poisoned with gadolinium (Variants 3 and 4 respectively).

Various states of these fuel assemblies were defined, concerning fuel and moderator temperatures, moderator densities, boron contents and Xe/Sm concentrations. Also, controlled states with different absorber materials were specified. The main parameters of assembly states are given in Table 1.

It is required to calculate multiplication factors, power distributions and the concentration of some important isotopes during burnup.

3. BRIEF DESCRIPTION OF THE CODES USED

To obtain results with a high accuracy to be used as a reference solution, a number of cases for the fresh and burnt state of all fuel assemblies were calculated with the Monte Carlo codes MCU-REA, MCNP-4B, CONKEMO and KENO-VI. Two of them (MCU-REA and CONKEMO) were used when performing the burnup calculations, too.

The results calculated with reference codes serve for determination of the accuracy of design codes TVS-M (Russia), APOLLO-2 (France) and CASMO-4 (Germany).

The brief description of the codes used for calculations is given below.

MCU-REA code

MCU-REA [1] is the advanced version of the MCU-RFFI/A code, certified by Russian safety authorities. It is based on the DLC/MCUDAT-2.1 nuclear data library.

MCU-REA is a Monte Carlo code for solving the neutron transport and burnup problems.

MCU-REA is a pointwise continuous energy code permitting one to model systems with any geometry. The subgroup method is used to describe the unresolved resonance cross section. It is possible to use a detailed description of cross sections in the resolved resonance region. For the most important isotopes an "infinite" number of energy points is used to describe the resonance curve. In this case cross sections are calculated during the Monte Carlo run at every energy point on the basis of the resonance parameter library. It permits one to perform the calculations without preliminary tabulation of cross sections and allows the user to estimate temperature effects independent of the cross section library state. For the thermal energy region, the Monte Carlo game is played using the $S(\alpha,\beta)$ scattering law for hydrogen bound in water or free gas model for others isotopes. One may solve the problems taking into account both the prompt neutron and the delayed neutron fission spectra.

It should be noted that along with the POINTWISE option of MCU-REA code the more fast MULTIGROUP option, which solves the transport equation using the 40-group approximation for thermal region (0–1 eV), was used for calculating some cases (Variant 1 and initial point of Variant 3).

The MCU-REA code and MCUDAT-2.1 library were verified and validated by using the results of more than 400 criticals.

The statistical error (1 standard deviation) in MCU-REA calculations of separate states at burnups 0, 10, 30 and 50 MWd/kgHM is less than 0.1% for K_{eff} and less than 2% for local values of fission rate. All burnup calculations were performed with statistical errors less than 0.15% in K_{eff} value.

CONKEMO code package

The code complex CONKEMO [2] was specially developed for burnup calculation. It consists of the following main program units:

– CONSYST prepares the 299 group cross-sections of medium based on ABBN-93 neutron data library [3];

– KENO-VI [4] is used for neutron flux calculations in arbitrary geometry (including hexagonal one) by the Monte-Carlo method;

– ORIGEN-S [5] performs isotope evaluation calculations;

– MAYAK provides the joint work of the codes in the complex, information flows, process the results.

Short description of the above mentioned codes are given below.

The CONSYST code is the main part of CONSYST2 cross-section provision system, which provides the use of ABBN-93 cross sections for various practical applications. CONSYST calculates microscopic group cross-sections of nuclides in the medium, neutron and photon cross-section of the medium etc. CONSYST provides cross-sections for such transport codes as ANISN, DOT, TWODANT, also it gives an opportunity to make use of ABBN-93 data in KENO-VI Monte Carlo calculations etc. CONSYST2 system also includes sets of service procedures.

KENO-VI is part of the American SCALE 4.3 system and performs precision calculations in arbitrary 3-D geometry by the Monte Carlo method.

ORIGEN-S is also part of the SCALE 4.3 system. Cross-sections from original ORIGEN libraries are updated during calculations. Multi-group (299 groups) library of fission products contains only capture cross-sections (as original ORIGEN library). These cross-sections are produced on the basis of the FOND 2.2 library of evaluated neutron files for 169 nuclides.

MAYAK makes possible the joint use of CONSYST processing code together with neutron transport codes (KENO and MCNP) with burnup codes (ORIGEN). Set of batch files provides sequential code start up.

The statistical uncertainty (1 standard deviation) in K_{inf} calculations obtained by KENO-VI code included in CONKEMO complex is equal to about 0.02% in states with power distribution calculations and is about 0.04% in the other states.

MCNP-4B

The Monte Carlo code MCNP-4B [6] is applied with a point-wise cross-section library generated by IKE Stuttgart. The library is mainly based on JEF-2.2 data, and some nuclides from ENDF/B-VI.

The statistical uncertainties (1 standard deviation) are approximately 0.0006-0.0007 for K_{eff} and 0.0045-0.009 for the local values of pin power.

KENO-VI code

The Monte Carlo code KENO-VI [4] is a part of the SCALE-4.3 package. Unlike the standard SCALE treatment, in the present investigation it is used with a JEF-2.2 based 292-group nuclear cross-sections library. The resonance treatment of the group cross-sections has to be performed in advance. This is done with the BONAMI code using the Bondarenko method for the unresolved resonance region, and with the collision probability code RESMOD [7] for the resolved

resonance region, solving the transport equation for the corresponding cylindrical cells on a very fine energy mesh.

The statistical uncertainties (1 standard deviation) are approximately 0.0005-0.0006 for K_{eff}.

TVS-M code

TVS-M (RRC KI, Russia) [8] is a 2-D spectral code for VVER pin cell and assembly burnup calculations, which uses 48-group (24 thermal groups, boundary energy of 0.625 eV) nuclear data library obtained from the same source as MCU-REA library. For resonance nuclides (Th, U, Pu) files of resonance parameters are also available giving a possibility to obtain cross sections for any point in energy region of resolved resonances. In the thermal energy region for oxygen and carbon the scattering matrices obtained in terms of gas model are used. For hydrogen bonded in water molecule the scattering matrix is obtained from the ENDF/B recommended data in terms of the Koppel model.

The TVS-M calculation procedure can be subdivided into two main steps: detailed calculation of pin cells of all types and the calculation of the fuel assembly (FA) as a whole.

When calculating the *pin cell* in the epithermal energy region a detailed calculation of group spatial-energy distribution of neutron flux is performed. Each group is divided into an arbitrary number of intervals equal in lethargy, and then the calculation is performed at each point of group division. To take into account group cross-section resonance self-shielding the subgroup approach is applied for the unresolved resonance region. In the resolved resonance region TVS-M calculate cross-sections of resonance nuclides for every energy point with the use of nuclide resonance parameters.

In the thermal energy region the TVS-M code solves the standard multi-group equation of thermalization with the neutron sources from the epithermal energy region formed previously.

Calculation of neutron spatial distribution is carried out by dividing the cells into an arbitrary number of annular material zones and by the use of the passing through probability (PTP) method.

For the determination of *fuel assembly* neutronic characteristics the TVS-M code uses the diffusion fine-mesh calculation. Along with the standard six-point scheme the refined scheme permitting to keep the accurate (i.e. obtained from solving of transport equation for the cell) connection between cell averaged neutron flux and values of flux and current at the cell boundary can be used.

The calculation of the fuel nuclide composition as function of burnup is performed with the use of the Runge-Kutta method for heavy nuclides from ^{232}Th to ^{244}Cm and for 98 fission products. The isotopic depletion is calculated for each fuel pin and for each region containing a burnable absorber.

APOLLO-2 code

APOLLO-2 [9] is a 2-D transport code, which features a modular architecture where the data flow is represented in a user-oriented supervision language. A multigroup library (biblio CEA-93-V3) based on JEF-2.2 evaluation is used. The energetic mesh is divided in 172 groups.

The main flux is calculated by the collision probability method (*Pij* method). The interface current method is used to calculate each assembly. In this case, a unit of assembly is sub-divided into cells and Collision Probability Matrices are computed for each uncoupled cell. The detailed flux can be then reconstructed from the knowledge of interface currents surrounding each cell.

For the collision probability flux calculation, the flux is supposed constant in each region. To represent in and out angular fluxes, 3 kinds of approximations can be used.

UP0 : uniform and isotropic angular flux.
UP1 : uniform and anisotropic angular flux.
LP0 : linear and isotropic angular flux.

With a UP0 angular flux, for each cell, collision matrixes can be calculated with the Wigner cylindrization approximation. The heterogeneous option allows to calculate transmission probability in a real geometry. With a hexagonal geometry, only the UP0 option is available (in a near future, UP1 option will be able to be used). The heterogeneous option was chosen to calculate the flux.

The used burnup chain is composed of 20 heavy nuclides from U^{234} to Cm^{247} and 76 fission products.

Pin power distributions calculated by APOLLO2 take explicitly into account energy release per fission and capture for each isotope.

APOLLO-2 code is validated for UOX and MOX fuels and widely used by EDF and FRAMATOME. This qualification is based on research facilities experiments (critical mock_up) and on commercial reactor measurements feedback.

APOLLO-2, linked to advanced nodal codes in the Framatome nuclear code package SCIENCE and in the CEA nuclear code package CRONOS, is qualified for computation of MOX cores in France and Belgium. Benchmarks on MOX cores using the SCIENCE package show a good accuracy for all measurements, consistent with that obtained on UOX cores.

CASMO-4 code

CASMO [10] is a multigroup two-dimensional transport code for burnup calculations on BWR and PWR fuel assemblies or simple pin cells. The code handles geometry of cylindrical fuel rods of varying compositions, in a square pitch array.

For these benchmarks, a test version of CASMO-4 with the capability of treating hexagonal geometries was used.

For nominal operational states of each fuel assembly, burnup calculations were performed with the cross section data shipped with this code package. This neutron data library is based mainly on data from ENDF/B-IV. Microscopic cross-sections are tabulated in 70 energy groups, covering the energy range from 0-10 MeV. It contains an updated neutron library with resonance shielding for Pu and Gd isotopes. Resonance calculations are done for these isotopes.

The effective absorption and fission cross-sections in the resonance energy-region for important resonance absorbers are calculated using an equivalence theorem. The basic principles for the resonance treatment are similar to those in the code WIMS.

The isotopic depletion as a function of irradiation is calculated for each fuel pin and for each region containing a burnable absorber. A predictor-corrector approach is used for the burnup calculation. The burnup chains, with the isotopes linked through absorption and decay, are linearized and 24 separate fission products, 2 pseudo fission products and 17 heavy nuclides are treated.

CASMO is verified/qualified for calculation of Pu recycling in German BWRs and PWRs. Combined with 3 dimensional coarse mesh reactor calculations on the basis of two group microscopic cross sections the core behavior and specific measurements on MOX containing cores are precalculated with good quality.

4. CALCULATION RESULTS

The available results of calculations obtained for the assemblies with the fresh fuel make it possible to compare:

- multiplication constants (K_{eff}) for various assembly states;
- various reactivity effects (Doppler, temperature effect, core overheating effect and so on);
- pin-by-pin power distribution.

In addition the K_{eff} dependence on burnup calculated both with design (TVS-M, APOLLO-2 and CASMO-4) and precise (MCU-REA, CONKEMO) codes is compared.

4.1 SEPARATE STATES CALCULATIONS

The K_{eff} calculation results for the assemblies with fresh fuel are given in Table 2. The data of this Table show that the agreement between the Monte Carlo results is very satisfactory. Maximum differences are found not to exceed 0.6-0.7% in K_{eff}. One of the possible reasons of the observed discrepancies is the different origin of nuclear data.

When the results calculated with the design codes are taken into consideration the scattering of the results somewhat increases. However the maximum difference does not exceed 1% in K_{eff} for all cases but the cases corresponding to MOX fuel assemblies under “accident” conditions (states S8, S16) where the discrepancies reach ~2%.

The MCU-REA and TVS-M codes, which are based on the same nuclear data source, demonstrate a very good agreement in case of LEU assemblies (Variant 1 and 3). Differences in K_{eff} do not exceed 0.35%. In case of MOX assemblies the differences are somewhat larger but for the most of cases less than ~0.75%, the TVS-M overestimating K_{eff} values. The largest discrepancies (of about 1.2%) are observed for the state S8 corresponding to the “accident” conditions.

The data of Table 2 and results on burnup calculations (see Figure 15-Figure 18) indicate that different codes probably differently determine “equilibrium” concentrations of Xe and Sm. So it’s rather difficult to compare the poisoning effect at the beginning of burnup.

4.2 REACTIVITY EFFECTS

The results of calculation of various reactivity effects are presented in Table 3 and Table 4. The value of reactivity effect R was defined as follows: $R=100\times(K_{eff}(S_i)-K_{eff}(S_j))/(K_{eff}(S_i)\times K_{eff}(S_j))$. The following effects were compared: Doppler and total temperature effects, soluble boron worth, control and U-Gd rods worth and effect of core overheating. However, only 3 codes (TVS-M, CONKEMO and APOLLO2) give Doppler and total temperature effects calculated at different temperatures, with and without Boron. To make more reliable conclusions, the results set have to be completed.

As is seen from Table 3 the codes MCU-REA, CONKEMO, TVS-M and APOLLO-2 demonstrate rather good agreement when calculating *the soluble boron worth*. The observed differences do not exceed 3-4% for LEU assemblies and 6-7% for the MOX ones, APOLLO-2 slightly underestimating the effect in comparison with the others.

The data of Table 3 shows that in case of uniform uranium assembly (Variant 1) TVS-M code underestimate *Doppler effect* value by 6-8% whereas CASMO-4 noticeably overestimates this effect. The results obtained with the other codes are very close. In case of MOX assembly (Variant 2) the highest (APOLLO-2) and the lowest (MCU-REA) Doppler effect values differ by ~19%. The results obtained with the other codes lie within a 9% interval. Large differences should be noted for the Monte Carlo solutions. TVS-M results get nearer to MCNP ones and APOLLO2 results get nearer to CONKEMO ones. APOLLO2 was also compared to TRIPOLI 4 (CEA Monte Carlo code) results and agreement is generally good. For the fuel assemblies containing U-Gd rods the differences between the results are approximately the same as in case of absence of the rods. Since in most of the cases the absolute value of the effect is rather small and Monte-Carlo statistical uncertainty is noticeable the agreement observed can be considered as satisfactory.

The data on *total temperature effect* calculation given in Table 3 shows that for all cases all Monte Carlo codes give very close results, the differences do not exceed 3.5%. The only exception is somewhat larger underestimation of this effect by the CONKEMO code in case of uniform LEU assembly (Variant 1). Possibly this good agreement can be result of some compensatory effects. More detailed studies are needed to make more definite conclusion. If we take into consideration the results obtained with the design codes the result scattering increases. It is possible to state that TVS-M code gives very close results to the others in case of LEU assemblies and systematically underestimate the effect (~ by 10-12%) for the MOX ones.

All the Monte Carlo codes agree well when calculating the *effect of core overheating*; the differences do not exceed 3.5%. The TVS-M code gives close results to the MCU-REA and other precise codes, whereas the APOLLO-2 show a slight tendency to overestimation of the reactivity effect in case of MOX assemblies.

As is seen from the Table 3 the results of *control rods worth* calculation are in a good agreement. The difference between maximum (CONKEMO) and minimum (CASMO-4) values does not exceed ~5%.

The results of calculation of *U-Gd pins worth* are shown in Table 4. As is seen from the Table the results agree rather well and in the most of cases the difference from the average value is not more than 3-4%. The maximum deviations are observed for the Xe/Sm poisoned states (S1, S9) of MOX assemblies and for the states corresponding to the “accident” conditions (S8, S16). Besides, it is possible to state some increasing of the discrepancies for MOX assemblies in comparison with the LEU ones. For instance APOLLO-2 systematically underestimates the effect value in case of Xe/Sm poisoned MOX assemblies by 11-15%. (The equilibrium Xe and Sm concentrations were not specified in the benchmark. So, concentrations takes by the participants could be different. It is then difficult to conclude on the states S1 and S9)

4.3 POWER DISTRIBUTION

The results of comparisons of pin-by-pin power distribution are presented on Figure 1-Figure 14. As is seen from the Figures all codes demonstrate a highly satisfactory agreement. The maximum discrepancies of local pin power values are about 3% for all states with the exception of state SA2 (state with B_4C control rods with 80-% enriched boron inserted) where they reach 5-6%. Besides, the CASMO-4 code somewhat overestimates U-Gd pin power (approximately by 10%) in case of assemblies with gadolinium pins in comparison with the other solution.

It should be noted that some codes such as MCU REA calculate the fission rate distribution instead of pin powers. On Figures 9 and 12, APOLLO2 values correspond to fission rate distribution as well. Pin powers distribution has been calculated too. However, in Gadolinium pins, the pin powers calculated with APOLLO2 are approximately 40% higher than fission rates. The main interest for this benchmark is to estimate correctly flux variation and reactivity impacts - particularly due to Gadolium pins disposal -. A comparison of reaction rates is sufficient.

4.4 BURNUP CALCULATIONS

The burnup calculations were performed with the use of both precise Monte Carlo codes (MCU-REA and CONKEMO) and deterministic codes (APOLLO2, CASMO-4, TVS-M). The comparison results are given on Figure 15-Figure 18.

The data of these Figures shows that for all burnup points the differences in K_{eff} do not exceed 1% for uranium assemblies and ~2% for the MOX assemblies. And within the burnup range of 0-30 MWd/kg the discrepancies are of the order of 0.5-0.6% (with the exception of very beginning where the Xe/Sm poisoning process could be described differently).

To interpret correctly the comparison results it is necessary to involve the information on burnup dependence of concentrations of basic nuclides and fission products.

CONCLUSIONS

The performed analysis shows that in the whole the codes used in calculations demonstrate a satisfactory agreement with each other and so they can describe reliably fuel assemblies containing MOX from weapon grade plutonium planned to be used in VVER-1000 reactors. It should be noted that this comparison is performed with two codes (CASMO-4 and APOLLO-2) qualified on experiments and commercial reactors.

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TABLES AND FIGURES

Table 1 State parameters

State	Fuel zones temp., K	Non-fuel zones temp., K	Moderator density, g/cm^3	C_B, in ppm	Absorber pin type	^{135}Xe, ^{149}Sm
S1	1027	575	0.723	600	-	Eq.
S2	1027	575	0.723	600	-	0.0
S3	800	575	0.723	600	-	0.0
S4	575	575	0.723	600	-	0.0
S5	473	473	0.875	600	-	0.0
S6	300	300	1.003	600	-	0.0
S7	1500	575	0.723	600	-	0.0
S8	2000	575	0.200	600	-	0.0
S9	1027	575	0.723	0	-	Eq.
S10	1027	575	0.723	0	-	0.0
S11	800	575	0.723	0	-	0.0
S12	575	575	0.723	0	-	0.0
S13	473	473	0.875	0	-	0.0
S14	300	300	1.003	0	-	0.0
S15	1500	575	0.723	0	-	0.0
S16	2000	575	0.200	0	-	0.0
SA1	1027	575	0.723	600	B_4C (natural)	0.0
SA2	1027	575	0.723	600	B_4C (enriched)	0.0

Table 2 K_{eff} values for the fresh fuel.

	State	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	SA1	SA2
VARIANT 1	APOLLO-2	1.2399	1.2939	1.3014	1.3099	1.3264	1.3354	1.2806	0.9986	1.3038	1.3647	1.3727	1.3816	1.4159	1.4408	1.3507	1.0098		
	TVS-M	1.2369	1.2858	1.2927	1.3004	1.3163	1.3241	1.2736	1.0019	1.3035	1.3579	1.3653	1.3735	1.4075	1.4318	1.3450	1.0136	1.0056	0.9360
	MCU-REA	1.2345	1.2865		1.3022		1.3260		1.0008				1.3735					1.0053	0.9355
	CONKEMO	1.2396	1.2944	1.3017	1.3101	1.3250	1.3316	1.2814	0.9987	1.3049	1.3662	1.3739	1.3828	1.4176	1.4389	1.3526	1.0110	1.0045	0.9336
	CASMO-4	1.2448	1.2843		1.3028		1.3243		1.0095		1.3546							1.0064	0.9403
	KENO		1.2911		1.3071		1.3311		1.0044		1.3610							1.0045	
	MCNP		1.2918		1.3073		1.3314		1.0041		1.3633							1.0055	
VARIANT 2	APOLLO-2	1.2141	1.2481	1.2572	1.2673	1.3028	1.3295	1.2322	0.9300	1.2476	1.2845	1.2939	1.3046	1.3530	1.3957	1.2677	0.9354		
	TVS-M	1.2117	1.2501	1.2583	1.2674	1.2986	1.3199	1.2358	0.9491	1.2480	1.2891	1.2975	1.3070	1.3520	1.3900	1.2741	0.9550	1.0308	0.9564
	MCU-REA	1.2124	1.2426		1.2585		1.3175		0.9415				1.2972					1.0249	0.9506
	CONKEMO	1.2064	1.2429	1.2515	1.2612	1.2955	1.3196	1.2276	0.9383	1.2395	1.2797	1.2886	1.2988	1.3477	1.3873	1.2635	0.9436	1.0210	0.9485
	CASMO-4	1.2237	1.2523		1.2705		1.3285		0.9389		1.2890							1.0384	0.9646
	KENO		1.2453		1.2636		1.3224		0.9381		1.2813							1.0254	0.9505
	MCNP		1.2478		1.2649		1.3255		0.9381		1.2835							1.0270	0.9520

Table 2 (Continuation)

	State	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	SA1	SA2
VARIANT 3	APOLLO-2	1.1353	1.1804	1.1873	1.1950	1.2131	1.2301	1.1682	0.9352	1.1882	1.2387	1.2460	1.2541	1.2877	1.3202	1.2259	0.9443		
	TVS-M	1.1364	1.1774	1.1836	1.1906	1.2106	1.2281	1.1664	0.9368	1.1920	1.2371	1.2438	1.2512	1.2877	1.3218	1.2255	0.9462	0.9432	
	MCU-REA	1.1333	1.1757		1.1889		1.2264		0.9336				1.2479					0.9416	
	CONKEMO	1.1357	1.1786	1.1851	1.1926	1.2110	1.2289	1.1670	0.9382	1.1897	1.2369	1.2437	1.2515	1.2869	1.3215	1.2248	0.9475	0.9393	
	CASMO-4	1.1400																	
	KENO		1.1783				1.2297				1.2387							0.9410	
	MCNP		1.1800				1.2313				1.2407							0.9418	
VARIANT 4	APOLLO-2	1.1688	1.1918	1.2002	1.2097	1.2399	1.2631	1.1770	0.9027	1.2003	1.2251	1.2339	1.2438	1.2857	1.3235	1.2097	0.9077		
	TVS-M	1.1599	1.1949	1.2025	1.2111	1.2388	1.2586	1.1813	0.9209	1.1933	1.2306	1.2386	1.2475	1.2878	1.3232	1.2165	0.9264	0.9922	
	MCU-REA	1.1523	1.1877		1.2019		1.2558		0.9097				1.2380					0.9864	
	CONKEMO	1.1511	1.1845	1.1924	1.2013	1.2322	1.2538	1.1703	0.9075	1.1819	1.2185	1.2266	1.2358	1.2789	1.3156	1.2040	0.9118	0.9829	
	CASMO-4	1.1696																	
	KENO		1.1896				1.2597				1.2235							0.9879	0.9191
	MCNP		1.1922				1.2623				1.2255							0.9886	0.9180

Table 3 Reactivity effects ($R=100*(K(S_i)-K(S_j))/K(S_i)*K(S_j)$) at zero burnup point calculated by various codes.

		Boron worth, %			Doppler effect, %						Temperature effect, %				CR worth		Core overheating	
					C_B=600 ppm			C_B=0 ppm			C_B=600 ppm		C_B=0 ppm		(B_4C)		C_B, ppm	
		T_m= 575K	T_m= 473K	T_m= 300K	T_f= 800K	T_f= 1027K	T_f= 1500K	T_f= 800K	T_f= 1027K	T_f= 1500K	T_m= 473K	T_m= 575K	T_m= 473K	T_m= 575K	nat.	enr.	600	0
S_j/S_i		**S12/ S4**	**S13/ S5**	**S6/ S14**	**S4/ S3**	**S4/ S2**	**S4/ S7**	**S12/ S11**	**S12/ S10**	**S12/ S15**	**S6/ S5**	**S6/ S4**	**S14/ S13**	**S14/ S12**	**S2/ SA1**	**S2/ SA2**	**S2/ S8**	**S10/ S16**
VARIANT 1	APOLLO-2	-3.97	-4.77	-5.48	-0.50	-0.94	-1.74	-0.47	-0.90	-1.66	-0.51	-1.46	-1.22	-2.97	-	-	-22.86	-25.75
	TVS-M	-4.09	-4.92	-5.68	-0.46	-0.87	-1.62	-0.44	-0.84	-1.54	-0.45	-1.38	-1.21	-2.96	-21.67	-29.07	-22.04	-25.02
	MCU-REA	-3.99	-	-	-	-0.94	-	-	-	-	-	-1.38	-	-	-21.74	-29.16	-22.19	-
	CONKEMO	-4.01	-4.93	-5.60	-0.49	-0.93	-1.71	-0.47	-0.88	-1.62	-0.37	-1.23	-1.05	-2.82	-22.29	-29.86	-22.87	-25.71
	CASMO-4	-	-	-	-	-1.11	-	-	-	-	-	-1.25	-	-	-21.50	-28.48	-21.19	-
	KENO	-	-	-	-	-0.95	-	-	-	-	-	-1.38	-	-	-22.10	-	-22.11	-
	MCNP	-	-	-	-	-0.92	-	-	-	-	-	-1.38	-	-	-22.04	-	-22.18	-
VARIANT 2	APOLLO-2	-2.25	-2.85	-3.57	-0.64	-1.21	-2.25	-0.63	-1.20	-2.23	-1.54	-3.69	-2.26	-5.00	-	-	-27.40	-29.05
	TVS-M	-2.39	-3.04	-3.82	-0.57	-1.09	-2.02	-0.56	-1.06	-1.98	-1.24	-3.14	-2.02	-4.57	-17.02	-24.56	-25.37	-27.14
	MCU-REA	-2.37	-	-	-	-1.02	-	-	-	-	-	-3.56	-	-	-17.09	-24.72	-25.74	-
	CONKEMO	-2.30	-2.99	-3.70	-0.62	-1.17	-2.17	-0.61	-1.15	-2.15	-1.41	-3.51	-2.12	-4.91	-17.48	-24.97	-26.12	-27.83
	CASMO-4	-	-	-	-	-1.14	-	-	-	-	-	-3.44	-	-	-16.45	-23.82	-26.66	-
	KENO	-	-	-	-	-1.16	-	-	-	-	-	-3.52	-	-	-17.22	-24.91	-26.30	-
	MCNP	-	-	-	-	-1.08	-	-	-	-	-	-3.61	-	-	-17.23	-24.90	-26.46	-

Table 3 (continuation)

		Boron worth, %			Doppler effect, %						Temperature effect, %				CR worth		Core overheating	
					C_B=600 ppm			C_B=0 ppm			C_B=600 ppm		C_B=0 ppm		(B_4C)		C_B, ppm	
		T_m= 575K	T_m= 473K	T_m= 300K	T_f= 800K	T_f= 1027K	T_f= 1500K	T_f= 800K	T_f= 1027K	T_f= 1500K	T_m= 473K	T_m= 575K	T_m= 473K	T_m= 575K	nat.	enr.	600	0
S_j/S_i		**S12/ S4**	**S13/ S5**	**S6/ S14**	**S4/ S3**	**S4/ S2**	**S4/ S7**	**S12/ S11**	**S12/ S10**	**S12/ S15**	**S6/ S5**	**S6/ S4**	**S14/ S13**	**S14/ S12**	**S2/ SA1**	**S2/ SA2**	**S2/ S8**	**S10/ S16**
VARIANT 3	APOLLO-2	-3.94	-4.78	-5.55	-0.55	-1.04	-1.92	-0.52	-0.99	-1.84	-1.14	-2.38	-1.91	-3.99	-	-	-22.22	-25.16
	TVS-M	-4.07	-4.95	-5.77	-0.50	-0.94	-1.74	-0.48	-0.91	-1.68	-1.18	-2.56	-2.00	-4.27	-21.09	-	-21.81	-24.85
	MCU-REA	-3.98	-	-	-	-0.94	-	-	-	-	-	-2.57	-	-	-21.15	-	-22.06	-
	CONKEMO	-3.95	-4.87	-5.71	-0.53	-0.99	-1.83	-0.50	-0.94	-1.74	-1.20	-2.48	-2.04	-4.23	-21.61	-	-21.74	-24.69
	CASMO-4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	KENO	-	-	-	-	-	-	-	-	-	-	-	-	-	-21.40	-	-	-
	MCNP	-	-	-	-	-	-	-	-	-	-	-	-	-	-21.43	-	-	-
VARIANT 4	APOLLO-2	-2.27	-2.88	-3.61	-0.65	-1.24	-2.29	-0.64	-1.22	-2.27	-1.48	-3.50	-2.22	-4.84	-	-	-26.87	-28.55
	TVS-M	-2.41	-3.07	-3.88	-0.59	-1.12	-2.08	-0.58	-1.10	-2.04	-1.27	-3.12	-2.08	-4.59	-17.09	-	-24.90	-26.68
	MCU-REA	-2.43	-	-	-	-0.99	-	-	-	-	-	-3.57	-	-	-17.18	-	-25.73	-
	CONKEMO	-2.32	-2.96	-3.75	-0.62	-1.18	-2.20	-0.60	-1.14	-2.14	-1.40	-3.49	-2.18	-4.91	-17.31	-	-25.76	-27.61
	CASMO-4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	KENO	-	-	-	-	-	-	-	-	-	-	-	-	-	-17.16	-24.74	-	-
	MCNP	-	-	-	-	-	-	-	-	-	-	-	-	-	-17.27	-25.05	-	-

Table 4 U-Gd pins worth, $\Delta K/K$, %

	State	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	SA1	SA2
LEU assembly	APOLLO-2	-8.44	-8.77	-8.76	-8.77	-8.54	-7.89	-8.77	-6.35	-8.87	-9.24	-9.23	-9.23	-9.05	-8.37	-9.24	-6.49	-	-
	TVS-M	-8.13	-8.43	-8.44	-8.44	-8.03	-7.25	-8.42	-6.50	-8.55	-8.90	-8.90	-8.90	-8.51	-7.68	-8.88	-6.65	-6.20	-
	MCU-REA	-8.20	-8.61	-	-8.70	-	-7.51	-	-6.71	-	-	-	-9.14	-	-	-	-	-6.34	-
	CONKEMO	-8.38	-8.94	-8.96	-8.97	-8.61	-7.72	-8.92	-6.05	-8.83	-9.46	-9.48	-9.49	-9.22	-8.16	-9.44	-6.28	-6.49	-
	CASMO-4	-8.42	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	KENO	-	-8.74	-	-	-	-7.62	-	-	-	-8.99	-	-	-	-	-	-	-6.32	-
	MCNP	-	-8.65	-	-	-	-7.52	-	-	-	-8.99	-	-	-	-	-	-	-6.34	-
	Average	-8.31	-8.69	-8.72	-8.72	-8.39	-7.58	-8.70	-6.40	-8.75	-9.11	-9.20	-9.19	-8.93	-8.07	-9.19	-6.47	-6.34	-
MOX assembly	APOLLO-2	-3.73	-4.51	-4.53	-4.55	-4.83	-4.99	-4.48	-2.94	-3.79	-4.62	-4.64	-4.66	-4.97	-5.17	-4.58	-2.97	-	-
	TVS-M	-4.27	-4.42	-4.43	-4.44	-4.60	-4.64	-4.41	-2.97	-4.38	-4.54	-4.54	-4.55	-4.75	-4.81	-4.52	-2.99	-3.74	-
	MCU-REA	-4.96	-4.42	-	-4.50	-	-4.68	-	-3.38	-	-	-	-4.56	-	-	-	-	-3.76	-
	CONKEMO	-4.59	-4.70	-4.72	-4.75	-4.89	-4.98	-4.67	-3.28	-4.64	-4.78	-4.81	-4.86	-5.11	-5.17	-4.71	-3.37	-3.74	-
	CASMO-4	-4.42	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	KENO	-	-4.47	-	-	-	-4.74	-	-	-	-4.51	-	-	-	-	-	-	-3.66	-3.30
	MCNP	-	-4.46	-	-	-	-4.77	-	-	-	-4.52	-	-	-	-	-	-	-3.74	-3.57
	Average	-4.39	-4.50	-4.56	-4.56	-4.78	-4.80	-4.52	-3.14	-4.27	-4.59	-4.66	-4.66	-4.94	-5.05	-4.60	-3.11	-3.73	-3.44

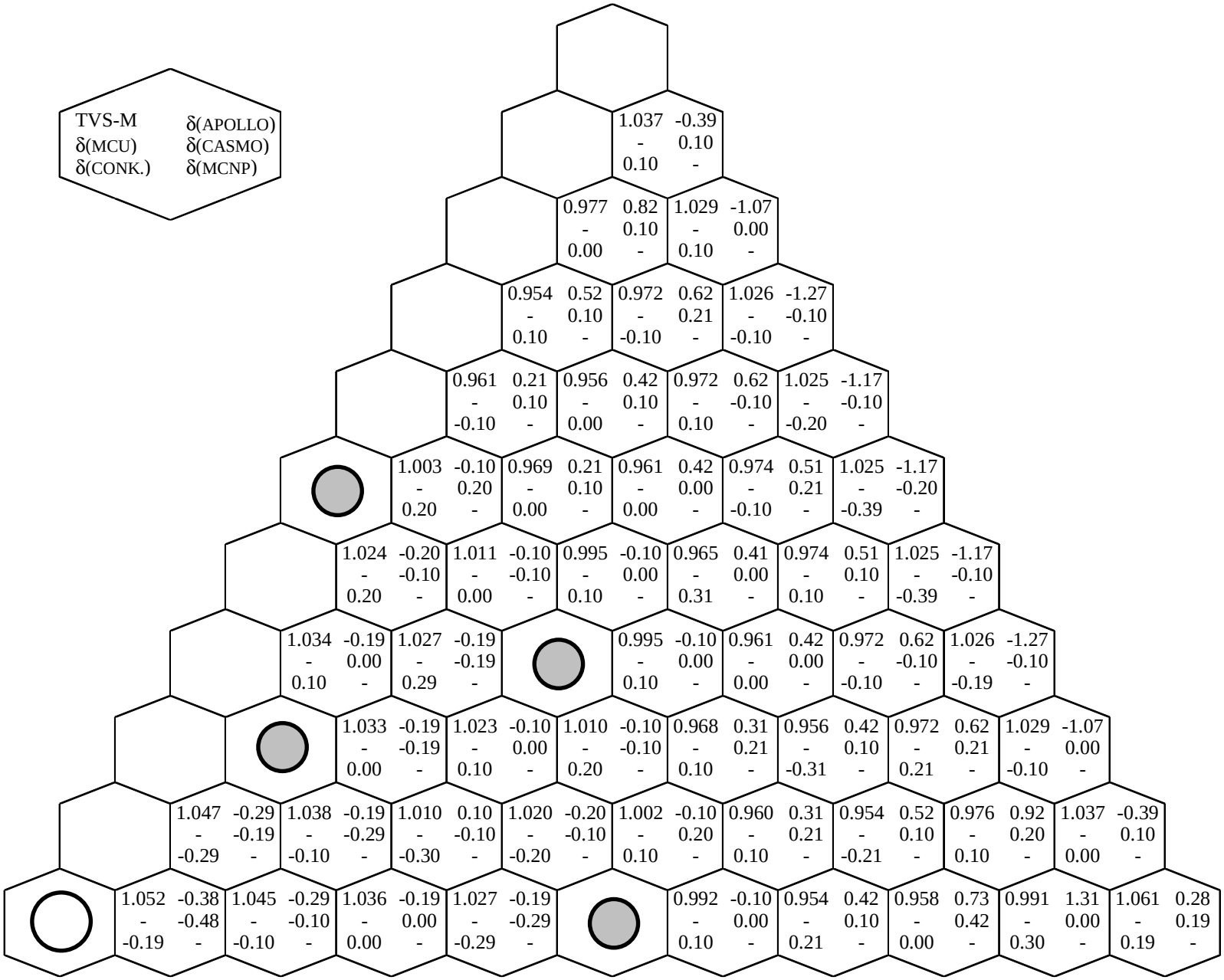

Figure 1 Pin power distribution calculated with TVS-M code and deviation of other codes results (%). Variant 1, state S1.

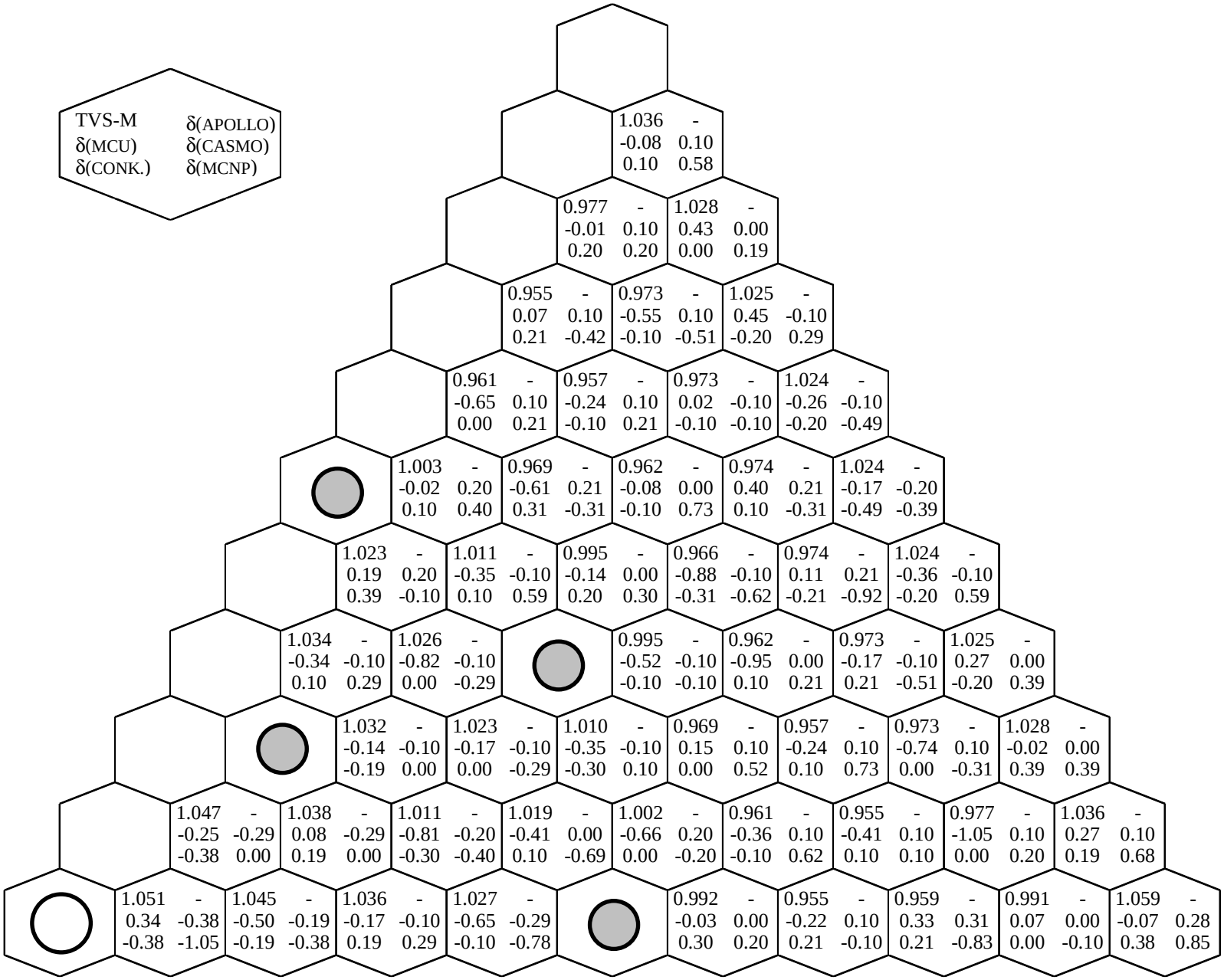

Figure 2 Pin power distribution calculated with TVS-M code and deviation of other codes results (%). Variant 1, state S2.

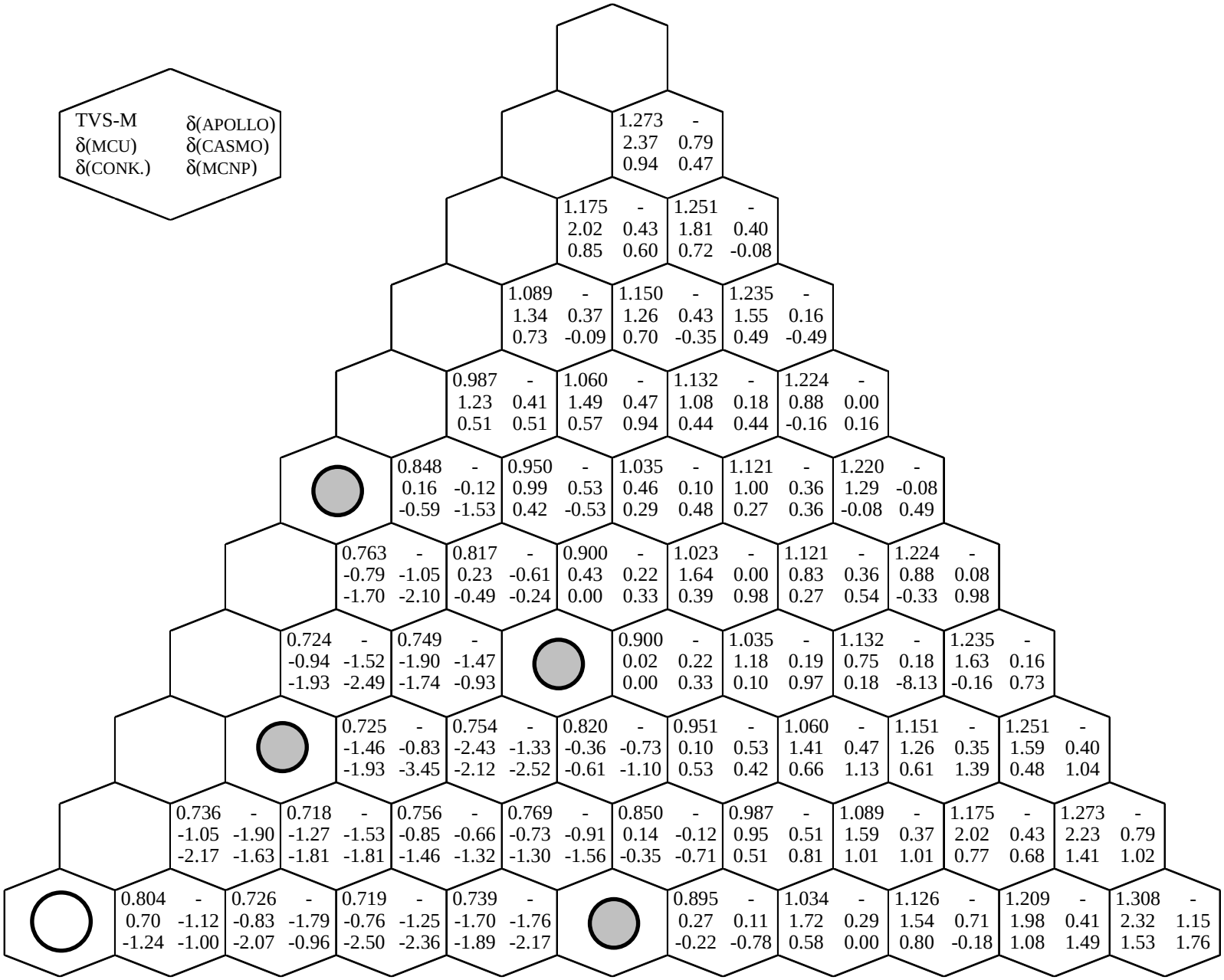

Figure 3 Pin power distribution calculated with TVS-M code and deviation of other codes results (%). Variant 1, state SA1.

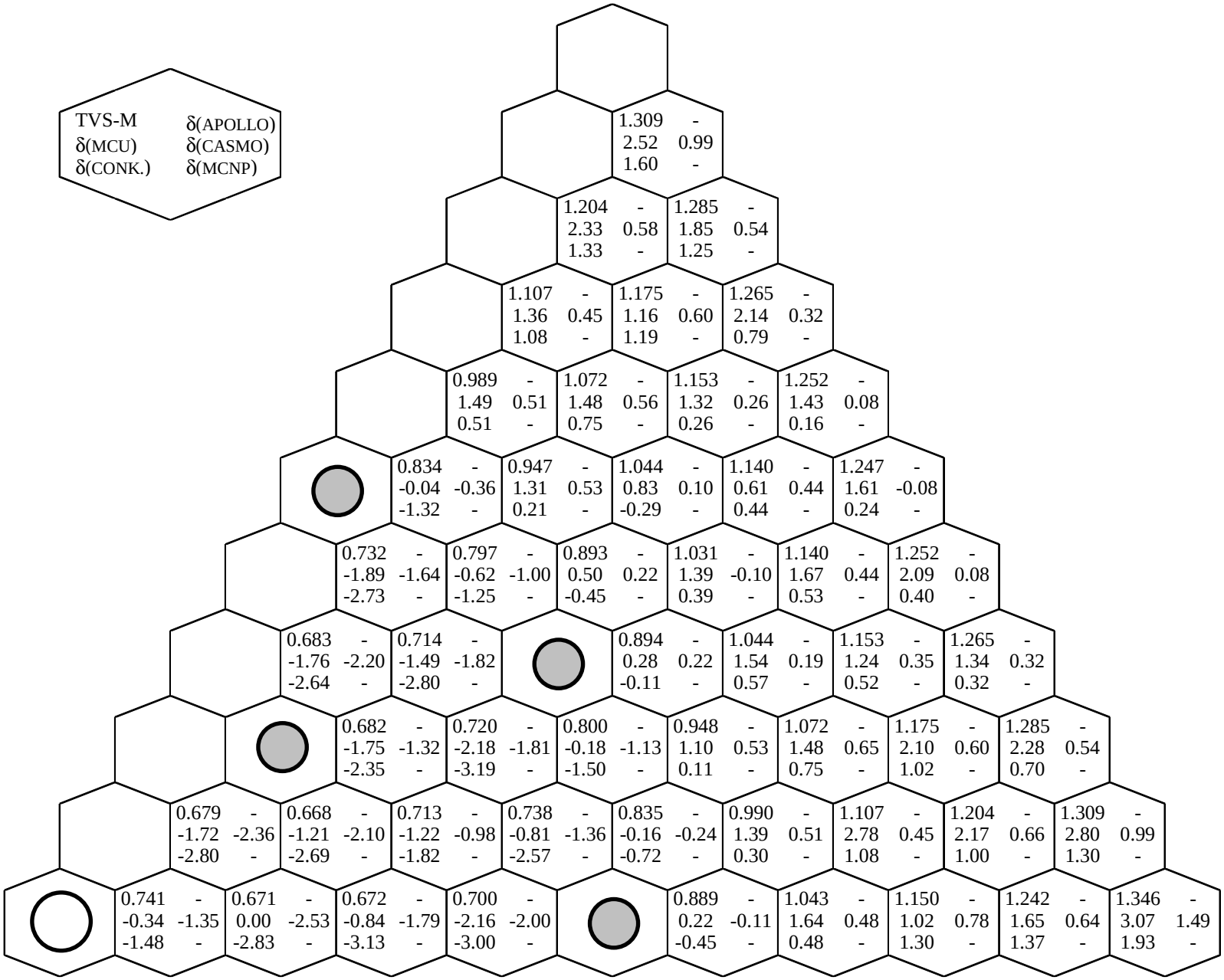

Figure 4 Pin power distribution calculated with TVS-M code and deviation of other codes results (%). Variant 1, state SA2.

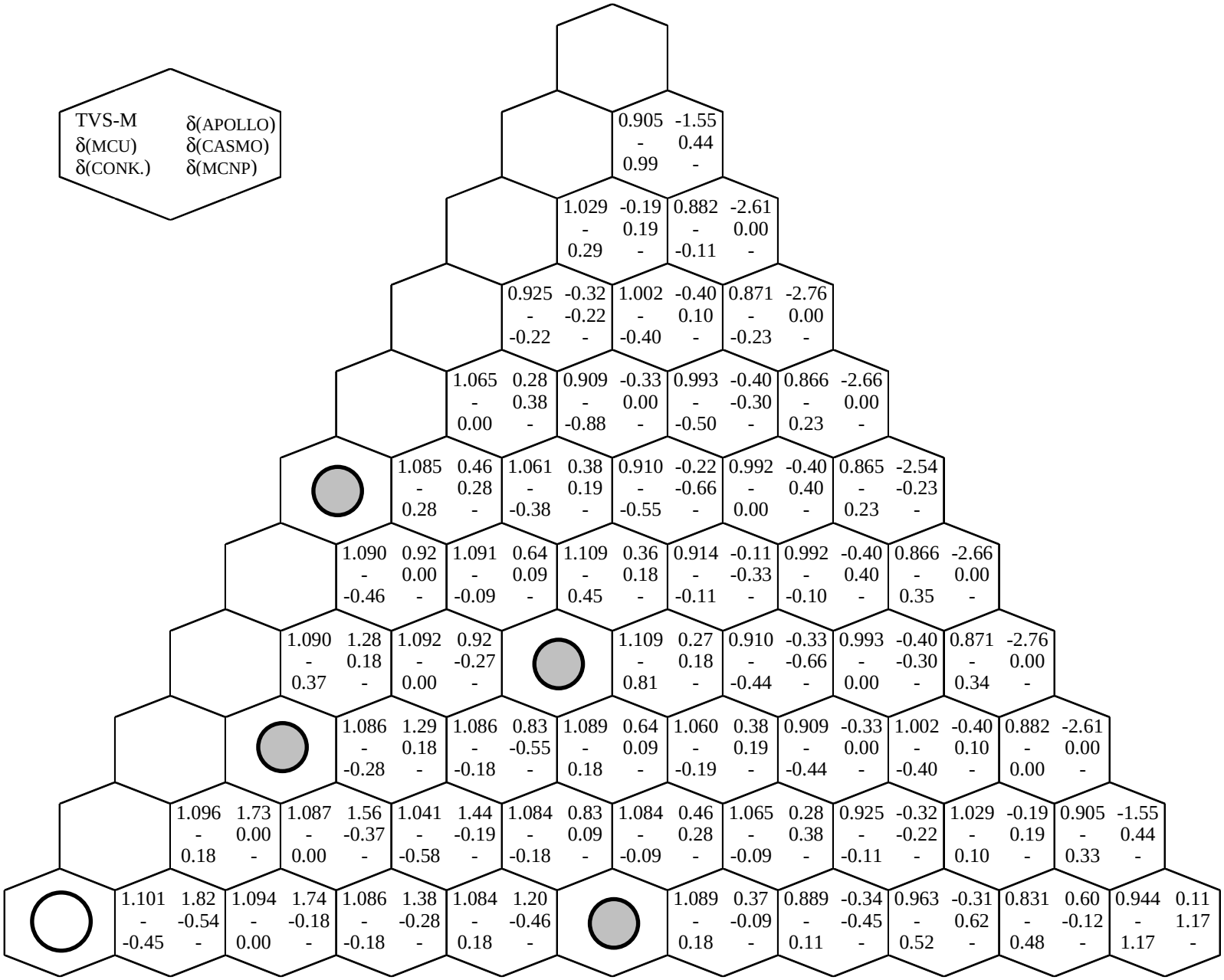

Figure 5 Pin power distribution calculated with TVS-M code and deviation of other codes results (%). Variant 2, state S1.

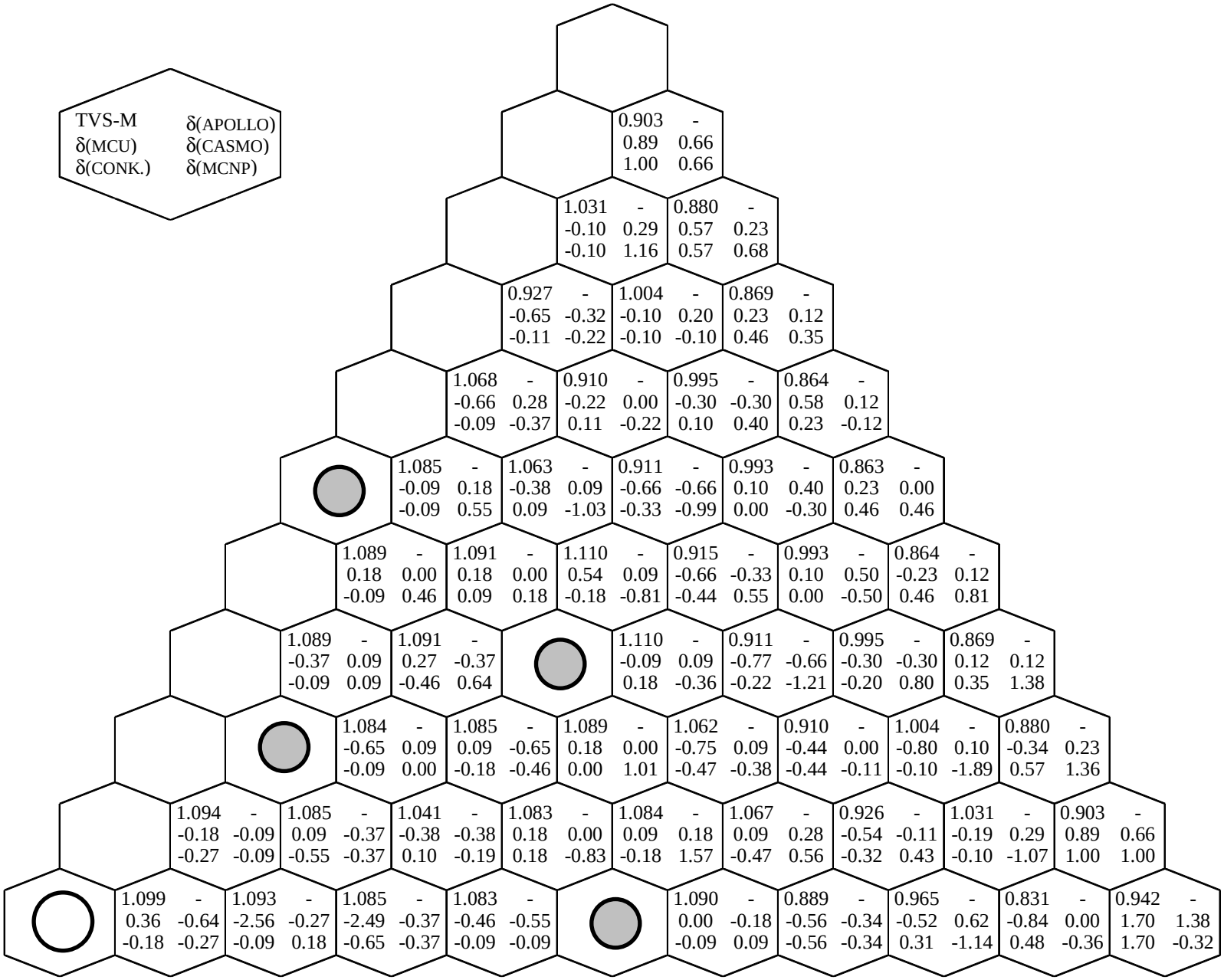

Figure 6 Pin power distribution calculated with TVS-M code and deviation of other codes results (%). Variant 2, state S2.

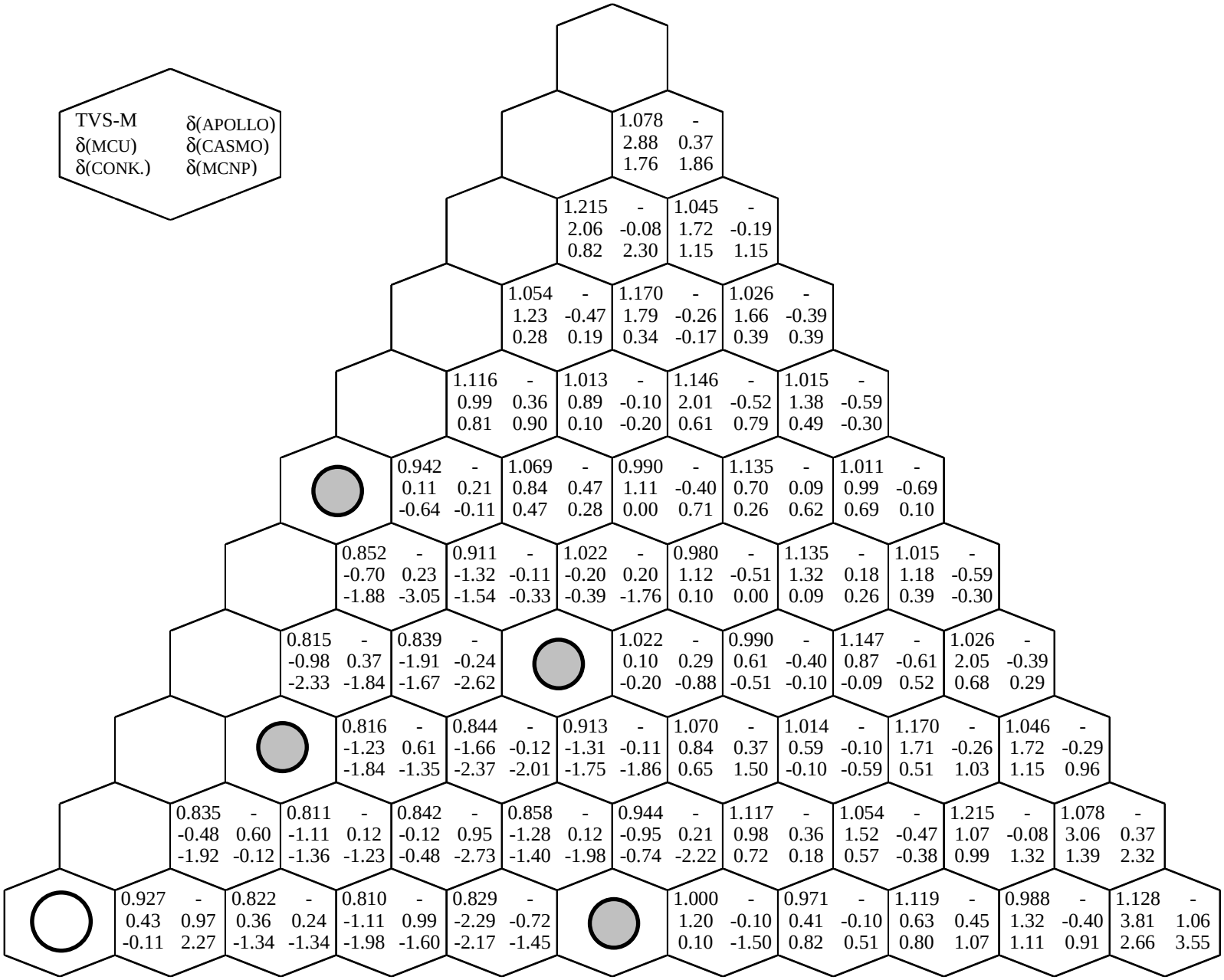

Figure 7 Pin power distribution calculated with TVS-M code and deviation of other codes results (%). Variant 2, state SA1.

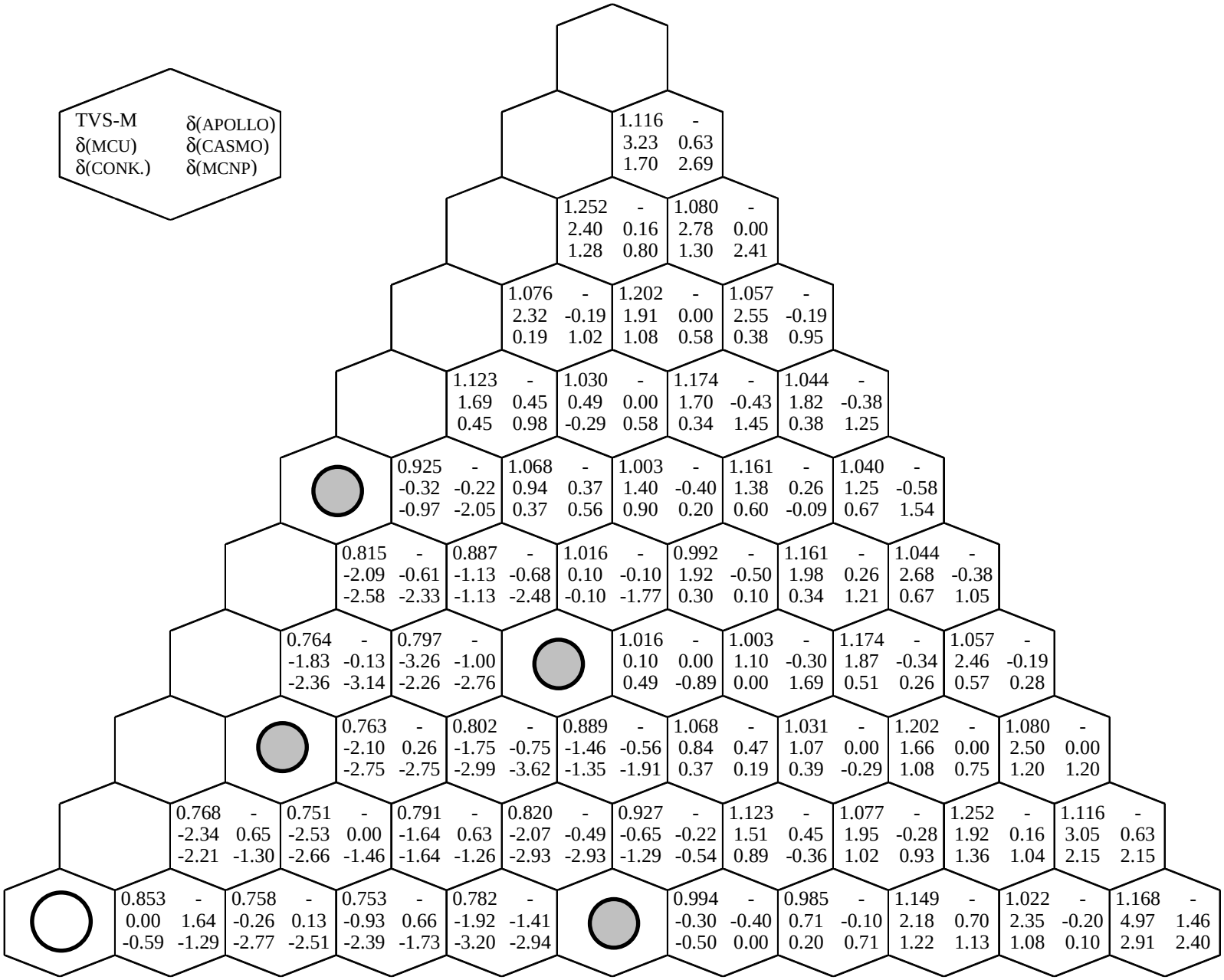

Figure 8 Pin power distribution calculated with TVS-M code and deviation of other codes results (%). Variant 2, state SA2.

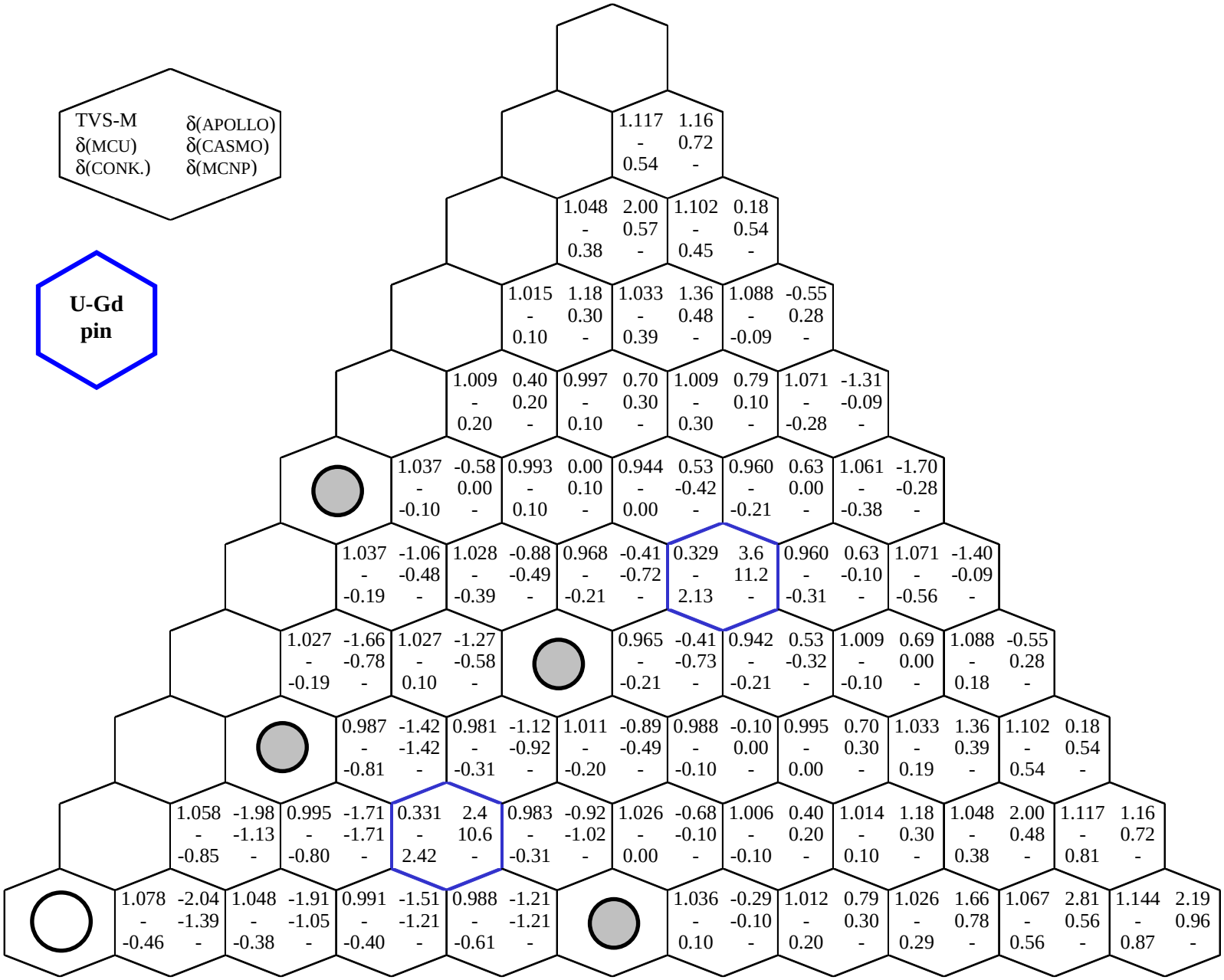

Figure 9 Pin power distribution calculated with TVS-M code and deviation of other codes results (%). Variant 3, state S1.

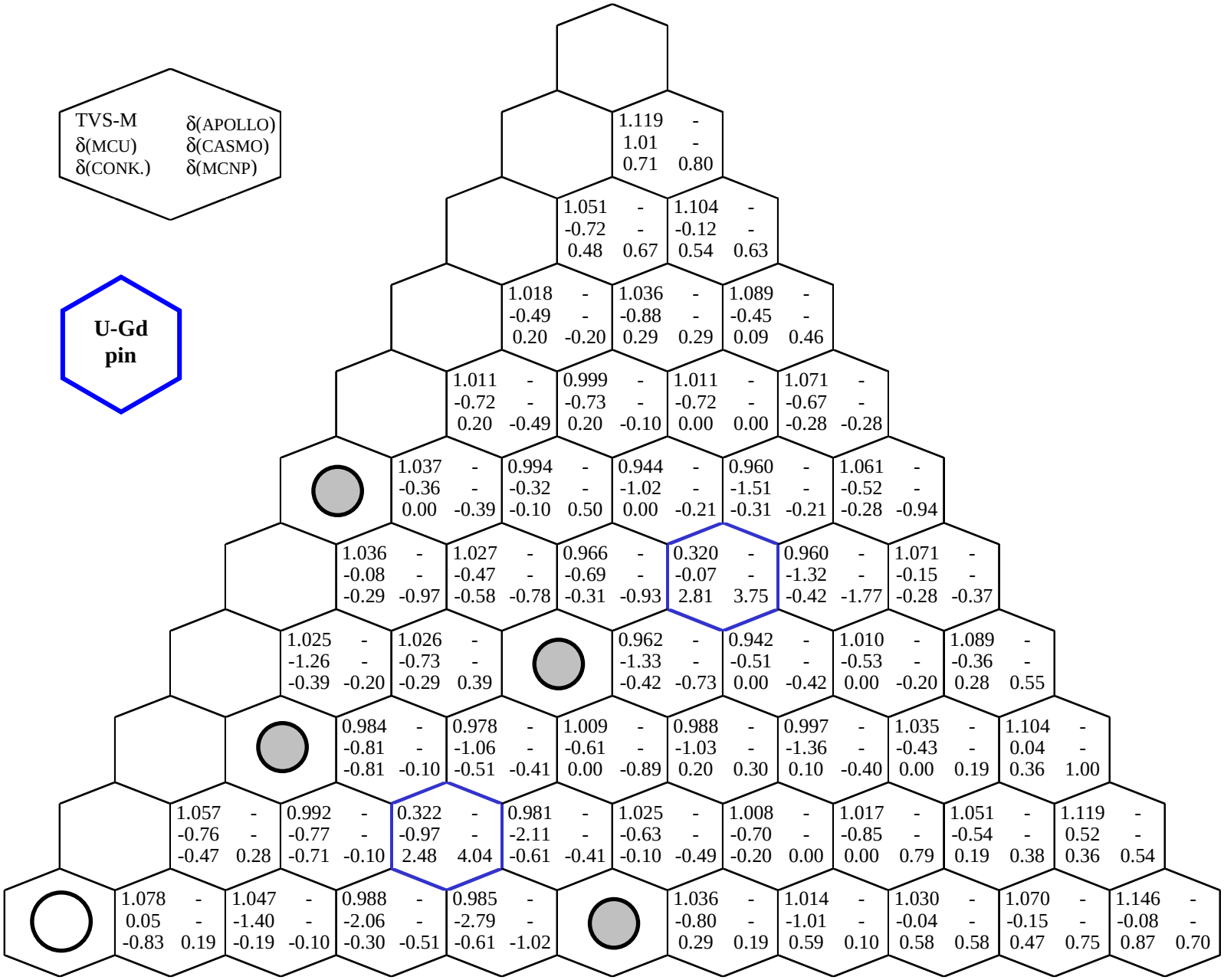

Figure 10 Pin power distribution calculated with TVS-M code and deviation of other codes results (%). Variant 3, state S2.

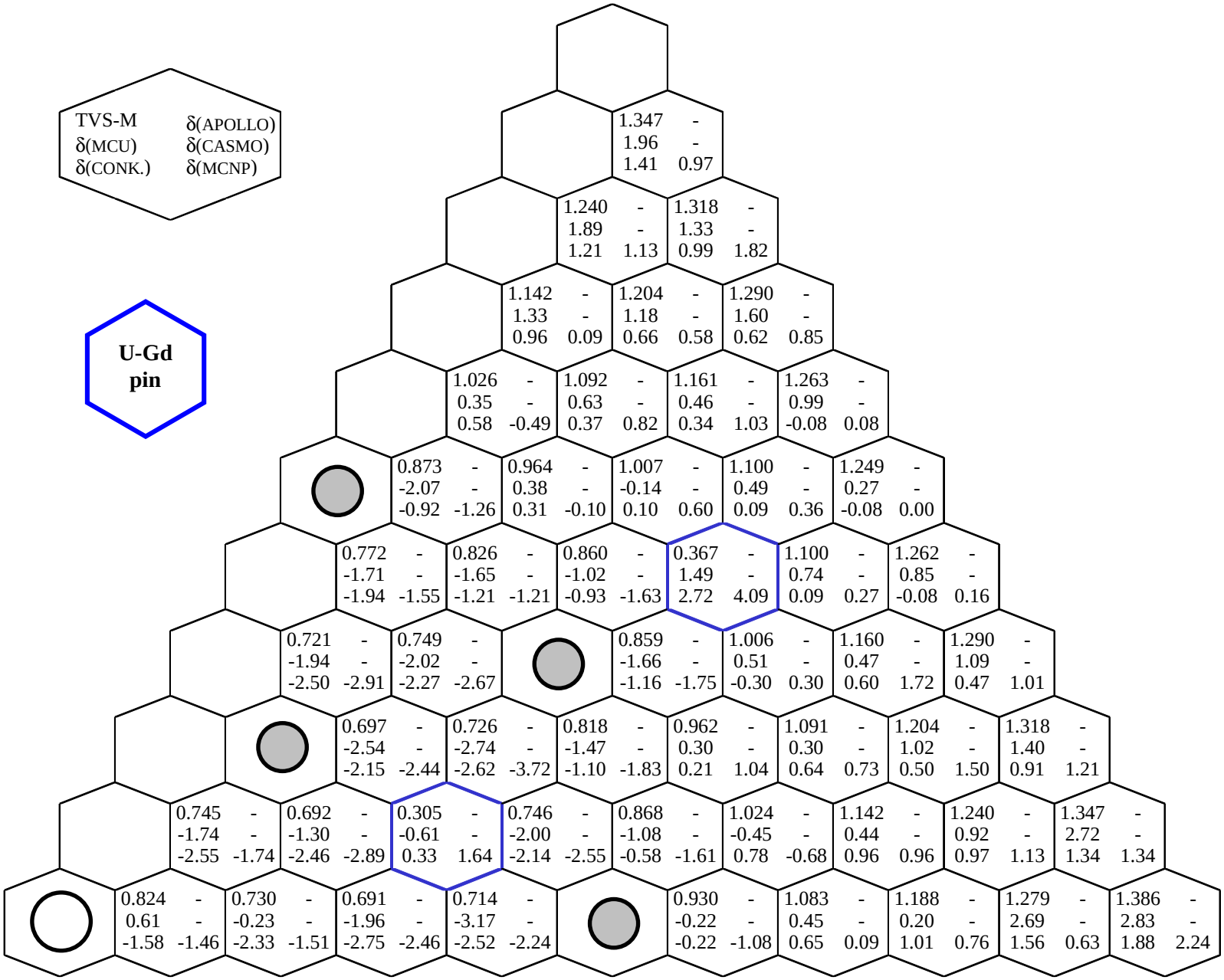

Figure 11 Pin power distribution calculated with TVS-M code and deviation of other codes results (%). Variant 3, state SA1.

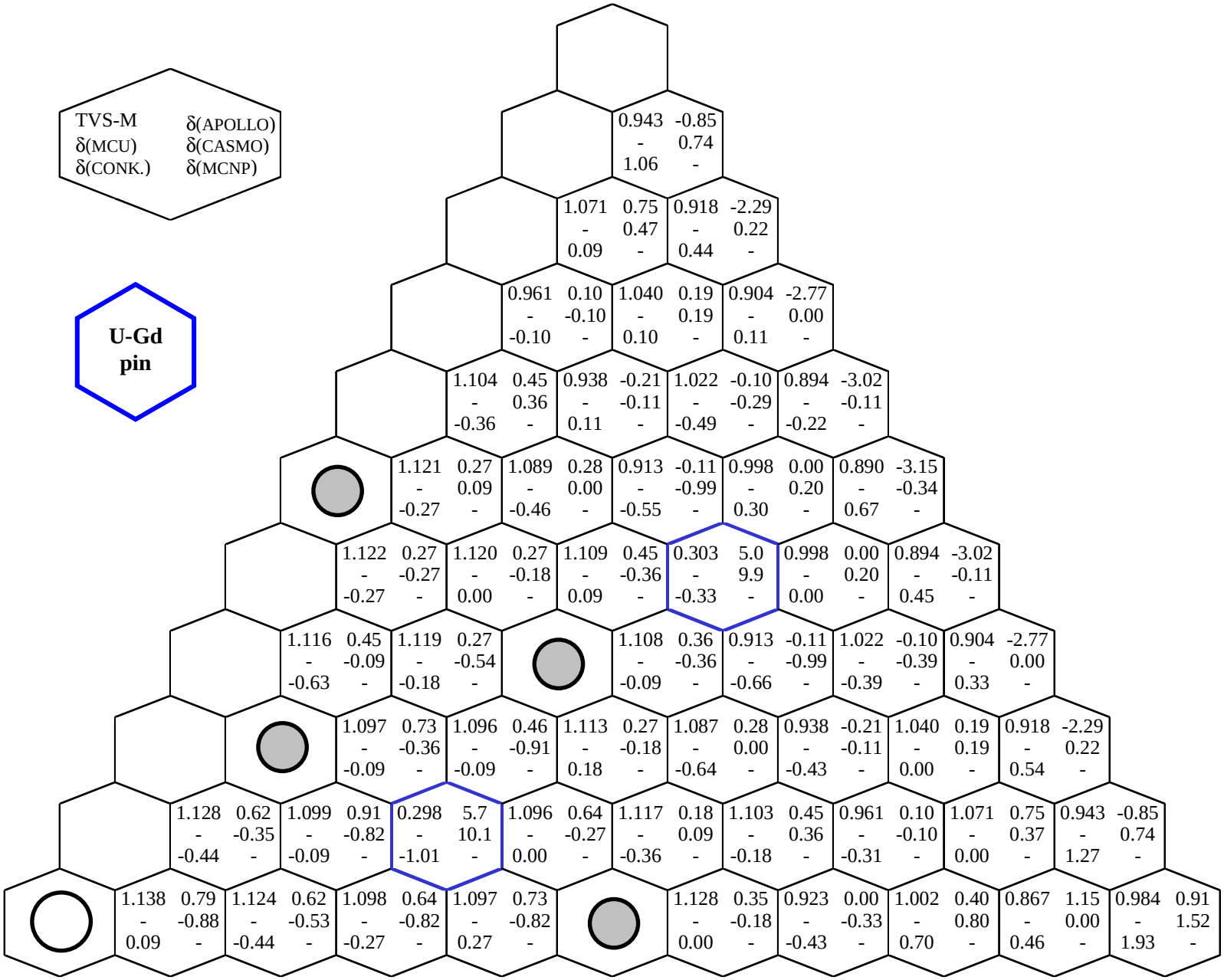

Figure 12 Pin power distribution calculated with TVS-M code and deviation of other codes results (%). Variant 4, state S1.

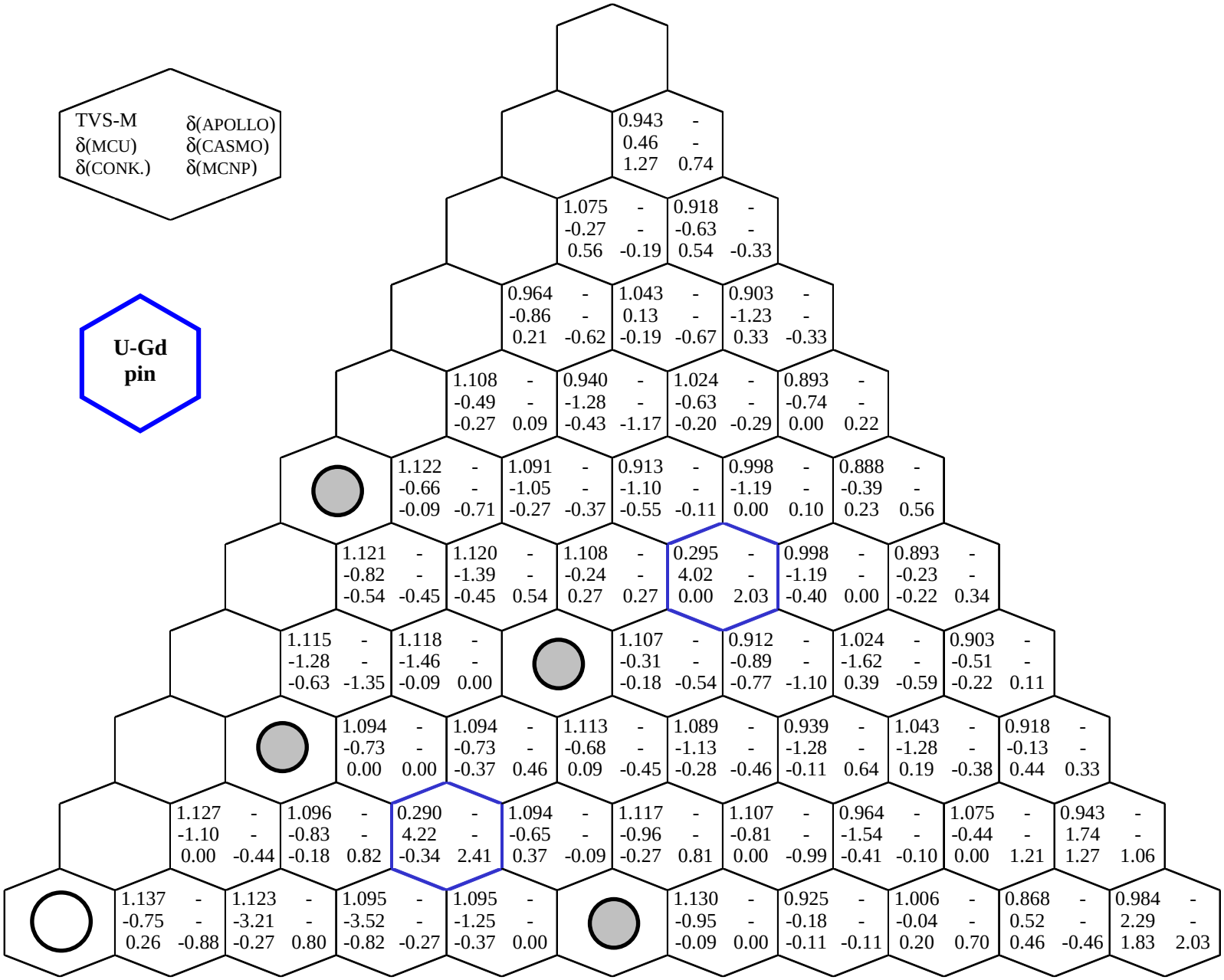

Figure 13 Pin power distribution calculated with TVS-M code and deviation of other codes results (%). Variant 4, state S2.

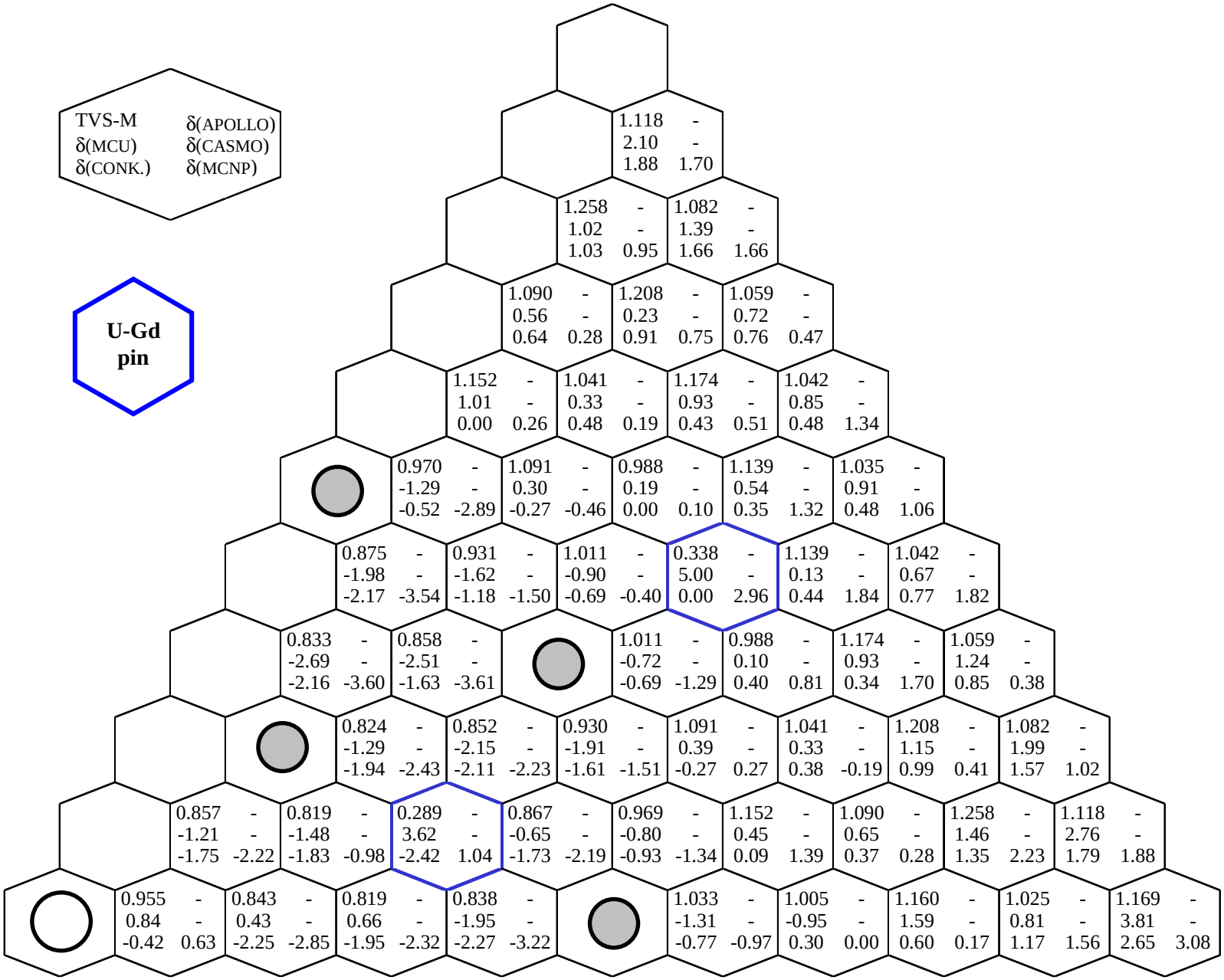

Figure 14 Pin power distribution calculated with TVS-M code and deviation of other codes results (%). Variant 4, state SA1.

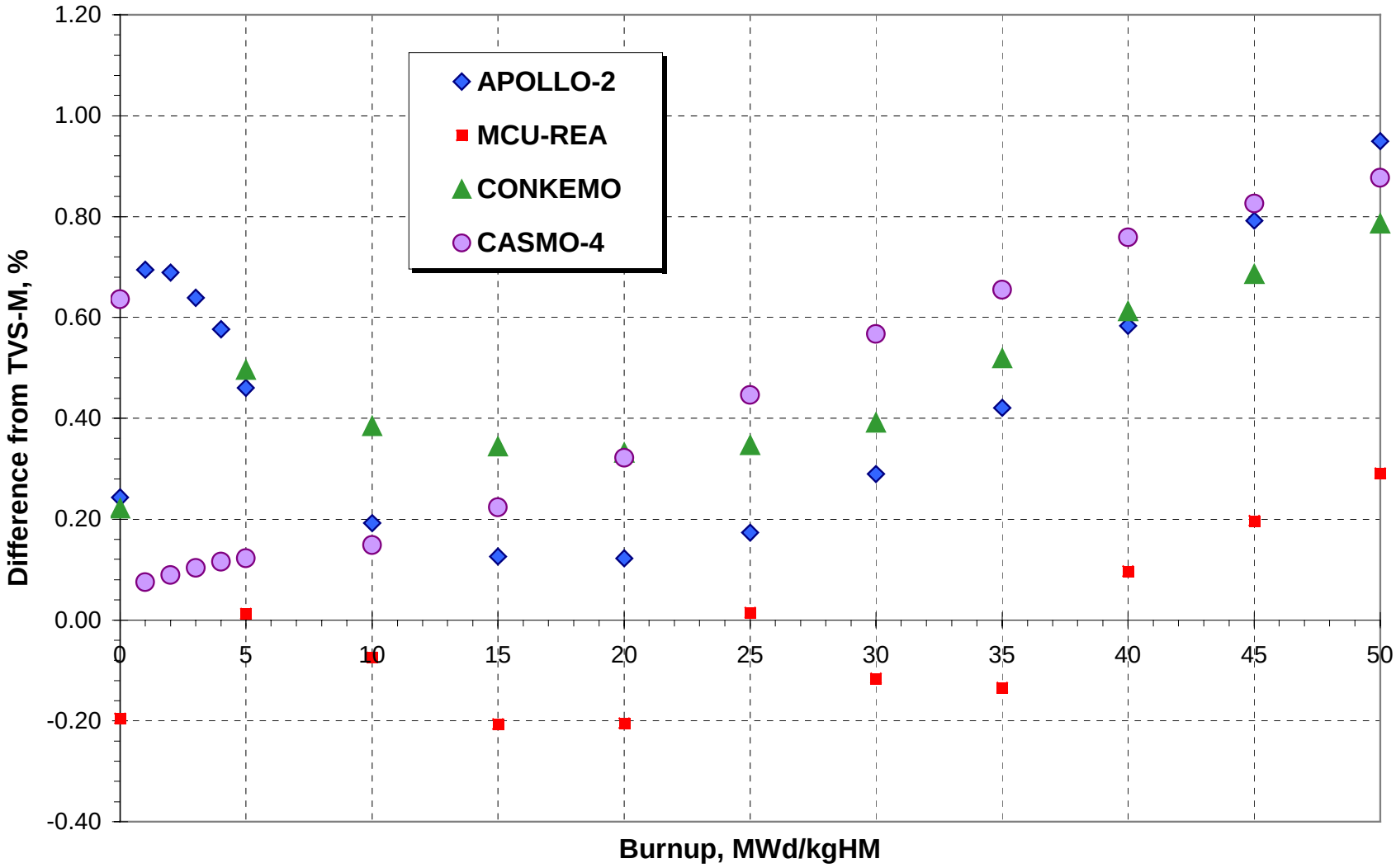

Figure 15 K_{eff} versus burnup for the LEU assembly (VAR1). Deviations from TVS-M

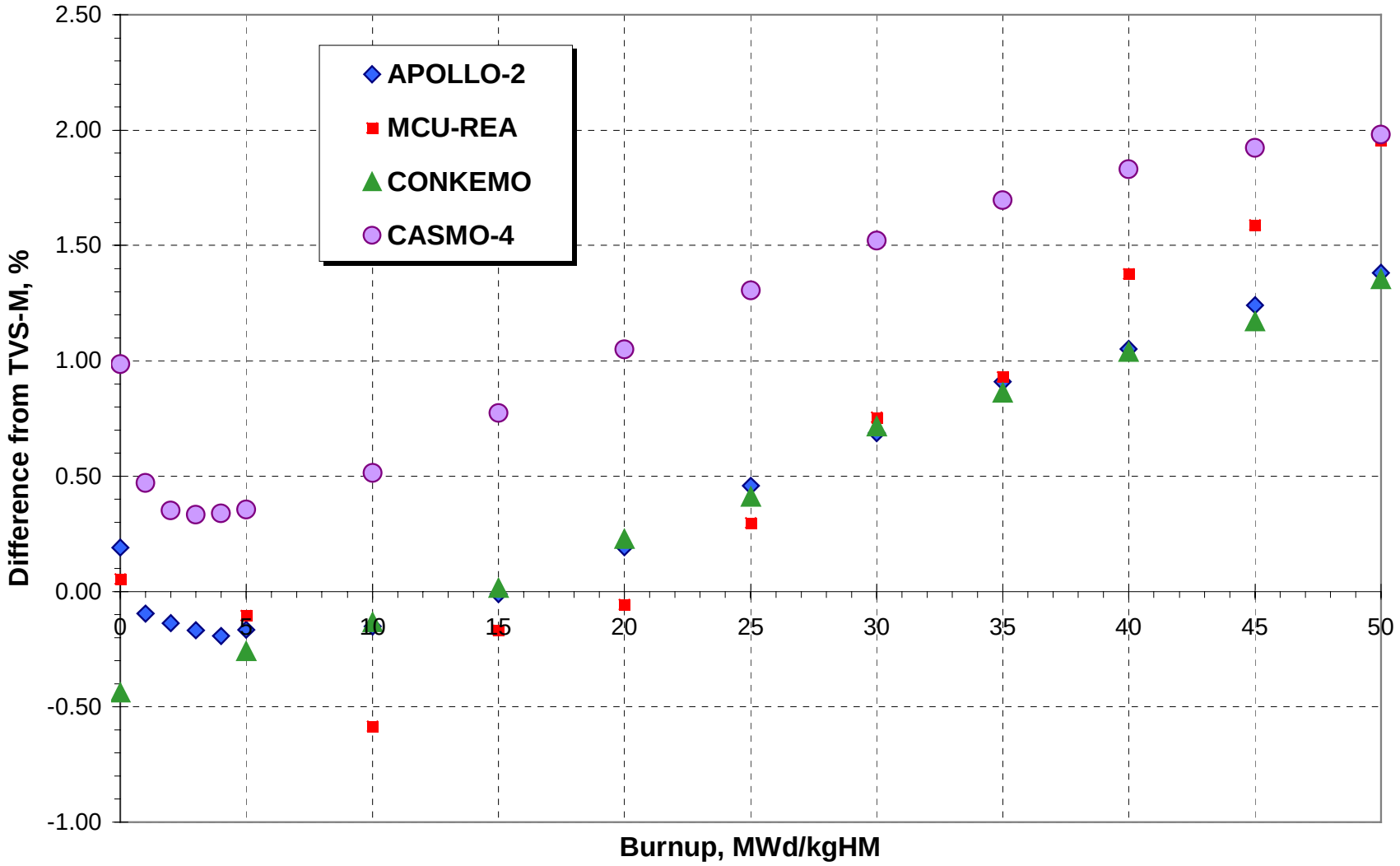

Figure 16 K_{eff} versus burnup for the MOX assembly (VAR2). Deviations from TVS-M

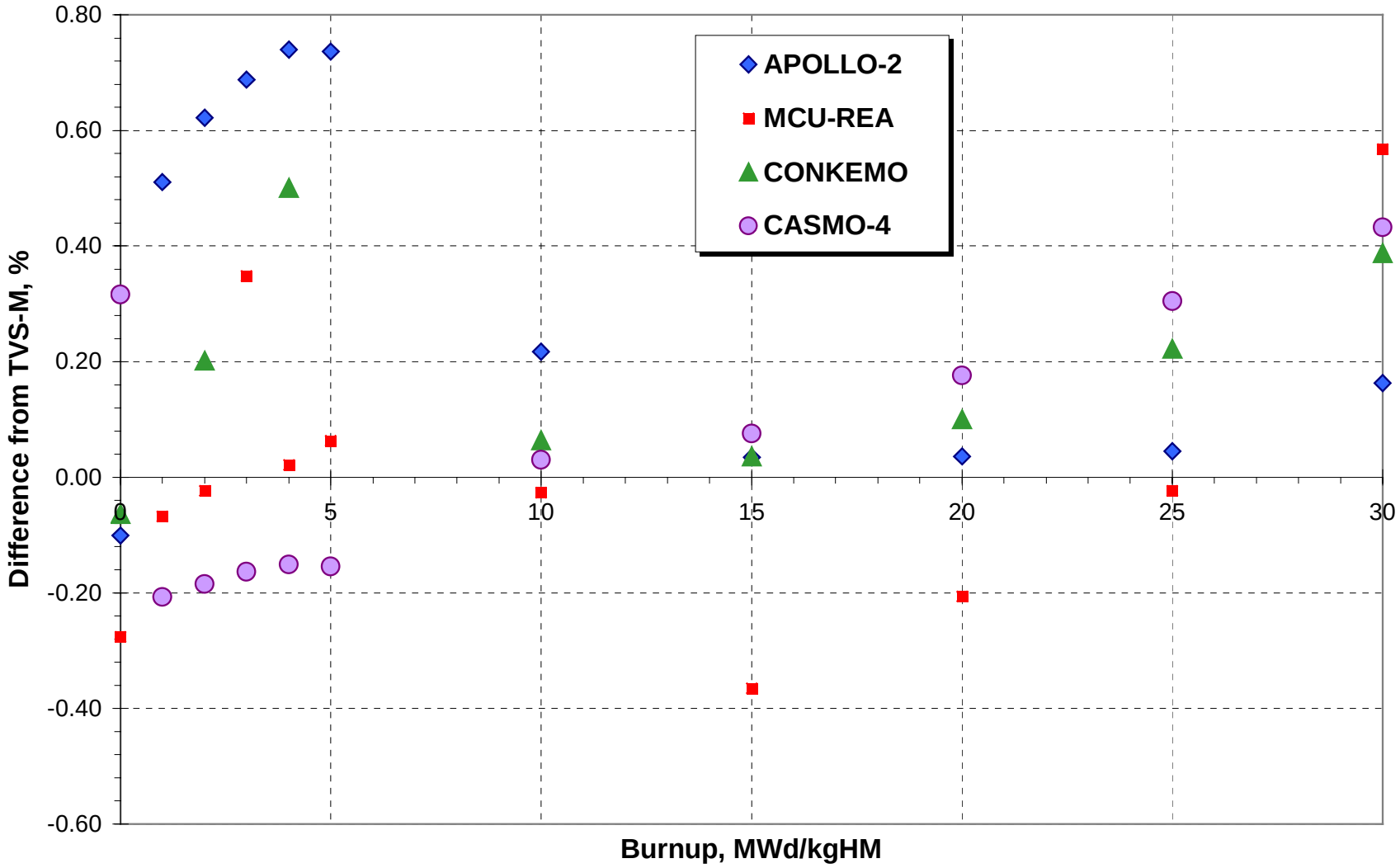

Figure 17 K_{eff} versus burnup for the LEU assembly with 12 U-Gd pins (VAR3). Deviations from TVS-M

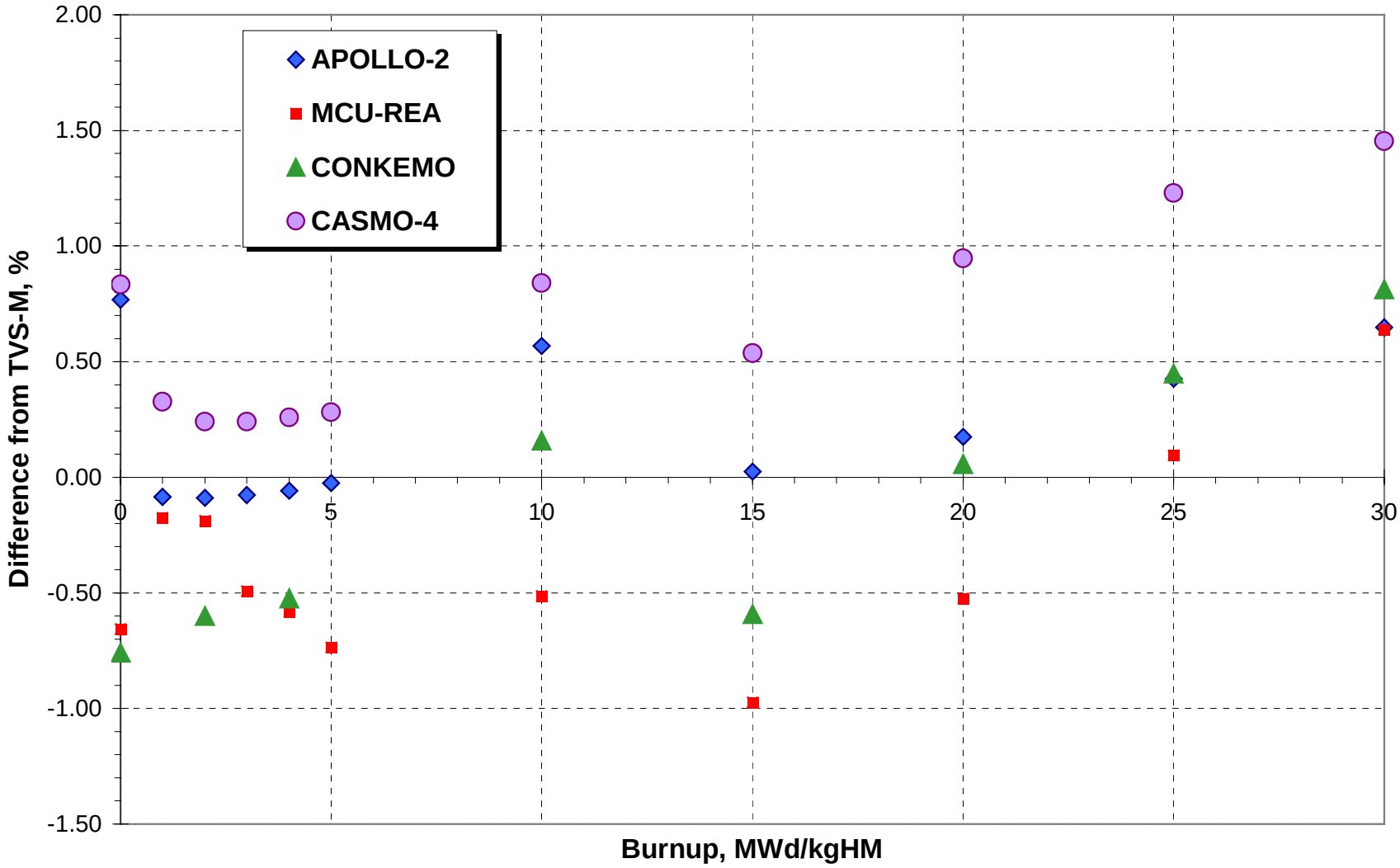

Figure 18 K_{eff} versus burnup for the MOX assembly with 12 U-Gd pins (VAR4). Deviations from TVS-M