PRACTICES FOR NEUTRONIC DESIGN OF RESEARCH REACTORS: SAFETY AND PERFORMANCES

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Abstract

In brief, the design aims to have a facility which is quickly operational and profitable, safe and able to evolve over 40 or 60 years, taking into account both the evolution of the requirements for experiments or production yet to be realized and the safety practices. This paper presents the AREVA current design and safety practices (both cannot be realized without the other) for the neutronic design of the research reactor (RR) cores. It completes the paper [1] and presents the general methodology of neutronic design studies for the safety and performance aspects and only slightly focuses on the reactivity shutdown systems and the neutronic calculation schemes. The main points are illustrated with examples of the Jules Horowitz Reactor (core designer point of view). On this basis of our general methodology, certain problems are separated in order to permit rapid reiteration at an individual level before the final synthesis. For example: to carry out generic studies of fuel management strategies and core reactivity control in order to manage the power peak (need core depletion calculation) and to be able to reason step 0 for certain optimizations of the core geometry and characteristics. For the neutronic calculation scheme, our current practice is to combine the use of the deterministic and stochastic codes. The strong points of each type of code are used to reinforce the safety and the performance of our cores. In this field, AREVA has a R&D framework involving and coordinating the participants from the various sectors (power reactors, research reactor, etc.) in the development of the general calculation methods and associated tools, in particular for Monte Carlo core depletion calculations. The CEA (along with APOLLO, CRONOS and TRIPOLI codes) largely supports us in this field. Comparisons between MCNP and TRIPOLI and between the various libraries (ENDF, JEF, etc.) are also performed. That includes the recalculation of existing reactors (OSIRIS, ORPHEE, AZUR, TRIGA, etc.). This enables us to complete the qualification of the codes and to acquire a better comprehension of the physical phenomena and safety of these cores. Finally, because this point is regarded as very important for safety design, our management system has to drive our technical teams. Some people need to circulate within the various kinds of reactors (power reactors, research reactors, propulsion reactors, etc.) to maintain our level of technical skill.

1. INTRODUCTION

In the field of research reactors, the skills of AREVA now rest upon the combination of two formerly separate teams: one which has recently designed FRMII and one which has recently designed the RES and Jules Horowitz reactors.

It is also noticeable that AREVA has been and remains the technical operator of many nuclear facilities including:

- Test reactors (now all shutdown): PAT, CAP , RNG;
- 1 test reactor (under construction) nearing completion: RES;
- Critical mock-up: AZUR (see poster session “The AZUR Pile: a research reactor with various training configurations”).

These features are very important facts for the core and reactor design capability including:

- An overall design and safety approach strengthened by both the German and French teams;
- Direct feedback of reactor operations and constant care of the operators.

This paper presents our current practices for the neutronic design of RR cores:

- §2 - General process of design for the reactors and §3 - Core design process: because having an efficient design process is decisive for safety;
- §4 - Focus on reactivity control systems: crucial systems for safety;
- §5 - Focus on neutronic calculation scheme: an important element to manage core safety;
- §6 - People: no safety without them;
- §7 - Conclusion.

2. GENERAL PROCESS OF DESIGN AND SAFETY FOR THE REACTORS

Since the 1990s, AREVA TA has developed:

- A consistent set of design processes covering most of the design activities to be performed for complex product conception:
  - The main design and development process - the so-called “Design and Development Process for Complex Industrial Facilities and Nuclear Reactors;”
  - Several engineering sub-processes covering different disciplines and different levels of the product breakdown structure. For the core design and safety studies, the relevant sub-process is called “Thermal-hydraulic and Core Neutronic Studies Process;”
- A consistent set of technical instruction reports;
- An internal safety organization.

2.1. Design processes

The main aims of the design and development process are consistent with the requirements of FD-X-50-410 [2], see figure 1:

- Giving the design shared timeline;
- Defining the successive design phases (Conceptual Design, Preliminary Design, Detailed Design phases);
- Defining the Milestones allowing the team to launch the next phase.

All the design Milestones are not identified in the figure 1 which identifies only the beginning and end milestones of the design phase. Intermediate milestones will be defined in the Design and Development Plan according to the product complexity and the design strategy. For each project, this Design and Development Plan is established tailoring the individual design processes to the project features and specificities and also highlighting the objectives (design data and the associated maturity level) to be met for each design milestone of the project. This plan provides a level of definition and clarity which allows all the project team to share a common view on the major requirements and conditions of project roll-out and implementation especially aspects dealing with: phases and milestones, processes involved, product related documentation set, schedule, reviews etc.

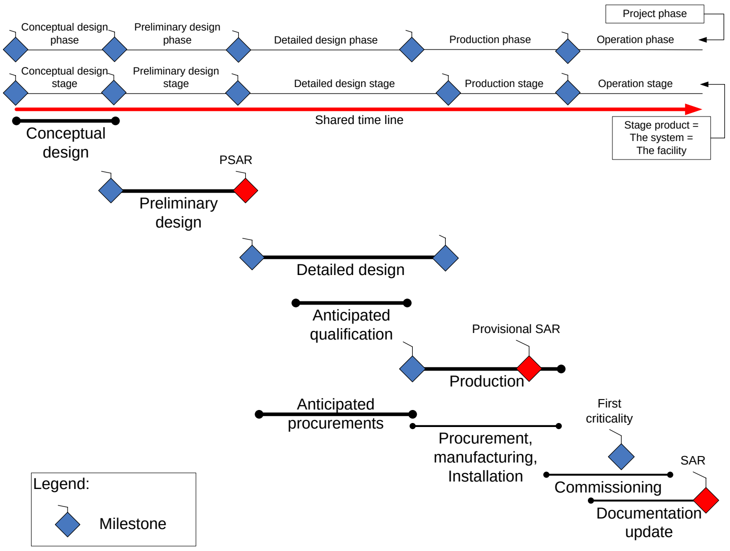

FIG. 1: Design Life Cycle

So to summarize, the synchronization of design activities is based on:

- A set of consistent design phases and Milestones to pace the design activities not only at plant level, but at system and component level too;
- The identification, from the beginning of the phases, of the data exchanges between activities: input data expected and associated producer, and output data to be produced and associated user.

2.2. Technical instructions reports

These documents represent the state of art in AREVA TA for safety and design. They contain definitions (variables, materials etc), advice, recommendations or rules, in particular for safety aspects (e.g. single failure application). They also cover the core design of RRs. Most opinions and recommendations are directly applicable.

These reports are not stagnant. They evolve with the design activities at AREVA TA.

2.3. Internal safety organization

Because AREVA TA is also a technical operator of nuclear facilities, there is a structured safety organization at AREVA TA. Research reactor projects benefit from this. The organization is:

- AREVA TA Safety Committee, which examines the different projects from a safety point of view (monthly) and gives internal advice and recommendations to the projects;
- A Safety Project Engineer in each project team. He is responsible for overall safety awareness and technical relations with the customer and, if the contract requires it, with Safety Authority;
- A safety team: safety engineers for the safety analysis and the monitoring of the Safety Analysis Reports drafting;
- Engineers in thermal hydraulics, neutronics, mechanics, radiation protection etc for safety assessments.

2.4. Conclusion

Since these processes and organizations were designed in the 1990s, they have been successfully used and subsequently improved upon for all projects performed by AREVA TA in the nuclear field (MTR, propulsion reactors, waste treatment facilities, research centres etc).

3. NEUTRONIC DESIGN PROCESS

Structuring data exchange and facilitating technical exchange within the project, the above method supports, at the same time, both the rigor and innovation. This is important for core design because of the requirement to install a large quantity of equipment within in a small volume, and with a high level of safety:

- Experimental or production devices (the raison d'être of the reactor);
- Fissile material to achieve high neutron flux;
- Moderation at the appropriate level to obtain adequate neutron flux and neutron spectra in the experimental devices and the longest possible lifetime;
- Coolant in order to transfer the energy of the nuclear reactions;
- Neutron absorber nucleus in order to control the core reactivity;
- Reflector materials to have a wide experimental volume apart from the core and to support the core lifetime;
- Structures in order to control the geometry of the whole core during normal or abnormal operation and accident conditions;
- Instrumentation for safety or management of the experimental load.

As a result, from the point of view of neutron design, many technical interfaces and data exchanges (see figure 2) are needed. However, the guideline is to be able to remain sure, simple and effective.

To be more precise, the main aims and key points of the different phases of core[1] design can be synthesized as follows:

1) Conceptual design: The first level of safety for the core is to design a core well fitted to the customer's true requirements (such a core will be used without major modifications): as a result, it is very important to have effective exchanges with the customer. The principal trap is to advance too rapidly to a solution without sufficient discussions with the customer and with the other participants in the project, especially because all the technical partcipants are not mobilized at the same time at the beginning of a project.

In practice, for the core design, this phase results in:

- Analysis of the desired experimental load with a first safety analysis of the impact of the various experimental devices on the design: presence of devices with fuel in the core and/or in reflectors (and parameters impacted), options of core design that depend on experimental devices (e.g. the flow circulation in a core when there are in-core energy experimental devices), the effect of the experimental load on organization of coolant circuits and feedback on neutronic design;
- Determining two or three solutions which have a high potential to advance, are reasonably implementable and are acceptable from the safety point of view;

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[1] Core design is mainly a matter of neutronics, thermal-hydraulics, mechanics, fuel physics and I&C (Instrumentation & Control). In our project management, there are completely linked. This paper is only about neutronics.

- Determining the design issues to be addressed for that reactor (i.e. identification of the technical risks). This point feeds the Design and Development Plan of paragraph 2;
- Development of Technical Specifications (Core-Fuel, Reactivity Control and Shutdown Systems): these documents define the functions to be ensured, in particular for the experimental loads and safety, the chosen criteria, the preliminary list of safety systems, structures and components (SSC) as well as the adopted solutions (at that moment, definition and definition justification are in the same document). This document also contains the definition of the experimental loads to consider (e.g. choice of devices standards, energy devices to consider).
- Development of reports with the interface data, giving the range for the various relevant parameters in relation to the other technical studies (as often as needed, but at least at the beginning and at the end of the phase):
    - Neutron data for thermo-hydraulic studies of safety and operations: kinetic relations, power-factors, absorber reactivity worth, device reactivity worth, residual power, feed-back coefficients (moderator, power, fuel): to manage the thermo-hydraulic safety assessments;
    - Neutron data for mechanical studies: mainly fluence and heating in various materials that are present within the high neutron flux volume: to manage the potential for mechanical failures;
    - Neutron data for radiation protection studies: source-term of fuel and experimental devices, activation of various materials: to manage the radiation exposures.

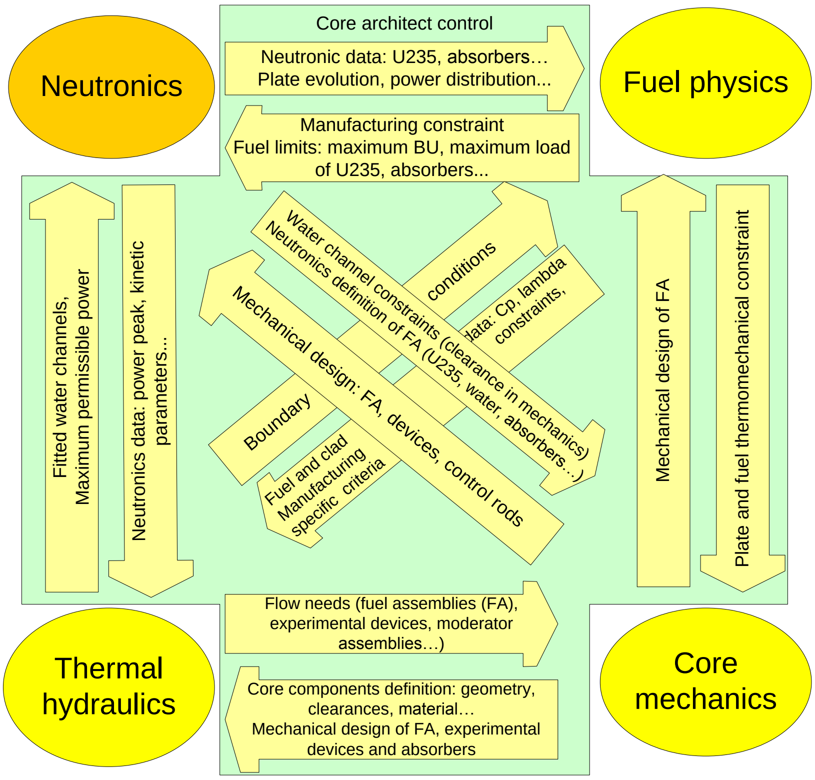

FIG 2: Core design – Internal main data fluxes

In the end, the main features of the core are examined during design reviews from the safety point of view. If not imposed by the customer in his requirements, the worth of the reactor nuclear power is specified (but not fixed).

2) Preliminary design: The objective of this phase is to undertake the choice of the core, to specify the performance requirements (performances in the experimental load, lifetime,

consumption of fuel assemblies or other components) and to carry out the safety analysis for the PSAR (Preliminary Safety Analysis Report).

This phase of studies reconsiders the interaction, from the point of view of safety and performance, between the various experimental devices and the core and reflector system:

- Determining particular devices with higher safety risks. Their insertion in the core and reflector systems allows the robustness of the concept (safety level) to be assessed and to undertake the required adjustments;
- Determining standard load of experimental devices and related performances, which allows the global design of the core and the associated safety studies,

In addition, preliminary design studies must also ensure our later capability (during detailed design or construction) of:

- Making the final choice of standard core control: compatibility between flux performance and realistic peaking factors;
- Making the final choice of refuelling strategy: aspect of economic performance, reactivity control and flux performance;
- Managing the neutronics - mechanics and neutronics - thermal hydraulic interfaces during the detailed design: taking into account the detailed mechanical design studies and the final characteristics of various circuits (primary coolant pump, flows in core and reflector etc).

This needs to manage certain adjustment variables.

The documents developed at the end of the conceptual design are built-upon. The maximum nuclear power of the reactor is fixed. General core control strategy as well as the refuelling strategy is defined. It is the same for the nuclear monitoring system of the core (start up neutron source and nuclear channels).

For the choice of the nuclear power, it should be noted that for experimental reactors, the economic performance and safety are convergent owing to the fact that we need a high level of neutron flux and not a high level of power. De facto, the residual power after the shutdown is overall minimized.

3) Detailed design: The objective of this phase is to carry out the detailed studies which are needed for the Safety Analysis Report (SAR), the realization of the installation, the Definition Files and Definition Justification Files and the operating documentation. Core control scheme and refuelling strategy are detailed and provided to the operator. The transition between the first core and the equilibrium core, detailed flux monitoring studies, detailed studies of lifetime of various components (e.g. reflector and absorber elements) are also realized.

During the preliminary and detailed phases, the core compliance approach constitutes a true backbone for the safety and performance studies. This approach, which is structuring the neutron design of the core, makes it possible to define and to take into account (by a multilateral approach):

- Constraints on the manufacturing and the tools for treatment of non compliances;
- Flexibilities offered to the operator e.g. fuel management, experimental load management.

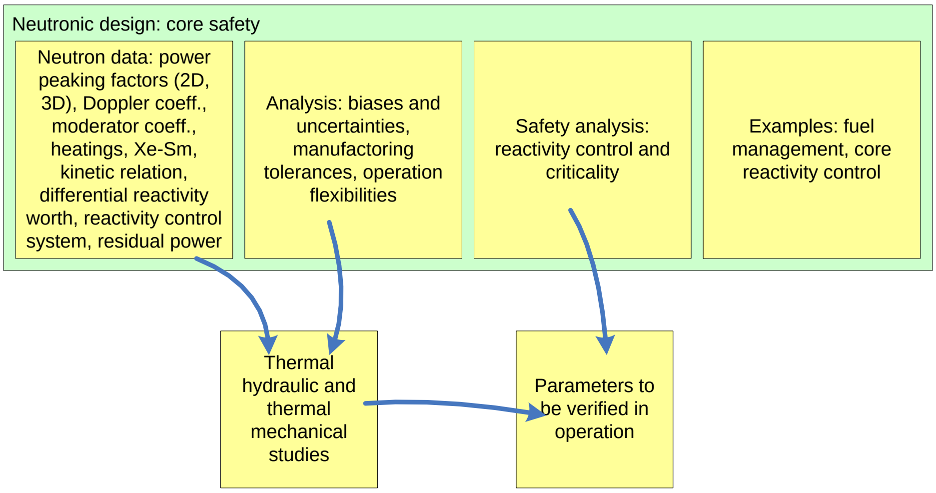

FIG 3: Technical approach for the parameters to be verified in operation.

In addition to the various necessary specialists, success rests on technical control of the whole by a core architect. His role is to control the data flows (see figure 2):

— Technical data from and to the customer (performance);
— Technical data flow between the various technical studies (via the notes of interface for example).

The core architect must also work with the architects of the other main systems, as well as with the safety project engineer.

To provide two practical examples of robust integration of the experimental loads, we have, within the preliminary design of Jules Horowitz reactor:

— Kinetic relation: the fact that the experimental devices in core can contain fuel has been taken into account. For the delayed neutron fraction, we considered that the most penalizing isotope among those able to be present in the devices was Pu239. Rather than have complicated compositions of these devices, we considered in a conservative way that the whole allowance of power to the in-core devices could come from fissions of Pu239. On this basis, we modified the delayed neutron fraction. It is on the basis of this penalized kinetic relation that the studies of reactivity transients were carried out thereafter;
— Power factor: a large number of various experimental loads have been considered during generic studies of device impact for the maximum power factors. However, we took into account an extra margin for 3D and 2D power-factors to make the later adaptation of some of these devices easier. These penalized factors were the basis for the thermo-hydraulic safety studies.

All this was done with a “design to cost” approach for these flexibilities.

4. FOCUS ON SHUTDOWN SYSTEMS

For the shutdown systems, our basic principles are to have:

— 2 shutdown systems which allow the operator to shut down the core in an easily reversible way (short, medium, long run);

- 1 shutdown system that has a simple and robust design, accessible from outside of the containment. This system is only for the shutdown in the medium and long term, and is rather of the one-shot kind.

The first two shutdown systems are coherent with the requirements [3] [4] and need, for each project, an analysis and an adaptation of the principles. To detail this point, we propose for these systems:

- The most complete possible separation between the two systems (physical actuators, nuclear channels, control, triggering system) and no common failure mode between them;
- If possible, a spatial separation between volumes for the experimental load and volumes for the shutdown systems;
- 2 different technologies;
- Depending of the project, the same trip thresholds;
- The greatest possible flexibility for the reactivity worth of the experimental loads.

Concerning the 3rd shutdown system, it must be as simple as possible, not instantly operative (to avoid its spurious shutdown). It must be operational in the medium or long term in the event of an accident, from the outside of the containment and with a small amount of energy. It allows the operator to send a neutron absorber in the whole facility pools to manage the criticality of fuel everywhere in the pools. It must not over-degrade the main materials (first and second barriers, pool structures). This system is not related to a post-Fukushima effect, it has been part of our design principles for many years.

Quantitatively, the shutdown systems are dimensioned on the basis of criteria with the following characteristics:

- The state of the core, for example: 20°C, without xenon;
- The configuration of core and reactivity control systems. This also includes the resulting reactivity jump from an initiating event and the single failure criterion. For example: Reactivity worth of all installed devices included, with the most reactive error of refuelling, with the most reactive rod of the first shutdown system in the most reactive position, all the other rods of the first control system down, with the effect in reactivity related to an postulated initiating event;
- The maximum worth of reactivity to be guaranteed for the core. For example: k eff (effective multiplication factor) < 0.9 or reactivity $< -1\$$;
- Consideration of the used calculation scheme and its biases and uncertainties.

The respect of the control criteria ensures the management of reactivity for all the considered situations. The whole of the situations must cover the whole of the facility operational range.

Example of the Jules Horowitz reactor:

- 2 reactivity control systems: hafnium tubes in aluminium guide tube in FA centre. When extracted, the absorbers are above the core. The drive mechanisms are in the crypt,
- 1 emergency system which allows the operator to send soluble poison in the reactor pool by a simple pipe.

1) First Shutdown System (FSS): drive mechanisms located in the crypt allow bringing the absorber tubes to a high position and they step back thereafter. Once the absorber tubes are in

the high position, there is no more mechanical bond between crypt and absorbers. The FSS sizing control criterion excludes the core divergence on the raising of this fail-safe FSS.

2) Second Shutdown System (SSS):

- 4 absorber tubes, ensuring control and preventive shutdown. The chosen Low Operating Limit rod position allows us to ensure a minimal worth for the preventive shutdown;
- 19 shim absorber tubes, ensuring the shimming of the global effects of reactivity (fuel burn-up, modifications of experimental load etc).

Comments:

- The FSS and SSS are associated with two different reactor protection systems. These two systems rest on the architecture of nuclear channels with 6 neutron detectors (3 for start-up channels, 3 for power channels) and a treatment on the basis of the 2nd max and 2-out-of-3 logic. It is a proven design with high reliability. Each system has a different logic of thresholds;
- Choices made for the geometry of the hafnium absorbers result on the one hand with a significant number of 27 absorbers and, on the other hand, by a low penalization in case of single failure: 2400 pcm with the uncertainties (all absorbers down except most effective).

5. FOCUS ON NEUTRONIC CALCULATION SCHEME [5]

Due to differences in the required performances, each type of research reactor leads to specific modelling needs. The following method is used to carry out our projects:

- Analysis of key values: fluxes, range of power, energy (lifetime), flexibilities etc.;
- Choice of the most reliable computing scheme and/or development (calculation codes, cross section libraries).

In terms of implementation, this method leads, for example, during the preliminary and detailed phases of the Jules Horowitz Reactor design:

- To rely on both deterministic codes (APOLLO2, CRONOS2) and probabilistic codes (TRIPOLI4 or MCNP) with the associated advantages providing the respective robustness on burn up calculations on one hand and the associated refinement in the geometric description and better flexibility for the elements that concern the calculated quantities (neutron and gamma heating, flux perturbation in experimental devices etc) on the other hand;
- To use the probabilistic codes at step 0 or in probabilistic depletion calculations using deterministic code inputs (codes getting material balance from deterministic calculation objects) or in depletion calculations with ORIGEN and MONTEBURNS or VESTA;
- To use the machine human interface CHARM, which allows us to generate the main part of datasets for the different codes from a single description of geometries and materials and also to analyze the results.

CHARM-V2 is a Pre Post Processor for APOLLO2/MOC, TRIPOLI4 and MCNP based on an Open Cascade technology. The CHARM project is developed by AREVA NP in collaboration with AREVA TA to integrate research reactor modelling needs.

The main advantages of this tool are listed as follows:

- A multipurpose user friendly graphical interface for design geometry, meshes, material association, to configure score and tally and also to visualize results;
- A common geometry for APOLLO2/MOC, TRIPOLI4 and MCNP;
- A suitable XML file format describing exactly a CHARM study which can be easily modified by a script for parametric studies, studies are also saved in HDF file format as for a SALOME study;
- A batch mode to automatically generate numerous input data.

CHARM has commonly been used to generate parametric geometries including more than 30,000 meshes.

6. PEOPLE

Nowadays, without the right people, there is no design. As a result, concerning people, our current strategy in order to have the right people at the right moment in spite of a fluctuating RRs market, rests on the following:

- Retaining a small group of engineers with good know-how of RRs and the associated calculation schemes (stochastic and deterministic approach);
- Sensitization of a broader group of engineers to the RR characteristics. These people otherwise work on other small cores (e.g. for propulsion reactors, for spatial reactors) or on larger cores (e.g. for Small Modular Reactors, for power plant reactors);
- R&D studies of new concept of RRs;
- Development of the related tools (determination of the necessary specific functionalities for RRs and testing of the developments) within the framework of AREVA code activities;
- Varied careers at AREVA TA including neutron study, neutron test (zero power reactor AZUR, RNG reactor then RES reactor, embarked cores), operation of other nuclear facilities, fuel manufacturing and other technical study (thermal hydraulics, fuel physics, mechanics, safety analysis etc). The intermediate size of AREVA TA (around 1500 people) is facilitating this strategy.

We also rely on the technical AREVA expert network, whether these experts are directly from AREVA TA or elsewhere in the group. In addition, we continue to have many contacts, exchanges and co-developments with the Commissariat à l'Energie Atomique.

7. CONCLUSION

This overview, focussed on the neutronic core design, would require a supplement with thermal hydraulic [6] and mechanic aspects on the level of the global design of core and main related systems (e.g. coolant systems) as well as with fuel and material physics aspects.

However our intent was not here to be exhaustive nor to propose new safety rules, but to present some practices for the core design. Nevertheless, it should be noted that most of the method presented here for the neutron design is applicable to these other domains.

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