# FLIGHT TEST APPROACH TO ADAPTIVE CONTROL RESEARCH

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## ABSTRACT

The National Aeronautics and Space Administration's Dryden Flight Research Center completed flight testing of adaptive controls research on a full-scale F-18 testbed. The validation of adaptive controls has the potential to enhance safety in the presence of adverse conditions such as structural damage or control surface failures. This paper describes the research interface architecture, risk mitigations, flight test approach and lessons learned of adaptive controls research.

## NOMENCLATURE

| | |
|---|---|
| 1553 | Mil-Std-1553 data bus |
| 68040 | research flight control computer |

| | |
|---|---|
| 701E | production flight control computer processor |
| ARTS IV | Airborne Research Test System, $4^{th}$ Generation |
| CAT | Choose-A-Test |
| DAG | Dial-A-Gain |
| DDI | digital display indicator |
| DFRC | Dryden Flight Research Center |
| DPRAM | dual-port random access memory |
| FAST | Full-scale Advanced Systems Testbed |
| FCC | flight control computer |
| HUD | head-up display |
| IRAC | Integrated Resilient Aircraft Control |
| IFCS | Intelligent Flight Control System |
| KIAS | knots indicated airspeed |
| MRAC | model reference adaptive control |
| NASA | National Aeronautics and Space Administration |
| NDI | nonlinear dynamic inversion |
| OBES | On-Board Excitation System |
| PVI | pilot-vehicle interface |
| RFCS | research flight control system |

## INTRODUCTION

The National Aeronautics and Space Administration (NASA) Dryden Flight Research Center (DFRC) (Edwards, California) completed adaptive flight control research flight-testing in January 2011 in support of the Integrated Resilient Aircraft Control (IRAC) project as a follow-on effort of the Intelligent Flight Control System (IFCS) project also conducted at DFRC[1]. The validation of adaptive controls has the potential to enhance safety in the presence of adverse conditions such as structural damage or control surface failures.

Challenges were addressed through the design and flight test of a model reference adaptive controller (MRAC), a closed-loop controller with varying parameters that are continuously updated to change the response of the system to a known response. Its purpose was to evaluate whether a very simple adaptive control algorithm can be adequately tested using traditional flight qualification methods and still serve as a useful level of safety enhancement to flight control. Key aspects of the technology were investigated such as the assessment of an appropriate level of complexity through pilot evaluations of handling qualities and the exploration of unanticipated human-algorithm interactions.

## RESEARCH CONFIGURATION

Two major hardware upgrades to the Full-scale Advanced Systems Testbed (FAST) included the modification of flight control computers (FCCs) and the integration of two dual-redundant, fourth-generation Airborne Research Test Systems (ARTS IV).

Flight control computer modifications - Standard F-18 FCCs are quad-redundant and incorporate 701E processors.[2] Previous Active Aeroelastic Wing[3] project modifications incorporated a Motorola 68040 research processor (Motorola Solutions, Inc., Schaumburg, Illinois) into each channel of the FCCs and dual-port random access memory (DPRAM), and software interfacing between the 701E (production processors) and 68040 (research processors). The research 68040 hardware and software combination comprises the research flight control system (RFCS).

Airborne Research Test System IV - Two dual-redundant ARTS IV units provide the flexibility needed for quick software development, testing, integration, and validation. The units augment the RFCS by providing external input/output, internal memory, and additional processing power. The general research interface architecture interfacing with the RFCS and ARTS IV systems is shown in figure 1.

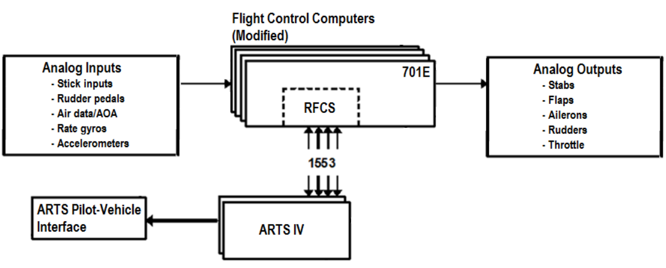


Figure 1. Simplified diagram of the research interface architecture.

Further design features include a pilot-vehicle interface (PVI) installed below the upfront controls in the cockpit that provides visual feedback to the pilot by means of a 2-by-20-character backlit Liquid Crystal Display (LCD). The PVI displays ARTS IV interpretations of proper experiment selection inputs, experiment modes, system status, and ARTS IV health messages.

## EXPERIMENT MODES, STATES, AND EXPERIMENT CAPABILITIES

Several experimental modes, states, and experiment capabilities are available that further facilitate flexible yet safe flight-test evaluation of adaptive control technologies.

Experimental modes - The research control laws have the ability to run in three research experiment modes: 1) RFCS Primary, 2) RFCS/ARTS mixed mode, and 3) ARTS Primary. In RFCS Primary mode, the F-18 production control laws are replicated within the RFCS to provide surface and throttle commands to the 701E while ignoring all ARTS IV commands. In the RFCS/ARTS mixed mode, surface and throttle commands from the RFCS replication control laws are merged with commands from the ARTS IV and sent to the 701E. In ARTS Primary mode, the ARTS IV performs all control law calculations internally and ARTS IV control surface and throttle commands replace RFCS control law commands. In all modes; however, the RFCS safety monitors all commands. These three distinct modes allow for a safe build-up approach to validate the supportability of the hardware and software to host adaptive control technologies.

RFCS states - There are three RFCS states which ultimately describe the transfer of control between the 701E and the RFCS: 1) disengaged, 2) armed, and 3) engaged. In the armed state, the 68040 processor begins to generate replication control law commands while the 701E retains control over the primary flight control system. In the engaged state, command of aircraft control is handed over from the 701E to the RFCS. Disengagement occurs automatically through software monitoring or manually by the pilot using one of several options available in the cockpit. Ultimately, the three-state transfer improves pilot authority over the sequencing of control transfer and improves situational awareness of the state of operations during test.

Experiment capabilities - Each experiment mode offers selectable experiment capabilities within the RFCS and ARTS. A primary capability of the RFCS includes replicated F-18 production control laws. The replicated control laws were used to conduct back-to-back flight dynamics comparisons with the 701E to ensure that the RFCS did not introduce any undesirable effects. On-Board Excitation System (OBES) capabilities added programmed digital signals to the RFCS and ARTS control system actuator commands for excitation of aircraft dynamics. Five combinations of simulated control surface failures are also programmed into the RFCS with the addition of four varying levels of simulated damaged wing scenarios.[4] Each was designed to present varying levels of challenging yet controllable failure scenarios. The ARTS hosted Pass-Thru experiments, which receive control surface commands generated within the RFCS, but not initially sent to the 701E. Instead, the ARTS IV passes the commands back to the RFCS unaltered before being read by the 701E.

Experiment selection - The experiment capabilities residing in the RFCS and ARTS IV units are selected by the pilot through Dial-a-Gain (DAG) and Choose-a-Test (CAT) entries using the standard F-18 digital display indicators (DDI)s in the cockpit. The DDI buttons representing "B," "C," and "D" are used to select a particular experiment capability correlating to predefined DAG (0-26) and CAT (0-26) number pair sequences stored in memory. Dial-a-Gain entries are used to select the controlling experiment mode. The first DAG (DAG 0) is reserved for RFCS Primary mode testing where the RFCS maintains sole control over the vehicle control surface actuator and throttle commands. The remaining DAG entries reside in either the RFCS/ARTS or ARTS Primary mode. Table 1(a) outlines the DAG flight configurations available for each experimental mode. Choose-a-Test entries are used to activate specific experiments. Table 1(b) outlines the CAT flight configurations available for each experimental mode. In the case that no DAG/CAT combination is entered, the default selection is DAG 0 CAT 0 indicating that no OBES inputs or simulated failures are activated and only replicated F-18 control laws are produced.

| Experimental Mode | DAG |
|---|---|
| **RFCS Primary** | **0** |
| **RFCS/ARTS Mode** | **1-13** |
| **ARTS Primary**<br>• Pass-through (Simulink)<br>• TARE<br>• Pass-through (C hand code) | **14 – 26** |

Table 1(a). Dial-A-Gain flight configurations.

| Experiment Category | CAT | Research Experiment |
|---|---|---|
| No Failures | 0 | No OBES or simulated failures |
| Simulated Failures:<br>(control surface/throttles) | <br>1<br>2<br>3<br>4 | Mixed control surface failures at 0° offset<br>• stabs<br>• ailerons<br>• rudders<br>• flaps |
| | <br><br>5<br>6<br>7<br>8 | Right LEF/TEF failed at 0° absolute<br>Collective flaps schedule multiplier<br>• 1.0<br>• 2.0<br>• 4.0<br>• 8.0 |
| | 9 | Right Stab failed at 0° absolute |
| RFCS On-board Excitation System (OBES) | <br>10<br>11<br>12<br>13 | Frequency sweeps<br>• differential rudder<br>• differential trailing edge flap<br>• differential throttle<br>• collective throttle |
| | <br>14<br>15 | Surface doublets<br>• collective<br>• differential |
| ARTS On-board Excitation System (OBES)<br>*Later replaced with MRAC experiments* | <br>16<br>17<br>18 | Doublets<br>• Low amplitude<br>• Medium amplitude<br>• High amplitude |
| ARTS (spares) | 19-26 | MRAC experiments<br>• Left stab failure<br>• Roll damping<br>• Pitch dampening<br>• Roll-to-pitch coupling<br>• Reduction in pitch static stability<br>• other spares |

Table 1(b). Choose-A-Test flight configurations.

## RISK MITIGATION TECHNIQUES

Risk management involves the identification of risks; assessment of their impact; and the implementation of tailored mitigations to minimize, monitor, or eliminate the credibility of risk. Effective risk management can control the probability, or impact, or both to test successes. Several risk mitigations implemented for this research are discussed below.

Designing out risk - To reduce pilot workload and improve situational awareness, much of the flight test risk was designed out of the research architecture and flight test approach. Two main design techniques used was the implementation of a “Class B” envelope and a DFRC developed ARTS “floating limiter.”

Flight-testing while in RFCS armed or engaged states was restricted to a predefined DFRC flight envelope termed “Class B” (figure 2). Analysis showed that test points within the Class B envelope would not allow transients to exceed aircraft load limits should a “hard-over” (maximum rate deflection of a control surface to its position limit) occur. Operating within this flight envelope minimizes structural concerns while providing sufficient altitude for recovery from unusual attitudes thus bounding risk to an acceptable level.

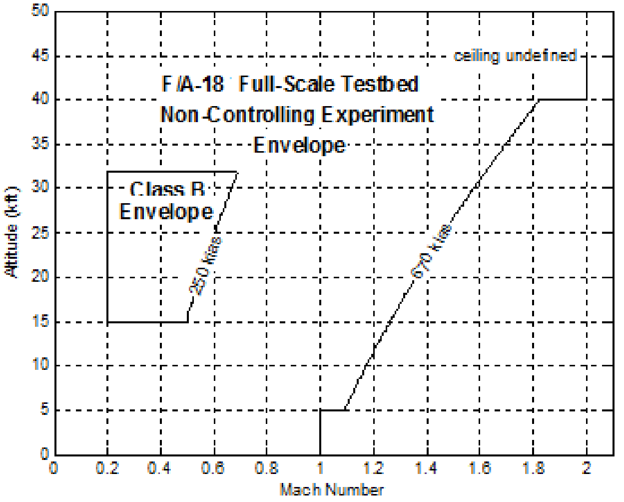


Figure 2. Class B envelope.

The Class B envelope was enforced automatically by RFCS software disengagement limits. Although these limits were monitored in the mission control center real-time, software-enforced limits reduced dependency on pilot reaction time to disengage the system if the airplane exited the envelope. Further plans are in work to open up the flight-test envelope due to the successful conclusions of the FAST project.

A DFRC-designed software feature called a “floating limiter” was implemented into the ARTS for further mitigation to limit the potential for hard-overs. Within the floating limiter (figure 3), a maximum rate of change is designed into the limiter. When a signal exceeds its specified maximum drift rate, the floating limiter boundary is hit and this signal is rate-limited, thus preventing a maximum rate deflection of the control surfaces to their position limit.

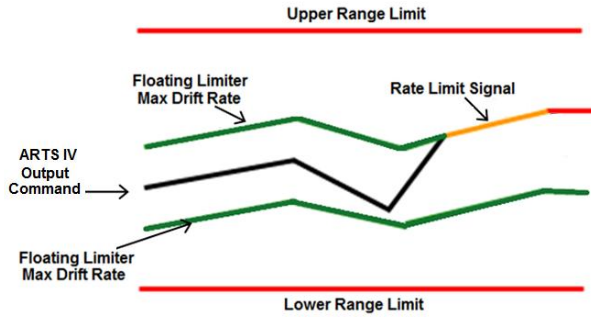

Figure 3. Floating limiter diagram.

Improving situational awareness - Flight test card development and test point sequencing served as another example of “designing-out” risk. Several verification checkpoints were incorporated into the flight test cards at key test point execution stages. For example, DDI entries for experiment capability selection and state transitions, and NWS inputs for RFCS engagement were performed with step-by-step verification checkpoints between the pilot and control room personnel. This helped ensure proper situational awareness of both the pilot and mission control center personnel. Verification checkpoints also provided an expected audible cadence that became indicative of flight testing free of unexpected events. This served as a metric to evaluate team situational awareness and readiness when an unexpected event occurred which threw-off the typical cadence. Specific recommendation is made to incorporate cadence metrics, when appropriate, to obtain human factor cues that can indicate stress risers, which may affect flight-test safety or efficiency.

Use of simulation - The DFRC simulation was as a build-up tool for flight planning and familiarization for both the pilots and key control room personnel. Additional pilots with varying input gain (based on amplitude) were trained and incorporated into the flight-test regime to obtain a more well-rounded collection of research experiment evaluation feedback. Training incorporated research control and system engineers as well as the mission controller to exercise expected test point cadence and prompting. Chase pilots were also brought into the simulation training to hear real-time flight-test prompts and visually assess expected transients of the research aircraft.

Despite the recognized benefits of the simulation for research verification and familiarization of tasks, a lesson learned was identified during flight testing that highlighted a shortfall of our approach. Often, test point evaluation in the simulation omitted in-flight test point set-up maneuvering much outside the boundaries of the test point. In flight, nuisances described as “pitch bobbles” were found while setting up for air-to-air tracking task maneuvers during flight testing. This finding highlighted the potential for unrealized safety issues if simulation testing is too narrowly scoped. When appropriate, control law algorithm testing should incorporate safety-of-flight verification of test-point set-up maneuvers in preparation for unanticipated human-algorithm interactions between test points.

## FLIGHT-TEST APPROACH AND RESULTS

A general build-up approach to verification and validation is shown in table 2. The schedule incorporated iterations of software development, simulation testing, ground testing, and flights of each system capability: RFCS, RFCS/ARTS, ARTS, NDI, and MRAC.

| Date | Test Type |
|---|---|
| Mar – April 2010 | RFCS Primary – ground test + 3 flights |
| July – Aug 2010 | RFCS/ARTS – ground test + 1 flights |
| Aug 2010 | ARTS Primary - 1 flight |
| Sept – Oct 2010 | NDI – ground test + 5 flights |
| Dec 2010 – Jan 2011 | MRAC – ground test + 11 flights |

Table 2. Verification and Validation schedule of the Full-scale Advanced Systems Testbed.

<u>RFCS and ARTS checkouts</u> - Initial RFCS Primary in-flight checks repeated validation of arming (including failed arming attempts), disarming, engagement, and both manual and automatic disengagement attempts specific to the RFCS. Flight dynamic maneuvers such as doublets, pitch, and bank captures; steady-heading sideslips; 360-degree rolls; 2-g loaded rolls; and 2.5-g wind-up turns were flown in order to investigate closed-loop control characteristics of the research architecture. Back-to-back comparisons of the flight dynamics maneuvers using the 701E control laws compared to the RFCS control laws were performed to confirm that the RFCS control laws provided proper replication. Further testing included a subset of OBES maneuvers and simulated failures programmed into the RFCS. RFCS/ARTS mixed mode validated proper PVI operation and the execution of an ARTS IV controlling experiment. The ARTS Primary mode was exercised using the ARTS IV Pass-Thru experiment capability (DAG

26, CAT 0). This experiment validated ARTS IV operation, timing, failure annunciation, and integration of the ARTS IV units with the 701E-RFCS system.

Results of the RFCS and ARTS checkout flights showed that RFCS and ARTS software behaved as expected with only minor discrepancies noted. Overall, results showed good flight-to-simulation match. Completion of the research mode flight tests laid the groundwork for follow-on flight-testing of NDI and MRAC controllers.

<u>Handling qualities task development</u> - Handling qualities tasks were used to evaluate predicted improvements to tracking performance and coupling between the axes and whether such improvements imposed tradeoffs of other aircraft flying qualities.

In-trail formation flight and 2-g tracking tasks were chosen because of pilot familiarity with the task, ability to be accomplished within the Class B envelope, and simultaneous longitudinal and lateral inputs, which allowed for the evaluation of control harmony between axes and investigation of potential undesirable axes coupling. An additional benefit of evaluating the in-trail formation task was its similarity to a typical refueling maneuver that a damaged operational airplane may need to encounter while utilizing adaptive control technologies.

The set-up of the in-trail formation started with the pilot aligning a canopy centerline indicator with the tail hook of the lead aircraft. After simultaneous axes input (gross acquisition), the pilot targeted placement of the left head-up-display (HUD) bracket corner to be visually aligned with the missile rail tip of the lead aircraft (fine tracking). The depiction of the set-up and maneuvering is shown in figure 4. Table 3 outlines the performance criteria associated with the tasks of which were based purely upon pilot opinion.

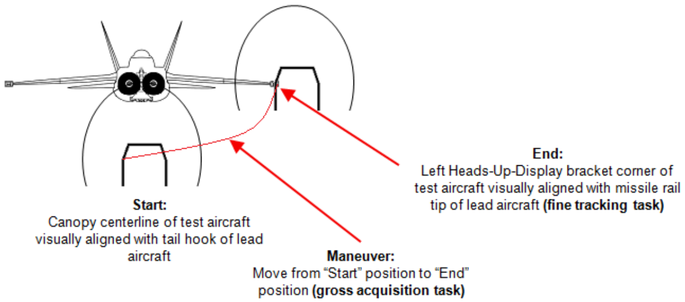


Figure 4. In-trail tracking task set-up and maneuvering.

| In-Trail task: Maintain ~1 ship-length separation nose-to-tail | | |
|---|---|---|
| **Gross Acquisition** | **Desired:** | ≤ 1 overshoot |
| | **Adequate:** | 2 overshoots |
| **Fine Track** | **Desired:** | Bracket on wing tip 80% of time |
| | **Adequate:** | Bracket on wing tip 50% of time |

Table 3. Performance criteria for in-trail formation task.

The 2-g air-to-air tracking tasks were performed using the air-to-ground reticle set to 140 mils deflection in the HUD. With approximately 1,000 ft nose-tail separation, the task began with an initial 2-g turn by both aircraft. Once the test aircraft was ready, the pilot would direct the lead aircraft to reverse the direction of turn. Once the lead aircraft reversed directions, air-to-air gross acquisition would begin followed by fine tracking using the piper. The depiction of the set-up and maneuvering is shown in figure 6.[5] Performance criteria for air-to-air tracking tasks are outlined in table 5.

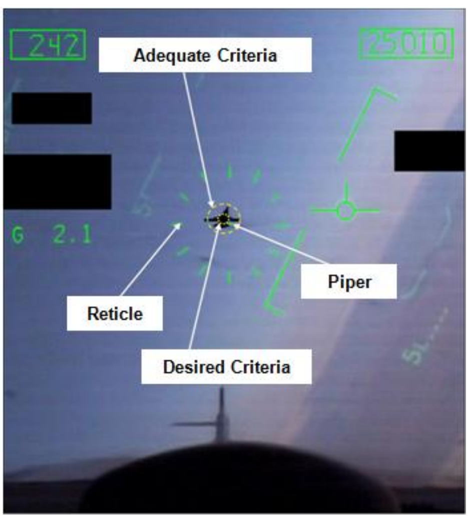

Figure 5. Air-to-air task set-up.

| Air-to-Air task: No closer than 1000 ft; Air-to-ground manual reticle at 140 mils | | |
|---|---|---|
| **Gross Acquisition** | **Desired:** | Reticle on aircraft with 0 overshoots |
| | **Adequate:** | Reticle on aircraft with 1 overshoot |
| **Fine Track** | **Desired:** | Pipper on center of mass 50% of the time |
| | **Adequate** | Pipper on aircraft 50% of the time |

Table 4. Performance criteria for air-to-air tracking task.

Nonlinear Dynamic Inversion - A non-adaptive, NDI control law was loaded into the ARTS IV system for flight-test validation as the baseline control law to enable follow-on MRAC flight testing and validation to evaluate the system's ability to handle closed-loop control law logic. Nonlinear Dynamic Inversion is a technique for control law design based on feedback linearization to achieve desired dynamic response characteristics while accounting for real-world vehicle dynamics.[6]

As with the RFCS and ARTS flight testing, basic flying qualities of the NDI were assessed using typical test maneuvers. Experiment configurations were selected to show that the NDI control law was robust enough to remain controllable for a variety of simulated failure conditions.[6]

In-trail formation flight tasks and 2-g air-to-air tracking tasks were performed for both gross acquisition and fine tracking. Task performance was evaluated by the pilots using Cooper-Harper and pilot-induced oscillation rating scales.[7] Specific tracking performance requirements and desired handling qualities were targeted to verify that handling qualities and reference model tracking was adequate to allow NDI to be used as a baseline control law to compare follow-on MRAC, having provided equivalent ratings between the actual system and the design reference model.

Overall NDI behavior showed equivalent baseline control law handling qualities aside from minor deficiencies such as heavier stick forces and un-loading during roll maneuvers.[7] Success of the baseline NDI controller gave the green light to proceed with in-flight demonstration of the strengths and weaknesses of a simple textbook model reference adaptive controller.

Model reference adaptive controller - Conventional methods for verification and validation testing of flight controls software rely upon predictable responses to test scenarios and are ensured by control gains that are either fixed or scheduled. However, adaptive flight controls incorporate time-varying gains. These varying gain values are harder to predict and impose difficulty in flight qualification to a safety-critical level. In response to this difficulty, the MRAC experiment was designed to evaluate whether a very simple adaptive control algorithm can be adequately tested using traditional flight qualification methods and still serve as a useful level of safety enhancement to flight control.

The MRAC contains three modes of varying levels of complexity.[8] The simplest control mode (sMRAC) has a single adaptive gain in each of the pitch and roll axes. The second control mode (onMRAC) retains the same number of adaptive gains while introducing additional complexity into the algorithm that adjusts the values of the gains in response to undesirable aircraft dynamics. The third control mode (onMRAC+) adds a second adaptive gain in each axis to account for failures or damage scenarios that exhibit undesirable coupling between the axes. Each controller mode was evaluated against a suite of simulated failures, ranging from changes to the aircraft's pitch and roll damping to failures that introduced significant coupling between the axes. Flight-test maneuvers and handling qualities evaluations were also performed with tasks similar to the NDI flight-test regime across five pilots and ten research flights.[8/9]

The predefined 2-g air-to-air maneuvers were flown during all MRAC complexity modes. In general, all three complexity modes showed improvement in tracking error for reductions in both pitch and roll damping over the previously tested NDI controller[8]. Performance between adaptive controllers was barely distinguishable during reduced pitch damping testing, yet improved with complexity for reduced roll damping failures.[8] Handling qualities showed that the MRAC+ mode provided consistently better ratings than the other two modes. However, when compared to the healthy aircraft state, the MRAC+ mode showed degraded handling qualities and increased pilot workload.[8] With respect to roll to pitch input coupling, flight test results show reduced coupling and improved handling qualities ratings with increased MRAC complexity that were equivalent to a healthy aircraft state[9].

## LESSONS LEARNED

1. Design-out unnecessary risk to prevent excessive mitigation management during flight test.

2. Audible test card checkpoints can serve as a metric to assess test readiness real-time among the flight-test team.

3. Consider the total flight-test profile to uncover unanticipated human-algorithm interactions during simulation testing, as appropriate.

4. A wide range of pilots with varying pilot techniques will be needed to study pilot-controller interactions.

5. Full-scale flight test is critical to the development, maturation and acceptance of adaptive control laws for operational use.

## CONCLUSION

Ultimately, the IRAC adaptive flight controls project contributed to the relatively small set of adaptive control flight data available to the flight-test community. Such data provide additional aid to future control designers and their selection of the appropriate level of complexity for their application. Furthermore, the flight-test data provide a better understanding of potential interactions between pilots and adaptive systems. Lessons learned may offer improved safety involving further flight-testing of adaptive control laws.

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