

# **Reactor Power History from Fission Product Signatures**

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## **Abstract**

As a transparency aid for international verification processes it would be beneficial for international monitors to be able to independently verify a reactor fuel's operational history from fission product signatures released during fuel dissolutions. Previous efforts at power history verification from fission product signatures have been limited in scope and without significant success. Unique characteristics of some stable and radioactive nuclides such as variations in fission product yields from changing fissioning systems, changes in absorption cross-sections due to different neutron flux spectra, and the fission product half-lives create significant differences in the concentration of such nuclides as a result of varying reactor power histories. This paper discusses a method developed at Texas A&M University for determining reactor power history from trace fission product signatures using a combination of signatures. This system has been tested with simulated results from the TRANSLAT assembly simulation code and significant improvements in power history verification have been found.

## **Introduction**

Further transparency in international verification processes can be gained with an ability to independently certify a reactor fuel's operational history using measurements of fission products. Such ability would allow inspectors to validate that a specific fuel assembly(s) was used in a reactor in the exact manner the reactor operator claims. Potential fission product isotopes (or monitors) have been identified to do so. This paper presents discussions of the potential monitors, the properties of useful monitors, simplified monitor production model development, and use of those models. The discussion concludes with further research to be done along with specific outcomes expected at completion.

## **Monitor Identification**

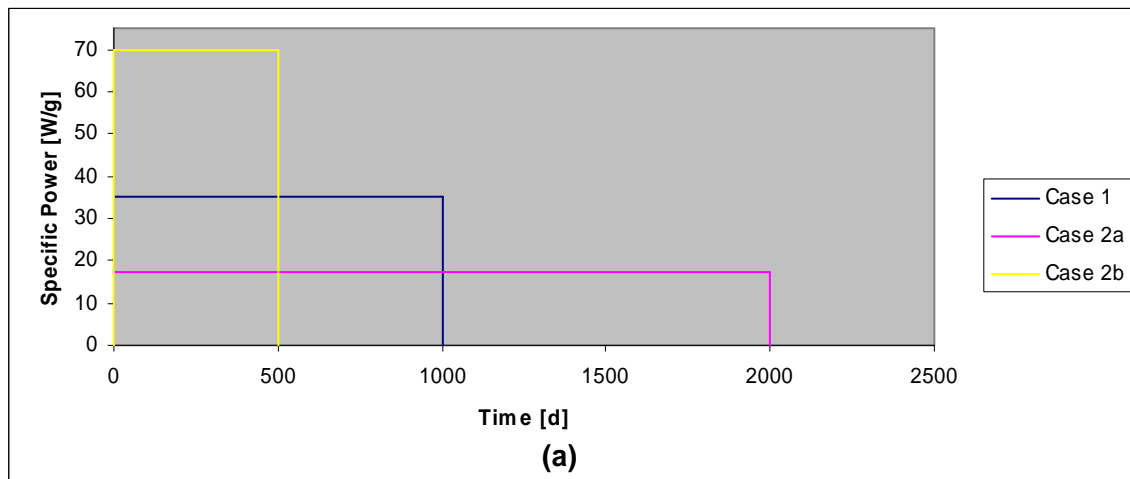
The concentration of monitors in spent fuel depend upon the production and loss characteristics of that isotope as well as the specific design and operation history of the reactor fuel. Monitors of interest are those which have specific properties that cause the monitor to be produced in different concentrations as a result of different power histories. Only fission product monitors were considered. However, it was discovered that both radioactive and stable isotopes can function effectively as monitors.

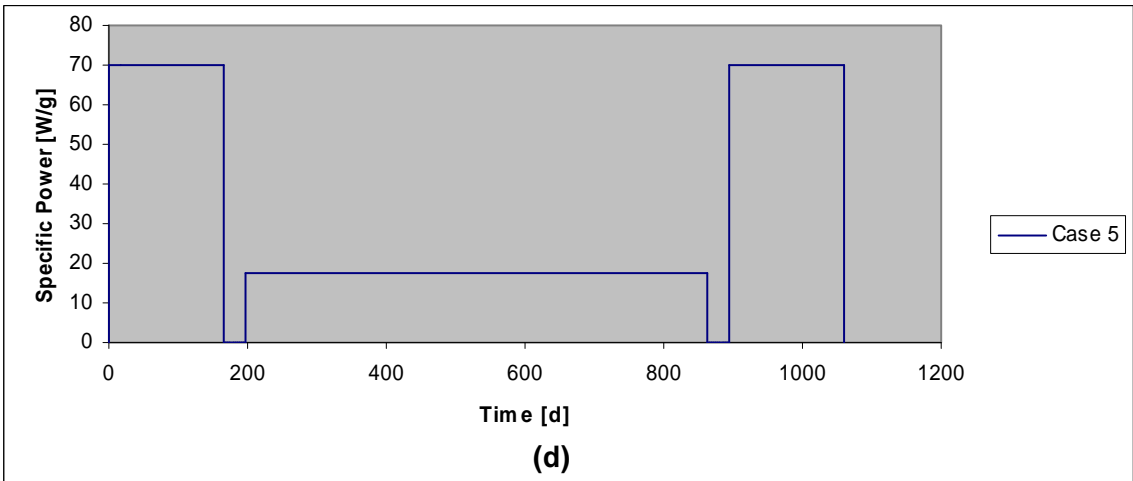
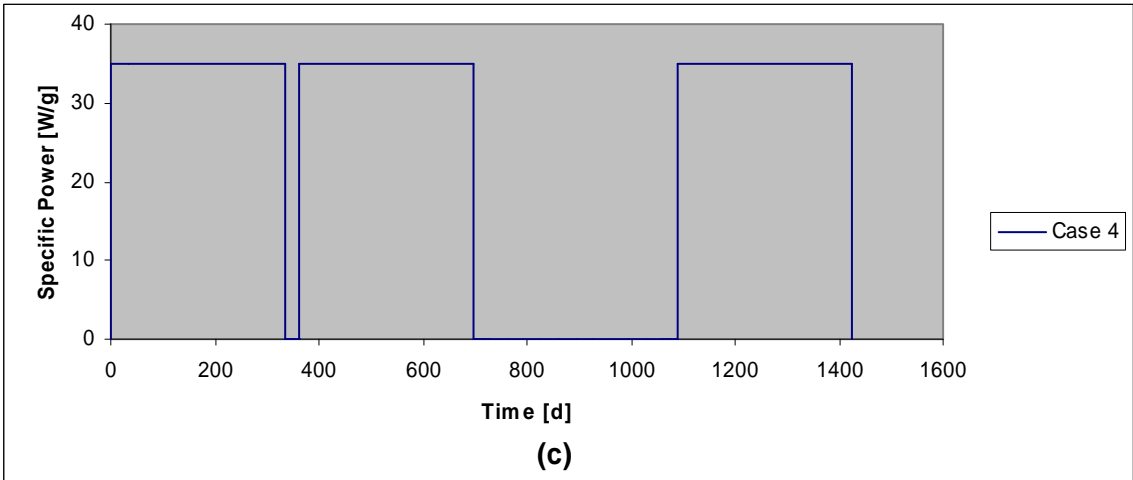
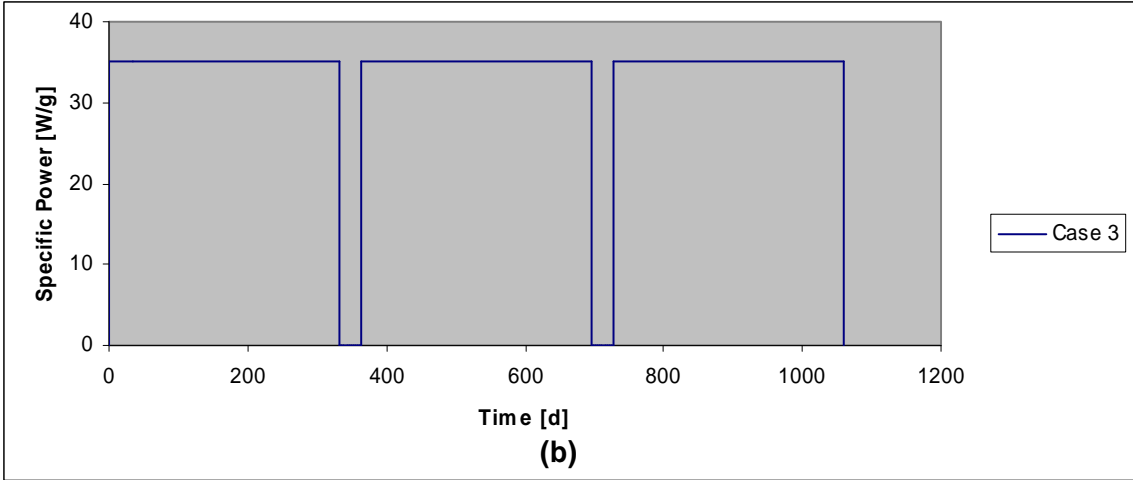
A radioactive monitor must have a half-life approximately corresponding to the length of average burn cycles of a reactor, typically a hundred to several hundred days. A half-life that is too short will cause the monitor to rapidly reach a concentration which is in

equilibrium with, and proportional to, the current specific power level of the fuel. Thus, such a monitor is unable to retain information about previous burn cycles. (It should be noted that monitors with short half-lives may still be useful as such monitors can identify the specific power of the last burn cycle of a fuel). Monitors with long half-lives take too long during buildup (reactor operation) to respond to changes in specific power. Of course, the problem with a radioactive monitor is that the signature will eventually disappear. Ideally, this problem is avoided by the use of stable monitors, though for best results both radioactive and stable will likely be necessary.

Stable monitors are more complex than radioactive monitors. This is because a stable monitor will depend on the decay of radioactive parent nuclides to create the useful signature. It is really the properties of the radioactive parent that determine the potential of a stable monitor. The parent must have a large enough absorption cross-section that production of the stable monitor from decay of the parent is limited or insignificant during reactor operation. Thus, only during reactor shutdown is decay of the parent a significant production mechanism for the stable monitor. In this manner, a reactor shutdown boosts the concentration of the stable monitor relative to its concentration during a continuous burn. One restraint on the stable monitor itself is that it must have a small absorption cross-section. If the absorption cross-section is too large, the monitor will rapidly reach equilibrium and lose any information about any previous shutdowns.

In order to confirm potential monitors as identified by their properties a PWR pin-cell was modeled in the lattice physics code TRANSLAT [1]. The pin-cell model was run for eight different cases varying specific power and shutdown time as shown in Figure 1. All cases had the same final burnup.





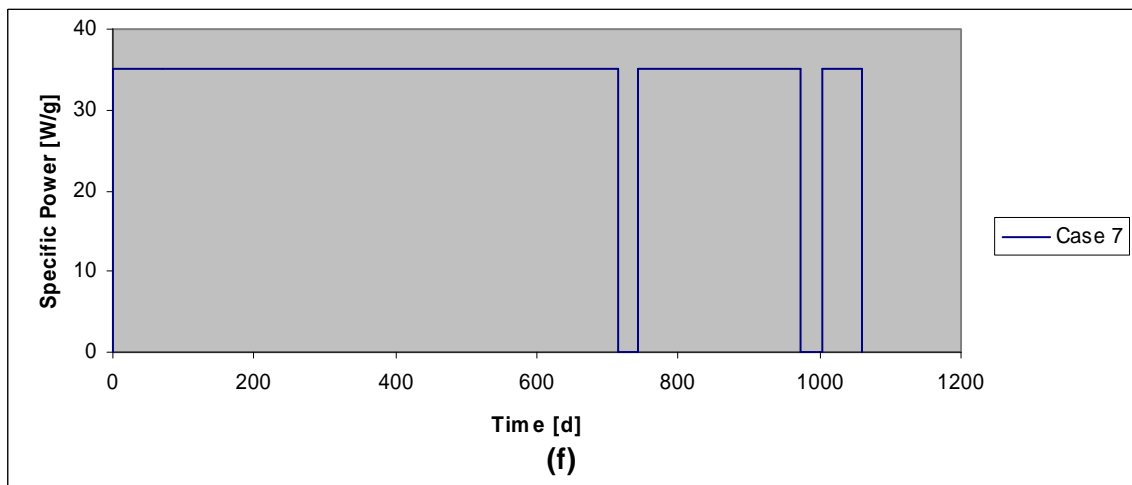
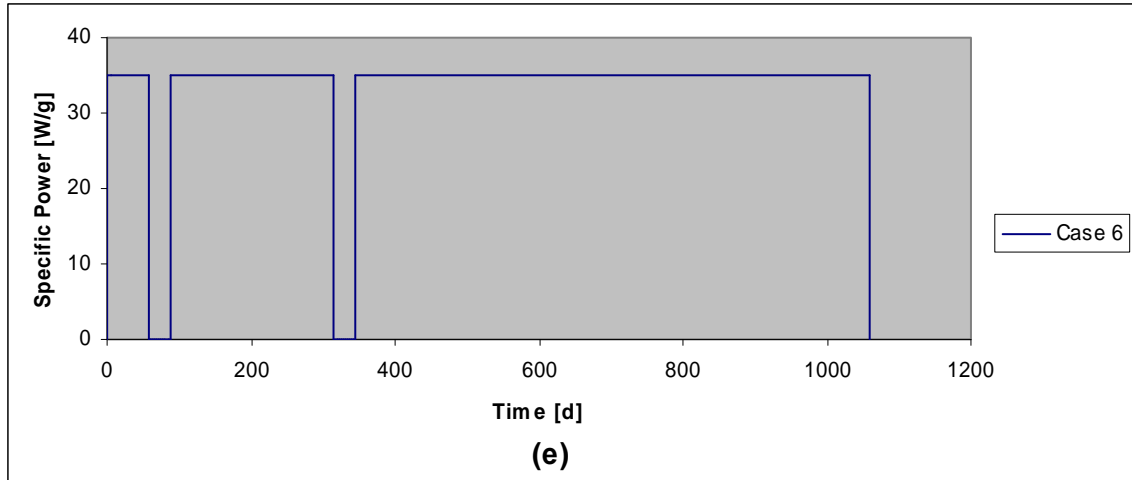


Figure 1. PWR pin-cell cases run for monitor confirmation: (a) Case 1, Case 2a, Case 2b, (b) Case 3, (c) Case 4, (d) Case 5, (e) Case 6, (f) Case 7

With the data generated by the PWR pin-cell cases the potential monitors shown in Table 1 were confirmed as viable options. Examples of monitor behavior are given in Figure 2. It should be noted that not all the monitors listed have the same spread demonstrated by the examples below.

Table 1: Monitor Isotopes

Radioactive	Stable
Te-127m	Sm-147
Ce-144	Ba-134
Sn-123	Gd-154
Pm-147	Nd-144
Ru-106	Pd-106
Ag-110	-
Sb-125	-
Cs-134	-

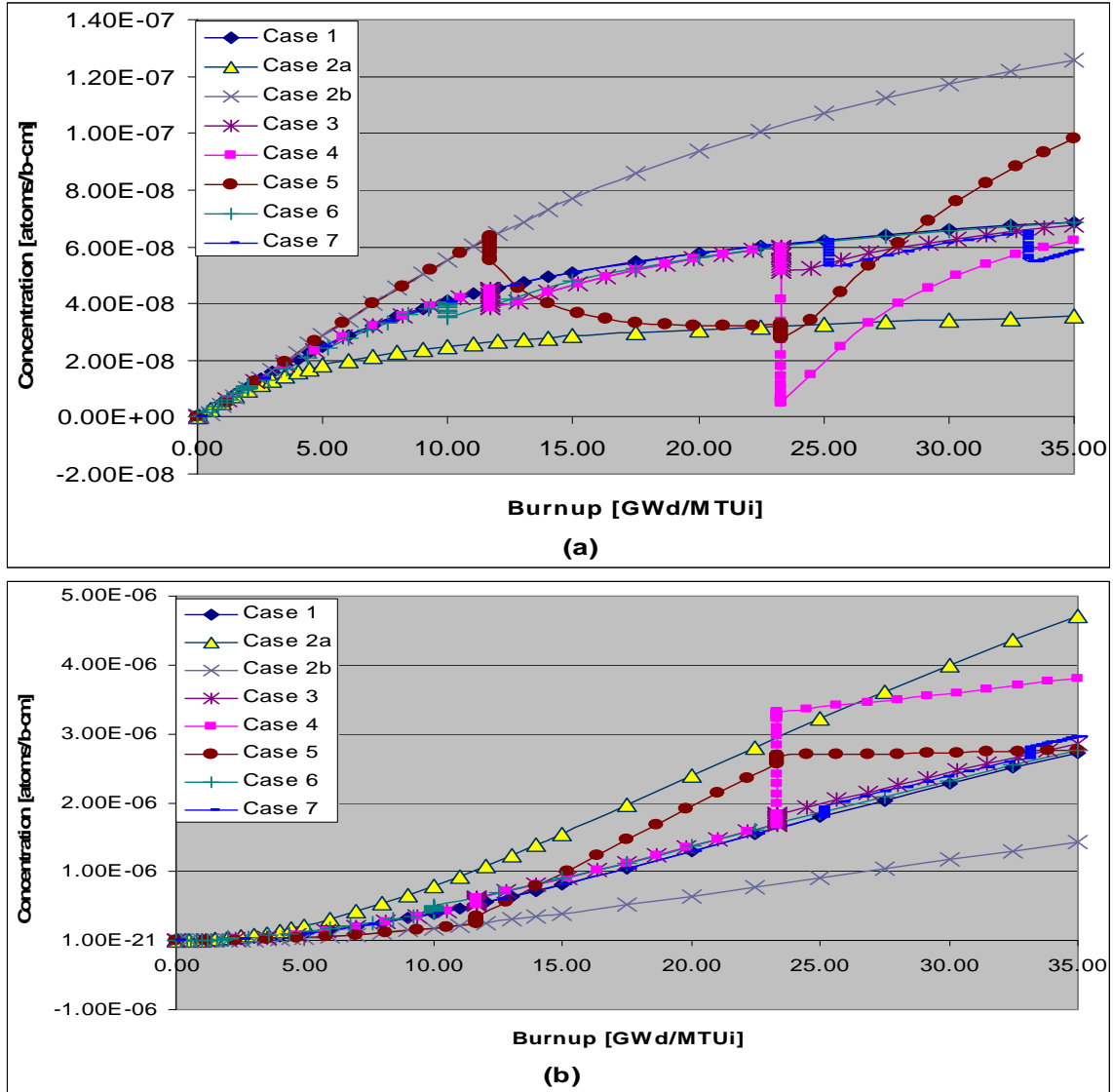


Figure 2: Monitor concentration for PWR pin-cell cases as a function of burnup: (a) Te-127m (radioactive), (b) Sm-147 (stable)

## Monitor Analytical Formulation

After suitable monitors were identified, analytical models were developed such that an average specific power may be extracted when a value for a monitor concentration is input. This section focuses on radioactive monitors.

The differential equation for production/destruction of Te-127m is

$$\frac{dN_{Te127m}}{dt} = Y_{f,U235} \sigma_{f,U235} N_{U235} \phi + Y_{f,Pu239} \sigma_{f,Pu239} N_{Pu239} \phi - \lambda_{Te127m} N_{Te127m} \quad (1)$$

where  $Y_{f,x}$  is the fission yield of Te-127m from isotope  $x$ ,  $\sigma_{f,x}$  is the fission cross-section of isotope  $x$ ,  $N_x$  is the number density of isotope  $x$ ,  $\phi$  is the neutron scalar flux, and  $\lambda_x$  is the decay constant of isotope  $x$ . The fission yields used in this work are cumulative fission yields extracted from the ORIGEN 2.2 libraries. The flux in Equation (1) can be substituted for using an expression for the specific power:

$$\phi = \frac{P_s(t) \rho_U}{E_R \Sigma_f}, \quad (2)$$

where  $P_s(t)$  is the specific power at time  $t$ ,  $\rho_U$  is the Uranium mass density, and  $E_R$  is the recoverable energy from fission.  $\Sigma_f$  is the macroscopic fission cross-section for the fuel and includes fission from U-235 and Pu-239.

The integration of the differential equation is complicated as the number densities of U-235 and Pu-239 are time-dependent. However, the U-235 and Pu-239 concentrations in atoms/b-cm are well approximated by the following functions of burnup:

$$N_{U-235} = 7.3759E - 04 * e^{-4.4253E - 02 * BU} \quad \text{and} \quad (3)$$

$$N_{Pu-239} = 4.68273660E - 09 * BU^3 - 3.88865897E - 07 * BU^2 + 1.10780642E - 05 * BU + 1.38676236E - 06 \quad (4)$$

where  $BU$  is the burnup in GWd/MTU. Equation (3) and Equation (4) are specific to the PWR pin-cell model used in the cases run. Eliminating the time-dependence of the U-235 and Pu-239 concentrations with Equation (3) and Equation (4) allows Equation (1) to be integrated by use of a simple integrating factor yielding the result

$$N_{Te-127m} = \frac{\rho_U \bar{P}_{s2,Te-127m}}{Er \lambda_{Te-127m}} \left[ \frac{Y_{U-235}}{1+R^{-1}} + \frac{Y_{Pu-239}}{1+R} \right] \left( 1 - e^{-\lambda_{Te-127m} t} \right), \quad (5)$$

where

$$R = \frac{\sigma_{f,U-235} N_{U-235}}{\sigma_{f,Pu-239} N_{Pu-239}}. \quad (6)$$

Equation (5) is enabled by the creation of a weighted average of specific power defined as

$$\bar{P}_{s2,Te-127m} = \frac{\int_0^t dt' P_s(t') e^{\lambda_{Te-127m} t'}}{\int_0^t dt' e^{\lambda_{Te-127m} t'}} \quad (7)$$

The weighted average specific power is easily calculated for any step function of specific power. The monitor concentration is measured from spent fuel samples. Equation (5) has the following unknowns: burnup, the weighted average specific power, and total time. There are established monitors to determine burnup [2,3,4,5]. The average specific power and time can then be determined through an iteration scheme using all available monitors. For final verification, the weighted average specific power can be computed from the provided reactor declaration and compared with the calculated value.

### Comparison between Analytical and Computational Models

Using the actual burnup, weighted average specific power, and time from the existing cases, the models for two monitors (Te-127m and Ce-144) were used to calculate the final monitor concentration. The results are compared to TRANSLAT in Table 3. The difference between the analytical and computational models is small. The accuracy of this verification scheme would increase with the number of available monitor concentrations.

Table 3: Final Monitor Concentrations

	Case 1		Case 2a		Case 2b		Case 3	
	Te-127m	Ce-144	Te-127m	Ce-144	Te-127m	Ce-144	Te-127m	Ce-144
TRANSLAT	6.88E-08	1.44E-05	3.54E-08	7.65E-06	1.26E-07	2.28E-05	6.74E-08	1.39E-05
Model	6.74E-08	1.51E-05	3.38E-08	7.57E-06	1.29E-07	2.34E-05	6.59E-08	1.46E-05
% Diff.	<b>2.02</b>	<b>4.81</b>	<b>4.62</b>	<b>1.07</b>	<b>3.06</b>	<b>2.68</b>	<b>2.28</b>	<b>5.10</b>
	Case 4		Case 5		Case 6		Case 7	
	Te-127m	Ce-144	Te-127m	Ce-144	Te-127m	Ce-144	Te-127m	Ce-144
TRANSLAT	6.2E-08	1.07E-05	9.83E-08	1.56E-05	6.87E-08	1.43E-05	5.89E-08	1.31E-05
Model	6.01E-08	1.14E-05	9.81E-08	1.65E-05	6.73E-08	1.50E-05	5.77E-08	1.38E-05
% Diff.	<b>3.11</b>	<b>6.91</b>	<b>0.24</b>	<b>5.64</b>	<b>2.06</b>	<b>4.93</b>	<b>1.97</b>	<b>5.05</b>

### Conclusion

This work has identified fission product isotopes that may be useful as monitors for determining an average specific power for reactor fuel. The values necessary for average specific power calculation are burnup and monitor concentration. Burnup determination methods are documented [2,3,4,5]. An iterative process using models as developed above taking burnup and monitor concentration as inputs can yield the average specific

power with total time. The average specific power obtained is not the simple time averaged value. But, calculation of a comparison value should not be difficult using the reported power history. It is worth reiterating that the models developed are highly sensitive to the fission yield values used and tabulating these values correctly is important.

Further research will attempt to obtain the remaining values necessary to fully characterize power history including total shutdown time, specific shutdown duration, the time at which each shutdown occurs, and the specific power of each burn. It is envisioned that with enough quality monitors the specific power as a function of time (and thus all the parameters listed above) can be solved for directly. However, if this is not possible, attempts will be made to solve for each lesser parameter step by step.

## References

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