Progress in Catalytic Ignition Fabrication and Modeling: Fabrication Part 1

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16. Abstract

Previous engine testing with Catalytic Plasma Torch (CPT) technology at the University of Idaho has shown promising results in the reduction of NOx and CO emissions. Because this technology is not yet well characterized, past research has indicated that parametric studies of the CPT design should lead to greater control over the combustion event. This report details the process used to design and fabricate a highly adjustable research-grade CPT to be used in a variable compression ratio Cooperative Fuels Research (CFR) engine. CPT construction techniques originally developed by SmartPlugs, Inc. were used as a baseline for the next generation design and fabrication process outlined in this work. The design was improved by making the prechambers interchangeable with the feed-through and catalytic core assembly. The feed-through was simplified by using a compression style cap made by Conax® Technologies. Testing with the CFR engine shows that the redesigned CPT can withstand combustion pressures and facilitate gas phase ignition as effectively as the SmartPlugs design. With the new design and simplified fabrication process, families of CPT assembly combinations can be produced locally and inexpensively. This will allow quick and simple adjustment of many physical parameters believed to affect ignition timing and cycle-to-cycle variability.

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EXECUTIVE SUMMARY

Previous engine testing with Catalytic Plasma Torch (CPT) technology at the University of Idaho has shown promising results in the reduction of NOx and CO emissions. CPT igniters permit ignition of extremely lean fuel-air mixtures in internal combustion engines without sacrificing power. The resulting low-temperature combustion prohibits NO formation via the thermal mechanism and the dissociation of carbon dioxide back to CO. Fuel-air mixtures ignite on the catalyst surface isolated in a prechamber. The expansion of the subsequent flame front causes the rapid torch ignition of the main charge in the cylinder.

Because this technology is not yet well characterized, past research has indicated that parametric studies of the CPT design should lead to greater control over the combustion event. Supporting these studies requires development of local manufacturing processes. This report details the process used to design and fabricate a highly adjustable research-grade CPT to be used in a variable compression ratio Cooperative Fuels Research (CFR) engine. CPT construction techniques originally developed by SmartPlugs, Inc. were used as a baseline for the next generation design and fabrication process outlined in this work. The design was improved by making the prechambers interchangeable with the feed-through and catalytic core assembly. The feed-through was simplified by using a compression style cap made by Conax® Technologies. Testing with the CFR engine shows that the redesigned CPT can successfully withstand combustion pressures and facilitate gas phase ignition as effectively as the SmartPlugs design. With the new design and simplified fabrication process, families of CPT assembly combinations can be produced locally and inexpensively. This will allow quick and simple adjustment of many physical parameters believed to affect ignition timing and cycle-to-cycle variability.

DESCRIPTION OF PROBLEM

Modern engines are becoming increasingly fuel efficient due to increased pressure from government regulations for emissions and the increasing price of fossil fuels. One way to reduce emissions and fuel consumption in internal combustion engines is to lean the fuel-air mixture; however, this often results in decreased power output. A possible way to operate a combustion engine in the lean region without sacrificing power is to use a Catalytic Plasma Torch (CPT). The CPT was developed by Automotive Resource, Inc. (SmartPlugs, Inc.) in 1992 to allow for operation in an extended lean burn regime [1]. The technology could be applied to both spark-ignition and compression-ignition engines [2, 3]. In the last decade several CPT studies have been conducted at the University of Idaho [4,5,6,7,8]. A motivating force behind this work was the creation of a local process for designing and manufacturing CPT components and assemblies [9].

APPROACH AND METHODOLOGY

The primary subsystems used to assemble a CPT are: prechamber body, electrical feed-through, ceramic core, and the platinum wire. Early designs were intended to be inexpensive, but suffered in reliability and longevity. The following section describes some of the earlier design decisions and lessons learned about each of the subsystems.

Early CPT Designs

The prechamber body is made of brass, originally used to aid in heat transfer away from the hot catalytic core. The initial design used a tapered prechamber design that housed the catalytic core in the center and was directly open to the cylinder of the engine. The purpose of this was to decrease the spring effect of the burnt gasses in the upper section of the prechamber. The main function of the prechamber is to produce a flame torch emanating from the catalytic core contained inside and projecting into the main combustion chamber. Because of this, the prechamber design was modified to a “showerhead” tip that opened to the combustion chamber. The two prechamber designs can be seen in Figure 1.

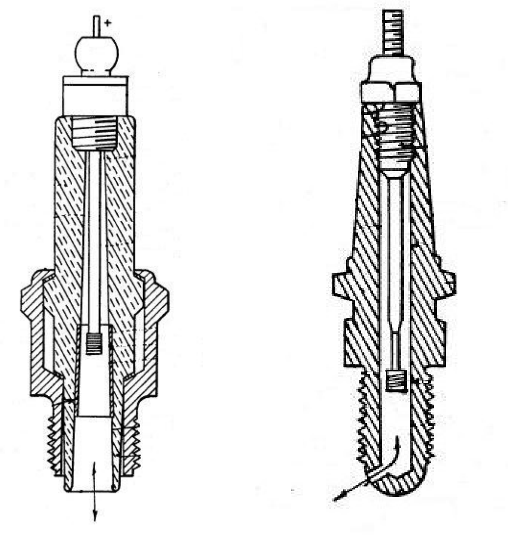

Figure 1: The original open-tip design is on the left, while the rounded showerhead design is on the right.

The rounded showerhead tip was then changed to a flat tipped design due to concerns that there may be interferences between the CPT and the piston in certain engines. The showerhead design utilized 8-10 holes at a 60 degree included angle with the same overall cross sectional area as the prechamber. This allows full flow into and out of the prechamber. This design also creates a torch-like ignition flame. One benefit of the torch ignition is that it penetrates a greater area of the main chamber, aiding combustion. The showerhead pattern can be seen in Figure 2.

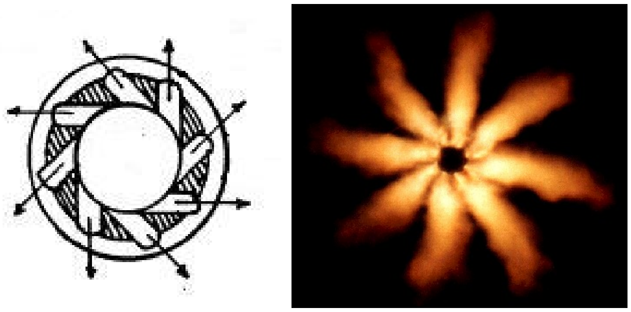

Figure 2: CPT showerhead as viewed from below. A cross section is on the left, and an image of the torch ignition is on the right.

Cold-starting, and in some applications – light load operation, of an engine using CPT depends on the igniter core being electrically heated by a platinum wire. This wire must be electrically isolated from the prechamber body so that no short circuiting can occur. Specifically, the center of the feed-through assembly must be electrically isolated from the prechamber to allow the catalytic core to be isolated as well. This ensures proper function of the CPT and for a good circuit to be made, otherwise the CPT will short circuit and fail.

The feed-through is electrically isolated and sealed using a dielectric adhesive that can withstand the extreme environment. A 12 volt source that is applied to the stud of the feed-through provides the power source to heat the catalytic core. To complete the circuit, the core is either grounded to the prechamber body at the bottom, or through the feed-through assembly at the top.

Material selection for the feed-through cap is very important. Since the igniter will undergo periods of heating and cooling, the thermal expansion of the materials need to be similar. If this were not the case, the CPTs would not pressure seal well and loss of compression from the combustion chamber would occur.

The feed-through was initially comprised of four different parts shown in Figure 3. The outer casing is constructed of stainless steel and is threaded on the outside to be attached to the prechamber. Inside the casing is a hollow ceramic tube that provides electrical and thermal insulation to the igniter core from the outer casing. Inside the ceramic tube, the igniter core attaches to a brass center which is connected to a 4-40 bolt with a threaded end that feeds through the outer casing.

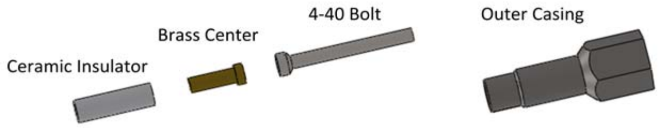

Figure 3: Components of the original electrical feed-through.

The original design for wire routing was to ground the catalytic core to the feed-through by using hanging ground wires that were strung from the core to the threaded portion of the feed-through. This can be seen in Figure 4. This method was effective at grounding the core, but there were problems with the durability of the exposed ground wire being exposed to combustion. Either the electrical connection became intermittent, or the wire would degrade and break over time. Also, attaching the ground directly to the prechamber made it difficult to rebuild or reuse.

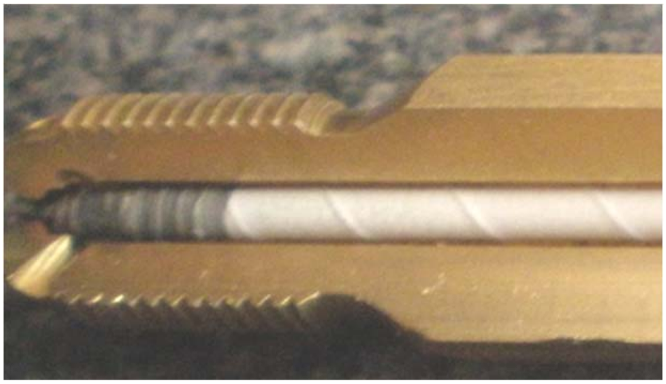

Figure 4: Ground wire on bottom of ceramic core.

To aid in increasing the lifespan of the platinum wire, a thin ceramic coating was sprayed over the outside of the core. The original design utilized a ceramic plasma spray coating. This spray worked well for its function in the original designs. The downside of this spray is the cost and time.

Next Generation CPT Design

After a thorough review of the original design, it was critical to develop the design into something that could be simply and inexpensively constructed in-house. This was necessary because the original manufacturer discontinued their research and design of the CPT, in large part due to lack of external funding. The University of Idaho has continued researching applications and operational characteristics of the CPT. Most recently this has been in conjunction with a variable compression ratio Cooperative Fuels Research (CFR) engine that has been converted to electronic fuel injection and the ability to operate on a large variety of fuel types. This section outlines the most recent changes made to allow in-house fabrication and testing of various CPT designs.

Prechamber Body

The body was designed and built mostly in conjunction with the current design. The showerhead tip was still implemented as well as using brass hex stock. The body uses a 6-hole showerhead with a 60 degree included angle to mimic the original design. This still allows for the beneficial torch-like effect. Also, it was assumed that due to the CPT's application on the CFR engine, a flat tip design would still have to be used for clearance issues.

The machining process involved a HAAS CNC lathe as well as a manual mill. Construction begins with a 5/8 inch diameter hex brass stock. The stock was machined to the appropriate length and outer diameter is turned down and threaded to install in the top of the cylinder head. The stock was then removed and reversed so that the center could be drilled out to the appropriate depth and diameter for the CFR application. Prechamber length and inner clearance diameter are two parameters known to effect ignition timing curves of the CPT. Finally, threading that allowed the feed-through assembly to be attached was done manually while still in the lathe, ensuring straight and accurate thread depth. A comparison of the original prechamber and the new prechamber is shown in Figure 5.

Figure 5: New designed prechamber shown on top, with an original prechamber pictured below.

The final prechamber fabrication process involved using a manual mill to drill the "torch" holes to the correct diameter and angle as to replicate the torch style ignition event. First, the stock was mounted into a vertical three-jaw indexing chuck that allowed accurate positioning of the stock for precise placement of the torch holes. The machine was then zeroed to the exact center of the prechamber so that proper offsets could be measured. The mill head was then angled at 30 degrees so that there is a 60 degree angle between opposing torch holes. To fully replicate the original design, the torch holes needed to create a clockwise "swirl" effect into the main chamber. To do this, the prechamber was offset in such a way that the holes were drilled at a tangent angle to the center diameter of the prechamber. With the proper offset, the prechamber was rotated in 60 degree intervals and each hole was drilled as shown in Figure 6.

The manufacturing process in replicating the prechamber design proved to be very successful and can be done easily with the resources on the University of Idaho campus. A final comparison of old and new prechamber proved the quality and completeness of the mentioned manufacturing process. The newly developed body was nearly exactly the same as the original design and well within the reasonable bounds of what could be made in the University of Idaho machine shop by any moderately trained student. A comparison of the bottom end of the prechamber body is shown in Figure 7.

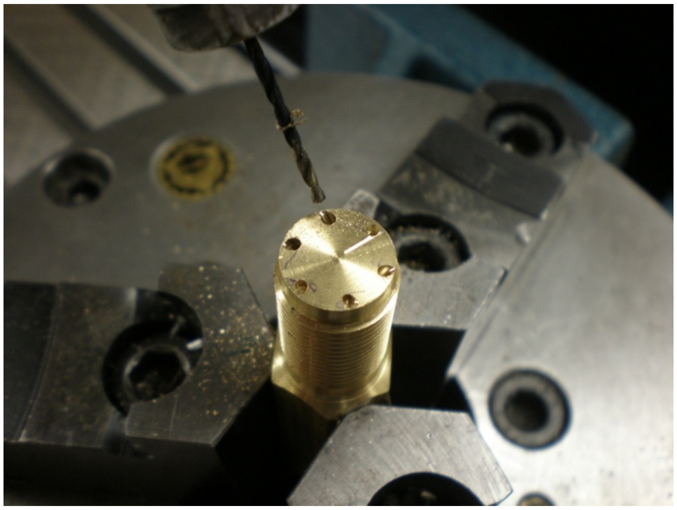

Figure 6: Mounting fixture for drilling angled holes in the tip of the prechamber.

Figure 7: Newly machined prechamber body is on the left, and the original disassembled prechamber body is on the right.

After creating a process to replicate the original CPT design, measurements were taken to explore the available clearance for an extended tip design. In the CFR engine, the CPT is installed where the original pressure transducer was located at the top of the combustion chamber. Measurements were taken from the bottom of the original CPT design to the top of the piston, and there is an additional 12mm of safe available depth to use even when the engine is at the highest compression ratio setting. This additional clearance will allow for multiple igniter tip designs to be explored in the future. Geometries under consideration include a semi-spherical tip and a cone tip.

The ability to create custom prechamber bodies will allow parametric studies of how variations in prechamber geometries affect engine operation and ignition characteristics. Tip geometry, number of holes, and the vertical and tangential angles of holes can be explored. Testing each with a given fuel composition, at the same engine operating conditions, and keeping track of ignition timing and heat release characteristics should provide many insights about tip geometries.

Electrical Feed-Through

The feed-through was the major focus of improving the original CPT design. The original design focused on reduced cost, resulting in a feed-through that was not reusable and highly sensitive to the assembler skill; with inexperienced assemblers unable to make a consistently functional feed-through. The primary goal for a research-grade CPT was to simplify the design and ensure a robust electrical connection that would withstand combustion pressures. In-house feed-throughs were manufactured, but proved to be tedious to assemble and required at least a full day of manufacturing/assembly and two more days for curing. Attempts to reuse in-house feed-throughs were unsuccessful.

A solution came from sources through a company that manufactures feed-throughs for use in extreme environment situations. Conax® Technologies manufactures specialty feed-through assemblies that incorporate a compression style seal that is both simple to assemble and reusable. The assembly consists of four major parts; body, follower, cap, and sealant. The body, follower, and cap are composed of 303SST stainless steel and are reusable. These components are shown in Figure 8. Different types of sealants are available through Conax and their properties are listed in Table 1.

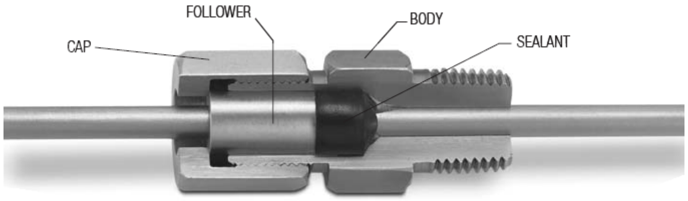

Figure 8: Cutaway view of Conax® feed-through assembly.

Table 1: Sealant Materials and Properties for MPG-125 Feed-Through Assemblies [10]

Sealant Materials	Temperature Range	Pressure Rating
Neoprene	-40°F to +200°F	1200 psig
Viton	-10°F to +450°F	1200 psig
Teflon	-300°F to +450°F	800 psig
Lava	-300°F to +1600°F	2000 psig
Grafoil	-400°F to +925°F	2400 psig

The manufacturer’s MPG series feed-through uses 1/8 inch nominal pipe threads (NPT) for application attachment and is only slightly larger than the original feed-through. Figure 9 shows the original feed-through compared to the replicated feed-through and the MPG series feed-through.

Figure 9: Comparison of feed-throughs. Left to right: MPG-125, in-house feed-through, and original design.

A mathematical simulation of the in-cylinder pressures in the CFR engine was used to approximate the peak pressures that the feed-through would have to operate. This was done over a whole range of compression ratios and fuel types [8]. The estimated peak combustion pressures are below the pressure ratings of the feed-throughs. The two seals that were chosen were Grafoil and Viton. The Viton seals can be used for low compression ratios and low load operation. They are desirable because they are reusable after disassembly. In higher pressure and temperature conditions the Grafoil sealant will be used. The purchased feed-through was a vast improvement over the in-house made feed-through. It has a built in, replaceable pressure seal, electrical insulation, and is easy to disassemble and reuse.

Initially there was some concern about the amount of compression between the seal and the ceramic core. It was thought that if the feed-through was overly tightened, it might crush the hollow ceramic core. In testing this failure mechanism, the ceramic core was still unharmed even after the feed-through was torque to failure – which occurred at several times beyond the recommended torque value.

Ceramic Core and Coatings

A coating to protect the platinum wire and secure it to the ceramic core is necessary. The original design used a ceramic plasma spray coating that had proven reliable, but was costly and has significant lead time. An in-house solution was desired to reduce the turnaround time for testing various assemblies. The first coating tested was a Boron Nitride aerosol spray coating. However, a quick bench test indicated that the coating could not withstand the heat generated from the platinum wire. After applying 12 volts to the platinum wire for five minutes the Boron Nitride coating started to flake off. This can be seen in Figure 10.

Figure 10: Boron Nitride coating after electrical heating of platinum wire.

The next coating that was tried was a high purity alumina ceramic paint. This had to be applied with a brush. It was critical that no silica be in the paint because the silica will poison the platinum and render the CPT useless. This coating was put to the same bench test as the Boron Nitride spray and did not fail. The alumina ceramic paint was applied to a core with 10 wraps of platinum wire wrapped at the end then installed in the CFR engine. This was successful at initiating combustion for about one minute of operation, but the CPT eventually stopped working when the platinum catalyst wire wraps bunched together, effectively short-circuiting the catalyst. An image of the removed ceramic core and wires are shown in Figure 11. Although the wraps did not stay in place, the alumina ceramic paint was not damaged or degraded.

Figure 11: Ceramic core and platinum wire with alumina ceramic paint covering the right side of the core.

Unfortunately, both of the above methods of protecting the platinum wire have proven unsuccessful. Some trial runs used a ceramic core with two internal passageways. The platinum wire is routed from the external end down one tube, and then exits through a small hole on the side of the tube. The wire is then wrapped around the bottom of the core, and then re-enters the second passageway in the ceramic tube. Each location where the wire passes through the sidewall of the ceramic tube was sealed with alumina ceramic paint. Preliminary testing of this construction method has shown high durability with the wire wraps staying in place after thousands of combustion cycles in the CFR engine. Ongoing testing will determine if this is a robust method for protecting the platinum wire.

The only other location that a coating or adhesive was used was to seal where the positive lead entered into the ceramic core. Figure 12 shows the ceramic adhesive painted around where the positive lead goes into the ceramic core. This kept the lead in place while making a seal against pressure losses up the ceramic core.

Figure 12: Ceramic adhesive paint used to seal the electrical lead at the top of the CPT.

Platinum Wire and Routing

The application of the compression-seal feed-through provided an opportunity to fix both the electrical isolation problem and the grounding issue previously described. The issue of electrical isolation was solved by the feed-through seal seating directly to the ceramic tube used in the catalytic core construction. Since the feed-through featured a compression style seal, there was no need for a centered electrical connection being isolated from the outer casing.

In addition to providing electrical isolation, the feed-through design provides a robust ground attachment. Instead of using an external grounding mechanism to the prechamber body, an internal ground that utilizes the compression seal was used. This was achieved by feeding the platinum wire between the ceramic tube and the feed-through body. A small groove was etched into the ceramic tube that allowed the wire and ceramic tube to be press fitted into the feed-through body. The wire was then wrapped around the outside of the ceramic tube between the sealant and follower creating a fully isolated and protected grounding point.

Power was supplied to the catalytic igniter by press fitting a steel rod into the center of the ceramic tube far enough to pass the Conax® compression seal, adding additional support to the ceramic tube. The steel insert can also be seen in Figure 12 above.

FINDINGS; CONCLUSIONS; RECOMMENDATIONS

To verify the next generation CPT design along each step of improvement, testing will be performed. The tests will be designed to take the guesswork out of decisions with the goal of determining the best options to end up with the best possible CPT design overall. This will ensure quality in design and reliability through further fuel research.

The most critical testing will be in determining a wire routing solution to guarantee the wire not to deform or break under normal operating conditions. The first design will use a notch at the bottom of the positive feed hole of the ceramic core to hold the wire in place rotationally while using 10 equally spaced grooves to hold each individual wrap in place. The ground wire will then be routed externally up the tube and ground to the feed-through. The second design will have no notch or grooves to hold the wire, but after the 10 wraps the grounding wire will be routed through a second hole into the ceramic core back up to the feed-through to complete the circuit. The third design will incorporate both methods. To test the designs they will be each installed into the CFR under the same operating conditions and checked periodically to determine how long before they fail or are rendered temporarily inoperable. Testing all three will allow for careful examination of how each change effects the operation of the CPT and determine if one of these options stands out over the others. One other method that has been considered is cutting 10 threads in the ceramic as to not have any bends or kinks in the platinum wire and then to feed the ground back through the tube. The main problem with this is trying to effectively cut threads in the ceramic core. This is an option that is still being researched, and if a method to successfully cut threads can be developed it will be tested along with the other three designs.

The next weakest point is the coating used to hold the wire wraps to the ceramic core. Before reverting back to the ceramic plasma spray coating, a nano-spring coating is available locally that may help the platinum wire stay in place. It involves growing nano-springs on the wire wraps and ceramic tube that effectively act like Velcro to hold the two together. However, it is unknown whether the nano-springs can withstand the severe environment inside the CPT prechamber. The testing of this coating will include a one hour bench test where a 12V source will be attached to the wire leads to determine how the coatings hold up to an hour under just electrical heating. Then the coating will be ran in the CFR engine under the same operating conditions and periodically checked until failure to determine which can withstand the harsh environment the best.

Another coating that will require testing is a platinum particle coating that can also be applied in-house. This coating will effectively increase the heating surface area resulting in better ignition of the fuels as well as a possible further reduction in NOx and CO emissions. This coating will be tested by measuring the resistance through the wire before the coating and after as well as applying a 12V source and measuring the heat output. If there is a significant difference, the CPT will be tested in the CFR and compared against a non-coated CPT to determine if the coating affects the combustion event and improves ignition.

Testing of the body will help determine if tip geometry has any effect on performance of the CPT in the CFR engine. It was determined that there is sufficient clearance to examine different tip designs in the CFR engine. Different tip designs that would be interesting to test are different hole patterns, spherical tip, cone tip, and different numbers of holes. To test this, an array of bodies will need to be made with each of the tip designs of interest. The bodies will then be fitted with all of the exact same core design and geometry as to make it so that they are all under the same conditions except for the tip design. Each CPT will then be tested in the CFR to determine if any particular design works better than the rest to ignite a given fuel under the same conditions and to document the effects of each change to the tip geometry.

Summary/Conclusions

The ability to manufacture small batches of custom CPT configurations offers a significant improvement compared to the previous supply path. There are several obstacles yet to overcome, but notable headway has been made toward designing CPTs that can be made in-house. In the research phase, having robust, customizable, and serviceable hardware will reduce development time and increase the speed at which discoveries can be made.

Developing the machining code, machining fixtures and expertise to manufacture prechamber bodies will allow experimentation with geometrical parameters previously unexplored. The new electrical path for the platinum wire also makes it possible to quickly swap the core and feed-through to other prechambers. This should allow quicker back-to-back comparison tests under the very similar ambient conditions.

Design changes and a variety of coatings have yet to be explored that will protect the platinum wire from damage due to combustion in the prechamber. Additionally, some coatings may offer increased platinum surface area that is expected to effect the operating characteristics of the CPT. These changes need to be researched and tested to ensure robustness and repeatability in the CPT operating environment.

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