Evaluating Low Concept Maturity Mission Elements and Architectures for a Venus Flagship Mission

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NASA's Planetary Science Division recently commissioned a Science and Technology Definition Team to design a potential Venus Flagship mission. The team developed a list of various mission elements that could serve as parts of an overall mission architecture, including orbiters, balloons at various altitudes, and landed platforms of varying number and lifetime. In order to determine the mission architecture that provided the best science within the desired cost range, teams of scientists developed priorities for the science investigations previously detailed by the Venus Exploration Assessment Group (VEXAG). By categorizing the suitability of mission elements to achieve the science investigations, it was possible to construct a Science Figure of Merit (FOM) that could be used to rate the mission elements in terms of their overall science capability. Working in parallel, a team of technologists and engineers identified the technologies needed for the different mission elements, as well as their technology readiness. A Technology FOM was then created reflecting the criticality of a specific technology as well as its technology readiness level. When the Science and Technology FOMs were combined with a rapid costing approach previous developed, it became possible to rapidly evaluate not only individual mission elements, but also their combinations into various mission architectures, accelerating the convergence on a flagship mission architecture that provided the best science within the flagship mission budget, as well as reducing reliance on unproven technology..

Nomenclature

C	=	Technical Criticality Score
CDH	=	Command and Data Handling
DRM	=	Design Reference Mission
EVE	=	European Venus Explorer
FOM	=	Figure of Merit
FOM_S	=	Science Figure of Merit
FOM_T	=	Technology Figure of Merit
G	=	Science "Goodness" Score
GNC	=	Guidance, Navigation and Control
HT	=	High Temperature (750 Kelvins)
JPL	=	Jet Propulsion Laboratory
MT	=	Mid-Temperature (500 Kelvins)
NASA	=	National Aeronautics and Space Administration
M	=	Technology Maturity Score
P	=	Science Priority
PMAD	=	Power Management and Distribution
STDT	=	Science and Technology Definition Team
VEXAG	=	Venus Exploration Assessment Group
VISE	=	Venus In Situ Explorer

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I. Introduction

THE development of optimal mission architectures for future planetary missions can be a costly and lengthy process. Determination of science value and mission costs usually requires detailed information about the mission design and science payload, along with spacecraft design details that may take hundreds of workhours to flesh out to the level necessary to compute the science value and cost. When the trade space is not large or there is substantial previous study work to draw on, this does not pose intractable problems. The recent Outer Planet Flagship Mission Studies[1,2] used science figures of merit (FOMs) effectively to assist in optimizing payload selections and mission designs (e.g., regional and global image coverage and resolution).

NASA's recent Venus Flagship mission study[3] was essentially starting from scratch, without the benefit of previous studies of a mission of this kind. This provided an opportunity to see if a science FOM could be used early in a mission study as a way of exploring the mission trade space. A process[4] for developing candidate mission architectures that included a Technology figure of merit and a cost estimate was developed and presented to the Science and Technology Definition Team (STDT) and to the larger Venus Exploration Assessment Group (VEXAG[5]) and the approach was subsequently approved to proceed.

The reason for including a technology FOM was two-fold. First, to identify specific technologies (primarily those addressing the extreme environment[6] posed by Venus) that would benefit a Venus Flagship mission launching in the 2020 to 2025 timeframe, and second, to determine the criticality of that technology for that mission. Here criticality means whether the mission as designed could still be performed, even if the technology was not sufficiently mature by the 2015 technology cut-off date to be used. This information would be included in the report for use by NASA in determining technology development priorities.

Finally, a novel rapid costing approach[7] was used to provide relative cost estimates for both major mission elements (orbiter, entry probes, airborne platforms, or landers) and overall mission architectures. The combination of these three FOMs allowed for rapid convergence on selection of promising mission elements and their combination into candidate mission architectures, as well as down-selection to the final STDT Reference Mission architecture. The Science FOM came back into play during selection of the notional instrument payload for the Reference Mission, where it was used to verify that the selected instruments adequately addressed the science represented by the overall Mission Architecture Science FOM and did not result in a reduction of the Science FOM for the reference mission as further detailed during the study.

II. Construction of Figures of Merit

The VEXAG has previously documented their science goals, objectives, and investigations for Venus[5]. In order to expedite their efforts, the scientists in the STDT split themselves into three subgroups: Atmospheres, Geochemistry, and Geology and Geophysics. These science subgoups re-organized and, in some cases, consolidated the VEXAG science investigations to create a list of prioritized science investigations. The priorities were characterized as:

1 = Essential to have
2 = Highly desirable
3 = Desirable
4 = Very Good to have

They then analyzed a very wide range of measurement techniques and associated instruments to determine the degree to which these techniques and instruments could satisfy the various investigations using a simple 4-level "goodness" scale:

3 Directly answers
2 Major contribution
1 Minor contribution or supporting observation
0 Does Not Address

Table 1 provides an illustrative subset of the priorities and "goodness" values for measurements and instrument types. The Goal, Objective, and Investigation refer to the VEXAG Science Objectives, the VEXAG Science Priority refers to their combined priorities, and the Flagship Priority was assigned by the STDT subgroups.

Table 1 – Selected Results of Science Subgroup Ranking of Objective Priorities and Measurement "Goodness"

Goal	Objective	Investigation	VEXAG Science Priority	Flagship Priority	Investigation Description from VEXAG document	*Instrument Type*	Radar (o)	Near surface, visible/NIR (a)	Radar Altimetry/InSAR(o)	Microwave and/or IR (o, a)	Radio Tracking (o)	Magnetometer (o,a,l)	Surface Corner Reflector (l)	Seismometer (l)	InSAR (o)
2 2	1 3	4 5	1	3	Characterize the flux of materials emitted from volcanoes, including chemically active and inactive species, aerosols and other particulates, and molten lava. temporal variations, and mass flux.		0	1	0	1	0	0	0	0	2
1 1 2 2 2 1	2 4 2 3 4 5	3 1 1 3 4 2	2	1	Characterize stratigraphy of surface units through detailed topography and images.		2	3	2	1	1	1	0	0	2
2 2 2 3	2 3 4 2	2 2 1 2	2	1	Characterize the structure and dynamics of the interior of Venus. Characterization of the current rate of internal activity will place constraints on the mechanisms and rates of recent resurfacing and volatile release from the interior.		1	1	2	1	2	3	2	3	2
2 2 2 2	2 3 4 6	4 6 3 4	2	1	Determine the structure of the crust as it varies both spatially and with depth. Of particular interest is knowledge of the thickness of the crust, intracrustal layering, and how surface-geologic contacts extend into the crust. Measure topography and gravity		1	1	3	1	3	2	1	3	2

A. Science Figure of Merit Construction

The entire STDT, supported by the Venus flagship study team at JPL, identified 13 potential spacecraft platforms or elements referred to as architecture elements, which would host the various instruments and measurement techniques and satisfy the desired science investigations.

The architecture elements are:

- Orbital.
- High-level Aerial (> 70 km altitude, above the clouds).
- Mid-level Aerial (52 – 70 km altitude, in the clouds).
- Low-level Aerial (15 – 52 km altitude, below the clouds).
- Near-surface Aerial (< 15 km altitude).
- Single-entry Probe.
- Multiple-entry Probes.
- Short-lived Lander (Single).
- Short-lived Lander (Multiple).
- Long-lived Lander (Single).
- Long-lived Lander (Multiple).
- Surface System with Mobility (surface or aerial).
- Coordinated Atmospheric Platforms.

The science subgroups then rated the ability of the various architecture elements to achieve the desired science investigations using the same method (i.e., "goodness) as used for the measurement techniques and instruments. The results of this effort are illustrated in Table 2.

At this point, it was possible to construct a simple science figure of merit (FOM) for each of the architecture elements by combining the priority of the investigation with the score for the ability of the architecture element to satisfy that investigation. This simple science figure of merit (FOM_S) was constructed for each investigation and platform combination using the formula:

$$\mathbf{FOM_S = (\tilde{5}\text{-}P) \; x \; G} \tag{1}$$

Where P is the priority and G is goodness. Summing these scores for each of the elements then produced for each element a total science FOM.

B. Technology Figure of Merit Construction

The technological difficulty was then assessed in an analogous fashion, where the study team determined the criticality for 15 different technologies for each of the 13 elements while the technology subgroup determined their maturity. The combination of the criticality and the maturity scores created a technology development FOM that then could be used to compare the degree of technology development required for each of the elements. The technologies considered included:

- Pressure vessel.
- Passive thermal control.
- Active cooling.
- High-temperature (HT) electronics platform avionics (command and data handling (CDH), guidance navigation and control (GNC), power modulation and distribution (PMAD), etc.).
- Mid-temperature (MT) electronics platform avionics (CDH, GNC, PMAD, etc.).
- HT actuated mechanisms (robotic arms, mobility, etc).
- HT telecom.
- HT sample acquisition.
- HT energy storage.
- MT energy storage.
- Power generation.
- Solar cells.
- Altitude control.
- Materials and fabrication (balloons, bellows, structures).
- HT health monitoring.

In parallel to the science FOM_S, a technology Figure of Merit (FOM_T) was also constructed by the technology members of the STDT for each mission architecture element using the formula:

$$\mathbf{FOM_T = C / M} \tag{2}$$

where C is technology criticality and M is technology maturity.

For criticality, the ranking from (0) to (3) is assigned to each architecture element for every investigation. Assigned values are:

0 Not needed for that element
1 Useful
2 Desirable
3 Must have

Similarly, maturity was defined on the basis of technology readiness levels (TRL), and ranked from (0) to (3), representing the following TRL ranges:

0 TRL 1 – 2
1 TRL 3 – 4
2 TRL 5 – 6
3 TRL 7 – 9

The STDT assessed criticality on the basis of mission impact, and the STDT technology subgroup assigned maturity values. Higher values of FOM_T meant large amount of technology and technology development. While the technology FOM does not impact the science-driven selection of mission architectures, it indicates how much technology needs to be developed to achieve them.

C. Rapid Cost Development

Finally, mission complexity ratings were developed and then translated into predicted mission costs using the rapid cost assessment methodology described in reference 7. This approach can predict relative mission costs for the various architecture elements when the missions are still in their preliminary study phase and not yet fully defined. The rapid cost assessment approach makes use of cost/complexity ratings for key space mission technical and operational categories. These ratings provide numerical cost driver indices to create an estimate of a mission cost without exploring the nuances of the actual spacecraft design.

These cost drivers are meant to capture the costs common to most missions. Not all cost drivers will be present in every mission, in fact it is highly unlikely that one mission will contain every cost driver. Similarly, cost drivers do not capture a totally complete picture of every mission, but rather give a rough idea of the key costs involved in a mission. The purpose of the cost drivers are to neatly categorize the sources of mission costs and thus make it possible to estimate the total cost of the mission without expending the resources of conducting a highly detailed study. Calibration of the cost indices with historical mission costs provides a basis for conversion of the complexity indices to rough dollar costs. However, this method is intended for scoping only and does not replace higher-fidelity methods, such as parametric or "grass roots" costing. The accuracy of the rapid cost assessment is currently estimated at ~10% to 20% for relative costs and ~30% to 40% for absolute costs.

III. Application to Mission Elements

The results of these analyses are presented in Table 2 and shown graphically in Figure 1.

Table 2 – Summary of Mission Elements and FOMs

Architecture Element	Description	Science FOM	Tech. FOM	Cost est.
Orbiter	Self–evident, but can dip into the exosphere for in situ sampling	177	0	$0.53B
High–Level Aerial	Altitude >70 km, above clouds	169	3	$0.47B
Mid–Level Aerial	Altitude 52–70 km, in clouds (about the same altitude as the VEGA balloons)	191	3	$0.42B
Low–Level Aerial	Altitude 15–52 km, below clouds, limited view of surface due to attenuation	176	14	$1.7B
Near–Surface Aerial	Altitude 0–15 km, NIR imaging of surface is possible, no surface access	170	20	$3.1B
Single Entry Probe	No surface access, descent science only	136	2	$0.45B
Multiple Entry Probes	No surface access, descent science only	171	2	$0.47B
Short–Lived Lander	Single lander, about 5–10 hours lifetime on surface, passive cooling	153	12	$1.1B
Short–Lived Landers	Multiple landers, about 5–10 hours lifetime on surface, passive cooling	214	12	$0.94B
Long–Lived Lander	Single lander, days to weeks lifetime, may require active cooling and RPS	223	21	$3.5B
Long–Lived Landers	Multiple landers, days to weeks lifetime, may require active cooling and RPS, long lived network possible	264	21	$3.5B
Surface System with Mobility	Active or passive cooling, mobility with surface access at multiple locations (e.g., rover with short traverse or metallic bellows with long traverse)	209	53	$7.1B
Coordinated Atmospheric Platforms	Large number (e.g., swarm) of in situ elements, with simultaneous measurements	129	21	$1.29B

There are some artifacts from this approach as presented. In considering single versus multiple identical elements it must be borne in mind that it costs more per element to develop one lander or probe than it does to develop multiple landers or probes (due to the fact that all design and some test costs can be amortized over the multiple copies). Therefore, the single versions of landers and probes shows a higher cost than the multiple versions, as these results show the per element cost. Also, the costs in Table 2 do not include launch vehicles or the science payload costs, which could vary substantially.

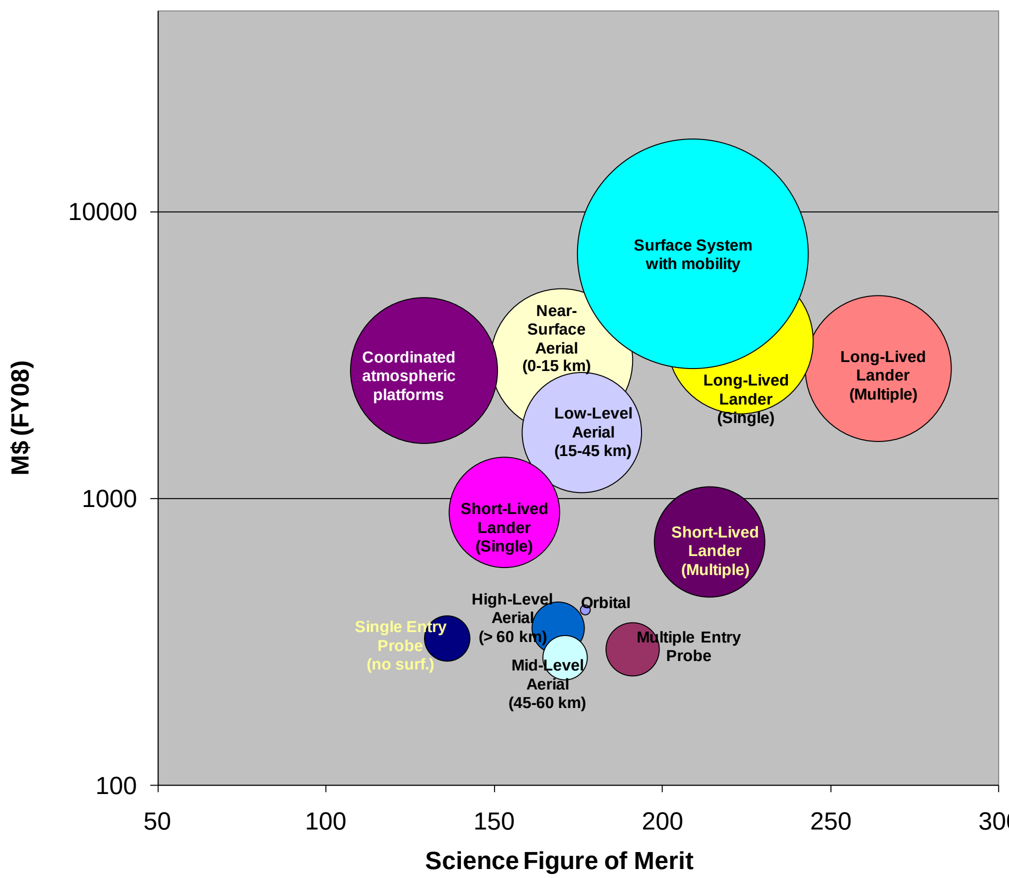

Figure 1 – Graphic Comparison of Candidate Mission Elements (Bubble Size is the Relative Amount of Technology Development Required for the Corresponding Mission Element

At this point, candidate Venus mission architectures can be created by using one or more of the architecture elements described in Table 2 and including estimates for associated launch vehicle[s] and the science payload.

IV. Application to Mission Architectures

To date, a significant number of Venus missions have either flown or been proposed using mission architectures included orbiters (Magellan), probes (Pioneer-Venus), balloons (VEGA), and short-lived landers (Venera). While the mission architecture elements of these past missions may be similar to those of the Venus Design Reference Mission, there will be major differences in the science instrument payloads and, hence, the kinds of science questions that can be addressed. The technological readiness of these previously used platforms is clearly high and results in low technology development ratings in the Venus flagship trade study. The opposite is true for platforms not previously used, particularly those involving long durations in the high-temperature regions of the lower atmosphere and on the surface.

Evaluation of the results of the element comparison led to important discussions that then informed the development of mission architectures. Perhaps key was the determination that, if properly equipped, a short-lived lander could provide the same science data as a descent probe. The two elements already had some overlaps in their notional payload, so for a modest additional investment, the total science returned could be greatly increased (thus increasing the science FOM for that element. Using this assumption made for some surprising results when mission architectures were assembled.

Based on these evaluations, the STDT and the JPL Venus flagship study team synthesized 17 mission architectures that spanned a large part of the design space to determine those that would most likely fit within the assumed cost cap of a Venus Flagship mission (although not all did) and achieve the highest-priority science. Launch vehicle costs were not included, and an additional 10 percent was added to account for the science instruments for each mission. Science figures of merit and total mission cost estimates were compiled for all of these architectures using the methodology describe above. The options are listed in Table 3, and the results are plotted in Figure 2.

Table 3 – Selected Mission Architectures

Mission Architecture	Science	Tech	Components			
Flagship Venera like	153	12	Flyby	Short lived lander		
Venus Mobile Explorer	386	53	Orbiter	Surface System w. mobility		
Pioneer-Venus plus	708	8	Orbiter	Multiple (4) Entry Probes	1 High Level Balloon	1 Mid-level Balloon
Seismic Network	264	21	Flyby	Long-lived multiple landers (4)		
Hi-lo Balloons	516	23	Orbiter	High-Level Aerial (> 60 km)	Near-Surface Aerial (0-15 km)	
Mid-level Balloons	544	17	Orbiter	Mid-Level Aerial (45-60 km)	Low-Level Aerial (15-45 km)	
Mult. Short Lived Landers plus	582	15	Orbiter	Short-Lived Lander (4)	Mid-Level Aerial (45-60 km)	
Coord. Atmos. Platforms	306	21	Orbiter	Multiple (4) coord. Platforms		
EVE-like concept	690	18	Orbiter	Short-Lived Lander (Single)	High-Level Aerial (>60 km)	Mid-Level Aerial (45-60 km)
Pioneer-Venus w. landers	562	14	Orbiter	Multiple (4) Entry Probes	Short-Lived Lander (Multiple)	
Long-Lived Lander	400	21	Orbiter	Long-Lived Lander (Single)		
EVE-Variant	635	17	Orbiter	Short-Lived Lander (Single)	High-Level Aerial (> 60 km)	Single Entry Probe (no surf.)
New Frontiers VISE like	76.5	6	Flyby	Short lived lander		
STDT Flagship	753	15	Orbiter	2 Mid-Level Aerial (52-70 km)	Short-Lived Lander (2)	
Geology Choice	347	20	Orbiter	Near-Surface Aerial (0-15 km)		
Atmosphere Choice	539	5	Orbiter	2 Mid-Level Aerial (52-70 km)	Multiple (2) Entry Probes	
GeoChem Choice	214	12	Flyby	Short-Lived Lander (2)		

Each of the science subgroups was encouraged to select an architecture that they felt would provide the maximum science return for their area of interest. The results are shown at the bottom of Table 2. Variations on previous missions, such as Venera and Pioneer-Venus were also included, as was a variant on the European proposed European Venus Explorer (EVE) mission concept and a New Frontiers class mission – the Venus In Situ Explorer (VISE). Finally, the team as a whole put together a best of breed concept to attempt to maximize science return at a cost within the guidelines. This mission proved to be significantly better than any of the other missions and is labeled the STDT Flagship in both Table 2 and Figure 3.

V. Conclusion

While there were several additional trades that had to be made before a reference mission architecture could be completely established (e.g, orbit design, launch vehicle selection, balloon type, etc.), the approach outlined above did allow for rapid convergence on a relatively optimal architecture which could then be subjected to more detailed design methods. The validity of the architecture chosen was re-established once the science payload was selected by re-computing the science FOM based on the ability of the specific instruments to meet the science objectives at the appropriate "goodness" level. The science score of the selected mission architecture (i.e., STDT Flagship) did not change, confirming that the analysis had been adequate despite the lack of payload definition at that time. The benefits of such an approach are sufficient in terms of both allowing for relative comparison of mission elements and architectures and rapid evaluation of alternatives, that it can serve as a model in conducting analysis of alternatives for future planetary exploration missions at low concept maturity levels, i.e., that are sufficiently novel or otherwise previously unstudied.

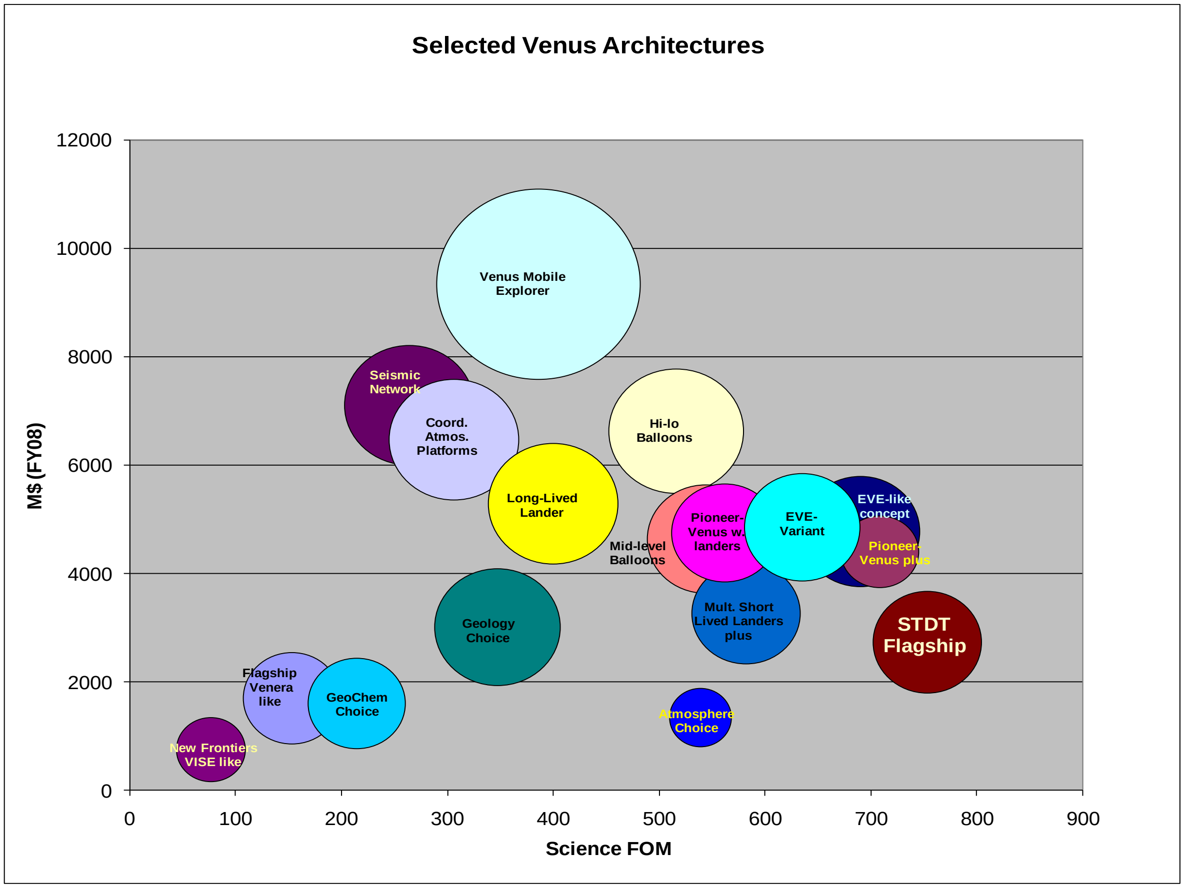

Figure 2 – Graphic Comparison of Candidate Mission Architectures (Bubble Size is the Relative Amount of Technology Development Required for the Corresponding Mission Architecture)

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