Submer

SYNANO VALIDATION PROGRAM TESTING

RESULTS REPORT

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Fluid:	Synano PP0		

Table of contents

Table of contents 2
1 Background 3
1.1 Submer Fluid Validation Service 3
2 Materials and Methods 3
2.1 Dielectric Properties 3
2.2 Fire Properties 4
2.3 Thermochemical properties 4
2.4 Material Compatibility 5
2.5 Longevity and stability 6
2.6 Thermal Testing Vehicle (TTV) performance analysis 6
2.6.1 Test methodology 7
2.6.2 Data Collection and Thermal Resistance Calculation 7
3 Results Summary 9
4 Detailed Test Results 10
4.1 Dielectric Properties 10
4.1.1 Breakdown Voltage 10
4.1.2 Dielectric dissipation factor, volume resistivity and dielectric constant 11
4.2 Fire safety 12
4.3 Thermochemical Properties 13
4.3.1 Thermal conductivity 13
4.3.2 Specific heat capacity 13
4.4 Material Compatibility 13
4.4.1 Weight change 15
4.4.2 Dimension change 16
4.4.3 Hardness change 18
4.4.4 Breakdown voltage 19
4.4.5 Dielectric dissipation factor 20
4.4.6 Acidity 21
4.5 Thermal Testing Vehicle (TTV) performance analysis 22
5 Conclusions 25
6 Annex 27
7 Change log 28

1 Background

1.1 Submer Fluid Validation Service

After multiple years of experience in immersion cooling for data centers worldwide, Submer has developed a comprehensive qualification framework known as the Submer Fluid Validation Service to evaluate and validate immersion cooling fluids for deployment in data center immersion cooling systems.

Synano PP0 is a single-phase dielectric nano fluid developed by Synano, consisting of a PAO-2 base oil modified with specific nanoparticles. The primary objective of the PAO-2 based nano-oil formulation is to achieve a higher flash point than the base PAO-2 fluid, thereby improving fire safety during operation. In addition to the enhanced flash point, the formulation aims to provide improved thermal performance for more efficient heat removal and a higher dielectric breakdown voltage to enhance electrical insulation reliability under immersion cooling conditions.

The Submer Fluid Validation Service evaluates whether these performance objectives are achieved through a comprehensive qualification program. The testing conducted includes assessment of dielectric properties (breakdown voltage, dielectric dissipation factor, volume resistivity and dielectric constant), fire safety (flash point), thermochemical properties (thermal conductivity and specific heat capacity), and material compatibility with common plastics, elastomers, adhesives and cable jacket materials found in IT hardware and Submer products, along with longevity and stability characteristics relevant to long-term operation in immersion cooling environments. Thermal performance was also assessed at system level using a thermal test vehicle (TTV), comparing the nanofluid directly against the PAO-2 base oil.

The results of this program verify whether the initial formulation objectives are achieved. Together with the fluid characterization and material compatibility results, these findings validate the safety of the fluid and determine whether Synano PP0 qualifies for the next validation stage, consisting of extended testing in a Submer SmartPod immersion cooling system.Materials and Methods

1.2 Dielectric Properties

The **breakdown voltage** (BDV) is critical to determine initial Synano PP0 dielectric strength to ensure both quality and safety margin for IT Hardware during system operation. The breakdown voltage was measured following the guidelines of the international standard IEC 60156 with VDE electrodes separated by a 2.5 mm gap. BDV results are reported as the average value of six measurements. To pass the dielectric strength test, fresh from barrel Synano PP0 should have a BDV value equal to or larger than 30 kV.

The **dielectric dissipation factor** is important to indicate the initial degree of polar components in the fluid and establish a baseline for future analysis. The dielectric dissipation factor of Synano PP0 was measured according to IEC 60247 at a temperature of 90 °C. This result is informative and therefore there is no maximum result required.

The **volume resistivity**, like the dielectric dissipation factor, is used to assess polar components in the fluid and ensure it falls within expected limits of resistivity. The volume resistivity of Synano PP0 was measured along with the standard IEC 60247 at a temperature of 90 °C. A minimum result of 2.00 GΩ·m is required to pass.

The **dielectric constant** is critical to assess the impact Synano PP0 could have on the signal integrity of IT hardware. The dielectric constant was measured as per IEC 60247 at 90 °C. This result is informative and therefore there is no maximum result required.

Table 1. A summary of the dielectric properties' tests, test methods and specifications.

Test	Method	Units
1.1 Breakdown voltage	IEC 60156	kV/2.5 mm
1.2 Dielectric dissipation factor	IEC 60247	-
1.3 Volume resistivity	IEC 60247	GΩ·m
1.4 Dielectric constant	IEC 60247	-

1.3 Fire Properties

Measuring the **closed cup flashpoint** is critical to ensure consistency with OCP Immersion Requirements Rev 2.1 Minimum Fluid Requirements, IEC 62368-1, NFPA 75 and other regional requirements. The closed cup flashpoint was measured using the Pensky-Marten's methodology according to the standard ASTM D 93, where a minimum result of 150 °C is required to pass. Under the Pensky-Marten's method, a brass test cup was filled with Synano PP0 that was heated and stirred following Procedure A from the standard. An ignition source was directed into the test cup intermittently with simultaneous interruption of the stirring to test if the vapors emitted by Synano PP0 were igniting. Once ignition was detected, the temperature was recorded. Experiments were carried out triplicate, and the shared results are the average of the three measurements.

1.4 Thermochemical properties

The evaluation of thermochemical properties is essential to characterize the heat transfer performance of the fluid under operational conditions typical of immersion cooled systems. Thermal conductivity and specific heat capacity directly influence the Synano PP0 ability to remove, transport and dissipate heat generated by electronic components. These parameters establish the baseline thermal performance and support system-level thermal design calculations.

Thermal conductivity is a critical parameter governing conductive heat transfer within the fluid. Higher thermal conductivity enhances the rate at which heat is transferred away from localized hot spots. The thermal conductivity was measured using a transient hot-wire method in accordance with ASTM D7896 over a controlled temperature range of operating conditions. Measurements were conducted at 25°C, 40°C and 60°C to reflect storage and nominal service temperatures. Results are reported as the average of three consecutive measurements at each temperature. This result is informative and establishes a reference value for thermal modeling; therefore, no minimum or maximum acceptance criteria is specified.

Specific heat capacity is fundamental in determining the amount of thermal energy required to raise the fluid temperature under dynamic load conditions. A higher specific heat capacity allows the fluid to absorb greater quantities of heat with smaller temperature increases, improving system thermal stability and buffering transient power spikes. The specific heat capacity of Synano PP0 was determined using differential scanning calorimetry (DSC) in accordance with ASTM E1269. Measurements were performed at temperatures between 16 and 56°C and it is reported as a value at 40°C. The reported value corresponds to

the average of three replicates. This result is informative and is used for system design calculations, therefore there is no pass/fail specification required.

1.5 Material Compatibility

Material compatibility of Synano PP0 with various common plastics, elastomers, adhesives, and other common wet materials found in IT hardware as well as Submer products were tested according to the OCP Material Compatibility in Immersion test method. A list of the different materials tested as well as the methodology used can be observed in (Tables 2-4).

Table 2. Conditions used in the material compatibility standard test.

Parameter	Value
Temperature (°C)	80
Duration (Hours)	336
Fluid volume (L)	400 mL – 1400 mL
Fluid properties to measure (pre- and post-test)	Color, BDV (breakdown voltage), DDF (Dielectric Dissipation Factor), Acid value
Sample properties to measure (pre- and post-test)	Dimensions, weight, color, Shore A hardness as appropriate for material hardness
Fluid sample loading rates (%)	Even and Uneven shape Materials 1.0 wt.%
Sample-handling apparatus	Oven, forced draft, adjustable to 80 °C ± 1 °C
Sample container	Glass, fitted with aluminum foil cover

Table 3. Summary of the tests performed, methods used and acceptance criteria.

Test	Method	Acceptance criteria
Weight change (%)	* SL-003-02	< 10%
Diameter change (%)	* SL-004-02	< 10%
Thickness change (%)	* SL-004-02	< 10%
Hardness change (%)	* SL-007-01	< 10%
Breakdown voltage (kV)	IEC 60156	≥ 20 kV
Dielectric dissipation factor (-)	IEC 60247	< 0.05
Resistivity (Ω·m)	IEC 60247	$\geq 1 \cdot 10^{9}$
Acidity (mg KOH/g)	IEC 62021	< 0.3
Color (-)	ASTM D1500	≤ 2.0

*Submer Technologies internal standard

Table 4. List of materials tested on the material compatibility tests and its relevance and expected results.

Type	Acronym	Material	Application	Expected result
	PMMA	Polymethyl methacrylate	SmartPod	Compatible

Structural plastics	ABS	Acrylonitrile butadiene styrene	IT Hardware	Compatible
	PA-66	Nylon, Polyamide	SmartPod	Compatible
	PP	Polypropylene	IT Hardware	Compatible
	PET	Polyethylene tereph-thalate	IT Hardware	Compatible
Seals	FKM	Fluorine rubber	SmartPod IT Hardware	Compatible
	NBR	Nitrile rubber	SmartPod IT Hardware	Limited compatibility
	Silicone	Polysiloxane	SmartPod IT Hardware	Limited compatibility
	EPDM	Ethylene propylene diene monomer rubber	SmartPod IT Hardware	No compatible
Cable jack-ets	PTFE	Polytetrafluoroethylene	Accessories	Compatible
	PUR	Polyurethane resin	Accessories	Compatible
	PVC	Polyvinyl chloride	Accessories	Limited compatibility
	PO	Polyolefin	Accessories	No compatible
Adhesives	Loctite 577	Dimethacrylate ester	SmartPod	Compatible
	Loctite 435	Ethyl cyanoacrylate	SmartPod	Compatible

1.6 Longevity and stability

The **acidity** of Synano PP0 was measured by averaging the results of fresh fluid triplicates to establish the baseline value for future analysis. Acidity was measured following the guidelines of the international standard IEC 62021, where there is no acceptance criteria strictly defined for this result.

Table 5. A summary of the longevity and stability tests, test methods and specifications.

Test	Method	Units	Spec
7.1 Acidity	IEC 62021	mg KOH/g	none

1.7 Thermal Testing Vehicle (TTV) performance analysis

Thermal performance evaluation conducted on an Intel LGA7529 thermal test vehicle (TTV), focusing on its behavior under various cooling configurations. The objective of this study is to characterize and compare the thermal performance of the nanofluid using different cooling methods applied to this new CPU form factor in the context of immersion cooling.

The tests address multiple aspects. First, three distinct configurations are assessed: natural convection immersion-optimized heatsink, forced convection heatsink, and targeted flow heatsink. These configurations were chosen to represent a spectrum of passive to active thermal management approaches typically considered in immersion environments. The test was run using the Synano fluid and its base fluid as reference.

In addition to conventional thermal tests at 45°C fluid inlet temperatures. These HTI scenarios are particularly relevant for evaluating the feasibility of "free" or waterless cooling that can be achieved in most environments using such fluid temperatures.

- Test rig setup with Intel LGA7529 TTV&PCB
- Heatsinks:

  - Natural Convection HS: 0.5mm fin thickness, 2mm fin pitch, heat pipes embedded into base, manufactured by Boyd.
  - Forced Convection HS: 0.5mm fin thickness, 2mm fin pitch, heat pipes embedded into base, manufactured by Boyd and two high-rpm 25mm RC fans.
  - Targeted flow heatsink: Intel AP targeted flow heatsink manufactured by JWS.
- TIM: Indium Corp Heat-Spring® HSHP indium foil (0.006")
- Fluid:
  - Synano PPO
  - Synano PPO base (PAO-2)

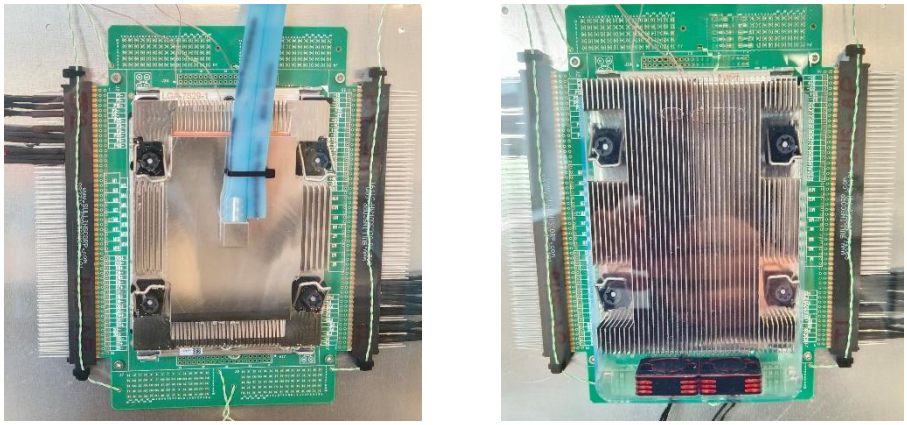

Figure 1. LGA7529 TTV PCB with (left) targeted flow heatsink and (right) forced convection heatsink.

1.7.1 Test methodology

Thermal tests were performed at two power setpoints: 500 W, representing the standard thermal design power (TDP), and 650 W, simulating more demanding system scenarios anticipating future higher TDPs. All heatsinks used for this study were mounted using Intel's recommended heatsink installation torque spec of 8 In-lb per PEEK nut.

The system (total) pump flow was set to 7.1 L/min when using the immersion-optimized natural convection heatsink and the FCHS. The tank level flow was set to 4 L/min when testing the targeted flow heatsink. Flow rates entering the targeted flow heatsink were controlled at three fixed points: 0.5, 1, and 2 L/min. The control temperature was monitored at the inlet of the heatsinks.

For each setpoint, the radiator fan power was automatically adjusted via PID control to stabilize the system. After stabilization, measurements were recorded for 10 minutes.

1.7.2 Data Collection and Thermal Resistance Calculation

Temperature data were logged using a Picolog datalogger integrated into the test rig. Thermal resistance (R) from case to fluid was calculated using the following formula:

$$R\ [°C/W] = \frac{T_{TTV} - T_{\infty}\ [°C]}{P_{TTV}\ [W]}$$

The measured system resistance, *R* is the sum of several resistances in series: TIM interfaces, heatsink conduction, and heatsink-to-fluid convective resistance. Only the convective term depends on the coolant; the rest are fixed by the assembly and remain constant if the stack is not disassembled between tests.

An improvement in fluid performance reduces the total resistance an absolute amount (K/W), but the relative improvement at system level is smaller, proportional to the share of the total resistance that the fluid path represents. Total system resistance remains the standard metric, as it reflects the actual thermal performance of the device.

During testing, the non-variable resistances are kept identical across fluids by preserving the mechanical assembly, so any difference observed in the total resistance is attributable exclusively to the variable convective term, therefore, to the fluid itself.

2 Results Summary

Table 6. Summary of properties and tests used in the fluid validation program for Synano PP0 along with the international standard used, the units measured, acceptance criteria and pass/fail condition.

Stage	Test	Method	Units	Spec	Value	Result
Dielectric properties	Breakdown voltage	ASTM D 1816	kV/2.5 mm	≥30	71.4	PASS
	Dielectric dissipation factor	IEC 60247	-	≤ 0.05	0.0053	PASS
	Volume resistivity	IEC 60247	GΩ.m	≥2.00	525	PASS
	Dielectric constant	IEC 60247	-	< 2.3	2.06	PASS
Fire safety	Flashpoint, closed cup	ASTM D 93	°C	≥150	164	PASS
Thermochemical properties	Thermal conductivity @ 25°C	ASTM D7896	W/m·K	none	0.135	PASS
	Thermal conductivity @ 40°C	ASTM D7896	W/m·K	none	0.133	PASS
	Specific heat capacity @ 40°C	ASTM D1269	J/kg·K	none	2030	PASS
Material compatibility	Material compatibility, 16 samples	OCP	-	none	Section 3.4	PASS‡
Longevity & stability	Acidity	IEC 62021	mg KOH/g	none	0.006	PASS

‡ Most critical materials pass the material compatibility test. For more information see section 3.4

3 Detailed Test Results

3.1 Dielectric Properties

3.1.1 Breakdown Voltage

The breakdown voltage (BDV) is a critical parameter for evaluating the dielectric strength of Synano PP0. The test results are plotted in Figure 2 and Table 7. The figure represents the average value of the 6 measurements performed and its standard deviation.

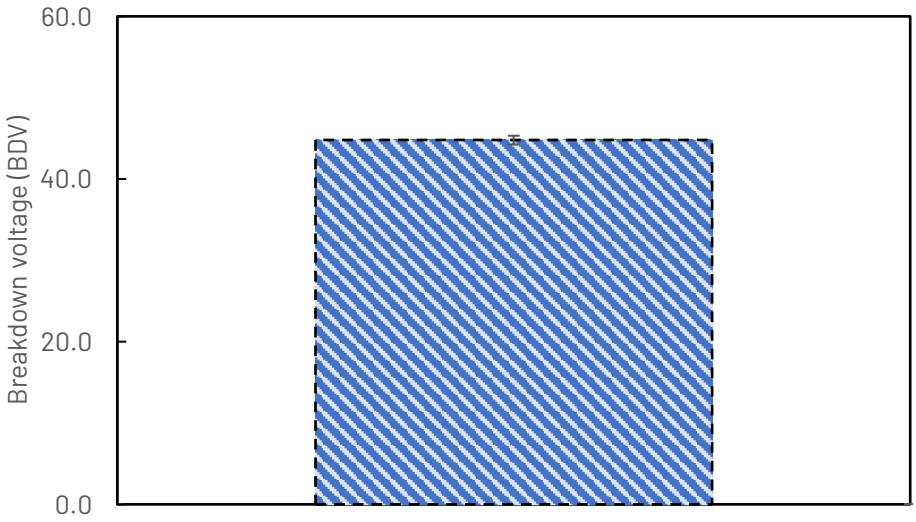

Figure 2. Average breakdown voltage of Synano PP0 as measured by IEC 60156. Error bars represent the standard deviation of 6 measurements.

The mean breakdown voltage measured was 71.4 kV, which is slightly above the ideal threshold of 40 kV specified by the acceptance criteria that Submer Technologies S.L. uses to evaluate new fluids (Table 7). For context, the BDV value of air using the standard IEC 60156 typically yields breakdown voltage values between 6 and 7 kV.

Table 7. Breakdown voltage results on Synano PP0 obtained using the international standard IEC 60156.

	Break down voltage measurements					
Breakdown voltage (kV)	80.3	70.4	69.5	69.6	68.0	70.5

Table 8. Standard deviation and average breakdown voltage value of the Synano PP0 determined by the international standard IEC 60156.

	Value
Mean (kV)	71.4
St. Dev (kV)	4.1
SD/Mean	0.06

In addition, the standard deviation of the breakdown voltage measurements was 4.1 kV, with a coefficient of variation (St. Dev./Mean) of 0.06. This low variation indicates that the measurements were consistent, and Synano PP0 breakdown voltage is reliable.

Table 9. Submer Technologies S.L Breakdown voltage acceptance criteria for new dielectric fluids using the international standard IEC 60156.

Property	Standard	Ideal	Acceptable	Unacceptable
Breakdown voltage (kV)	IEC 60156	≥ 40	40 > x ≥ 30	< 30

3.1.2 Dielectric dissipation factor, volume resistivity and dielectric constant

The electrical insulation performance of the fluid was evaluated by measuring the dielectric dissipation factor (DDF), volume resistivity, and dielectric constant according to the international standard IEC 60247. These parameters are key indicators of the electrical behavior of dielectric fluids used in immersion cooling systems, as they provide insight into dielectric losses, electrical conductivity, and polarization characteristics of the liquid.

Table 10. Dielectric dissipation factor, DC resistivity, and dielectric constant of Synano PP0 obtained using the international standard IEC 60247.

Property	Value
Dielectric dissipation factor (-)	0.0053
Volume resistivity (GΩ·m)	525
Dielectric constant (-)	2.06

The dielectric dissipation factor represents the fraction of electrical energy that is dissipated as heat when the fluid is subjected to an alternating electric field. Low DDF values are desirable because they indicate minimal dielectric losses and therefore better insulating efficiency. The measurement performed on Synano PP0 resulted in a dielectric dissipation factor of 0.0053. This value falls close to the ideal value defined for new dielectric fluids by Submer Technologies S.L., and it is only slightly higher than typical range reported for PAO-2 based fluids (**Table 11**). Such a low DDF value indicates low dielectric losses within the fluid and suggests high purity in the formulation.

Table 11. Submer Technologies S.L Dielectric dissipation factor, Volume resistivity and dielectric constant acceptance criteria for new dielectric fluids using the standard IEC 60247.

Property	Standard	Ideal value	Acceptable value	Unacceptable value
Dielectric dissipation factor (-)	IEC 60247	≤ 0.005	0.005 < x ≤ 0.05	> 0.05
Volume resistivity (GΩ m)	IEC 60247	≥ 100.0	100.0 > x ≥ 2.0	< 2.0
Dielectric constant (-)	IEC 60247	≤ 2.10	2.30 ≥ x > 2.10	> 2.30

Volume resistivity provides a measure of the resistance of the fluid to the flow of direct current (DC). High resistivity is essential for dielectric fluids to prevent electrical leakage and maintain electrical isolation of submerged components. The measured volume resistivity for Synano PP0 was 525 GΩ·m (5.25×10^{11} Ω·m), which is significantly above the minimum threshold of 100 GΩ·m defined for high-performance insulating fluids. This value is well within the typical range for dielectric liquids and indicates strong resistance to charge transport. Materials are generally considered conductive when their resistivity falls several orders of magnitude lower (e.g., below ~10^6 Ω·m). Therefore, the measured resistivity

confirms that Synano PP0 exhibits robust insulating behavior with a low likelihood of electrical leakage under normal operating conditions.

The dielectric constant of Synano PP0 was measured to be 2.06. The dielectric constant reflects the ability of the fluid to store electrical energy in the presence of an electric field and influences the electric field distribution within immersed electronic assemblies. Values typically observed for hydrocarbon-based immersion fluids commonly fall within the range of approximately 2.0–2.3. Elevated dielectric constants are often associated with increased polarity of the liquid and may correlate with the high dissipation factor observed for this fluid.

Overall, Synano PP0 exhibits strong dielectric performance across the three evaluated parameters. The dielectric dissipation factor (0.0053) is low, indicating minimal dielectric losses and efficient insulating behavior, albeit slightly above the ideal benchmark. The dielectric constant (2.06) falls within the expected range for hydrocarbon-based fluids, reflecting appropriate polarization characteristics and stable electric field distribution. Additionally, the volume resistivity (525 GΩ·m) is well above the minimum requirement for insulating liquids, confirming a high resistance to electrical conduction and a low risk of leakage. Collectively, these results indicate that Synano PP0 is a suitable dielectric fluid for immersion cooling applications with reliable electrical insulation properties.

3.2 Fire safety

The fire safety characteristics of the fluid were evaluated through flash point determination using the Pensky–Martens closed cup method (ASTM D93). Fluids with higher flash points present lower fire risk during storage, handling, and operation in data center environments.

Table 12. Flash point temperature values of Synano PP0 as determined by the international standard ASTM D93 (Pensky-Martens' method).

	Measurement 1	**Measurement 2**	**Measurement 3**
Flash point (°C)	165.5	164.2	164.6

According to the OCP material and fluid qualification guidelines for immersion cooling, the flash point acceptance criterion for dielectric fluids is ≥150 °C. The tested fluid exhibited a flash point higher than 164.8°C under closed cup conditions. This value is significantly above the minimum requirement and indicates a very low flammability risk under typical operating conditions. The measured value approximately falls within the high range of expected values for PAO-2 fluids, as results may vary between 150-165 °C depending on the formulations and additives.

The measured flash point confirms that the fluid provides a substantial safety margin relative to the OCP acceptance threshold. In addition, such high flash point is also in line with other international standards such as IEC 62368-1 and NFPA 75. Such a high flash point is advantageous for immersion cooling systems, where fluids may be exposed to elevated temperatures during operation but must maintain safe handling and operational characteristics.

3.3 Thermochemical Properties

The thermochemical properties of the fluid were evaluated to determine its suitability for heat transfer applications in immersion cooling systems. Thermal conductivity and specific heat capacity were measured according to standardized ASTM methods.

3.3.1 Thermal conductivity

Thermal conductivity was measured at two representative operating temperatures using ASTM D7896. At 25 °C, the fluid exhibited a thermal conductivity of 0.135 W/m·K, which slightly decreased to 0.133 W/m·K at 40 °C. This small reduction with temperature is consistent with the typical behavior of many dielectric fluids used in immersion cooling, where thermal conductivity tends to decrease modestly as temperature increases. No minimum acceptance threshold is explicitly defined for thermal conductivity in the OCP guideline; therefore, the measured values are evaluated relative to typical dielectric immersion fluids.

Typical thermal conductivity values for PAO-2 based fluids (with similar viscosity) fall within the range of 0.125–0.140 W/m·K at 40°C. The values obtained for Synano PP0 lie within this range, indicating comparable heat transfer capability. Notably, the addition of 0.1 wt% of alumina nanoparticles does not appear to produce a measurable enhancement in thermal conductivity, as the results remain aligned with those of conventional base fluids. As such, its performance is consistent with established immersion cooling fluids and is expected to provide effective heat dissipation from thermally dense components to the bulk fluid.

3.3.2 Specific heat capacity

The specific heat capacity of the fluid was determined at 40 °C using ASTM D1269. The measured value was 2080 J/kg·K. A high specific heat capacity is desirable for immersion cooling fluids because it allows the liquid to absorb a larger quantity of heat per unit mass while experiencing a smaller temperature rise. The measured value approximately falls within the expected values for PAO-2 fluids as results may vary between 2000-2150 J/kg·K depending on the formulation and additives. Since the OCP guidelines do not define a strict pass/fail threshold for this parameter but instead require reporting of representative thermophysical properties, the measured value is considered acceptable, and the test result is classified as PASS.

3.4 Material Compatibility

Synano PP0 materials compatibility was assayed to guarantee that there is no degradation of the fluid, SmartPod or IT Hardware components in immersion cooling applications. We have evaluated the changes of materials' physical properties as well as Synano PP0 physicchemical properties after immersing the materials of interest in the dielectric fluid for 336 hours at 80 °C.

Table 13. Summary of physical properties evaluation of the tested materials after immersion in Synano PP0 for 336 hours at 80 °C.

Sample	Weight (%)	Diameter (%)	Thickness (%)	Hardness (%)
ABS	PASS	PASS	PASS	PASS
EPDM	NO PASS	NO PASS	NO PASS	NO PASS
FKM	PASS	PASS	PASS	N/A
Loctite 435	N/A	N/A	N/A	N/A
Loctite 577	N/A	N/A	N/A	N/A
NBR	PASS	PASS	PASS	PASS
Nylon	PASS	PASS	PASS	PASS
PET	PASS	PASS	PASS	PASS
PMMA	PASS	PASS	PASS	PASS
PO	NO PASS	NO PASS	NO PASS	N/A
PP	PASS	PASS	PASS	PASS
PTFE	PASS	PASS	PASS	PASS
PUR	PASS	PASS	PASS	N/A
PVC	PASS	PASS	PASS	PASS
Silicone	NO PASS	NO PASS	PASS	NO PASS

Table 14. Summary of Physic-chemical properties of Synano PP0 used in the material compatibility tests after exposure to the material for 336 hours at 80 °C.

Sample	Breakdown Voltage (kV)	Dissipation factor (-)	Color	Acidity (mg KOH/g)
ABS	PASS	PASS	PASS	PASS
EPDM	PASS	NO PASS	PASS	PASS
FKM	PASS	PASS	PASS	PASS
Loctite 435	PASS	PASS	PASS	PASS
Loctite 577	PASS	PASS	PASS	PASS
NBR	PASS	PASS	PASS	PASS
Nylon	PASS	PASS	PASS	PASS
PET	PASS	PASS	PASS	PASS
PMMA	PASS	PASS	PASS	PASS
PO	PASS	PASS*	PASS	PASS
PP	PASS	PASS	PASS	PASS
PTFE	PASS	PASS	PASS	PASS
PUR	PASS	PASS	PASS	PASS
PVC	PASS	PASS	PASS	PASS
Silicone	PASS	PASS*	PASS	PASS

Table 15. Overall results of material compatibility of the tested materials.

Material	Expected results	Synano PP0 Results
ABS	COMPATIBLE	COMPATIBLE
EPDM	NON-COMPATIBLE	NON-COMPATIBLE
FKM + TPU	COMPATIBLE	COMPATIBLE
Loctite 435	COMPATIBLE	COMPATIBLE
Loctite 577	COMPATIBLE	COMPATIBLE
NBR	LIMITED COMPATIBILITY	LIMITED COMPATIBILITY
Nylon	COMPATIBLE	COMPATIBLE
PET	COMPATIBLE	COMPATIBLE
PMMA	COMPATIBLE	COMPATIBLE
PO	NON-COMPATIBLE	NON-COMPATIBLE
PP	COMPATIBLE	COMPATIBLE
PTFE	COMPATIBLE	COMPATIBLE
PUR	COMPATIBLE	COMPATIBLE
PVC	LIMITED-COMPATIBILITY*	COMPATIBLE
Silicone	LIMITED COMPATIBILITY	NON-COMPATIBLE

The expected results column represents the anticipated outcomes based on previous knowledge and experience with dielectric fluids based on synthetic hydrocarbons. The actual test results were compared against these expectations to verify Synano PP0 performance on the material compatibility tests.

Compatible materials showed full compatibility with Synano PP0 as expected. The results of material compatibility tests indicate that the fluid does not chemically interact nor degrade these materials, maintaining their integrity and expected performance. The consistency in the expected and actual test results confirms the reliability of Synano PP0 in applications and components that would use these materials.

Non-compatible materials such as EPDM and PO matched the expectations, showing severe deformations on the materials side. This outcome aligns with previous knowledge, indicating that these materials should be avoided in the components that constitute the immersion cooling tanks and IT hardware and accessories as much as possible. These materials are not compatible with PAO-2 fluids. As this is the base of the Synano PP0, same results were expected. Remarkably, none of the physic-chemical properties of Synano PP0 were severely affected by the exposure to EPDM and PO, leaving the fluid fully operational after exposure to those materials.

Limited compatibility materials such as Silicone show slight changes in the physical properties of the material. While these materials may tolerate exposure to Synano PP0 to some extent, prolonged exposure or extreme conditions could lead to partial degradation or performance issues.

3.4.1 Weight change

Weight of the samples was measured using a precision electronic balance accurate to the nearest milligram. Each sample was carefully placed on top of the balance pan, ensuring that it was stable a properly positioned. Weight was recorded once the balance stabilized, providing an accurate assessment of the samples' mass.

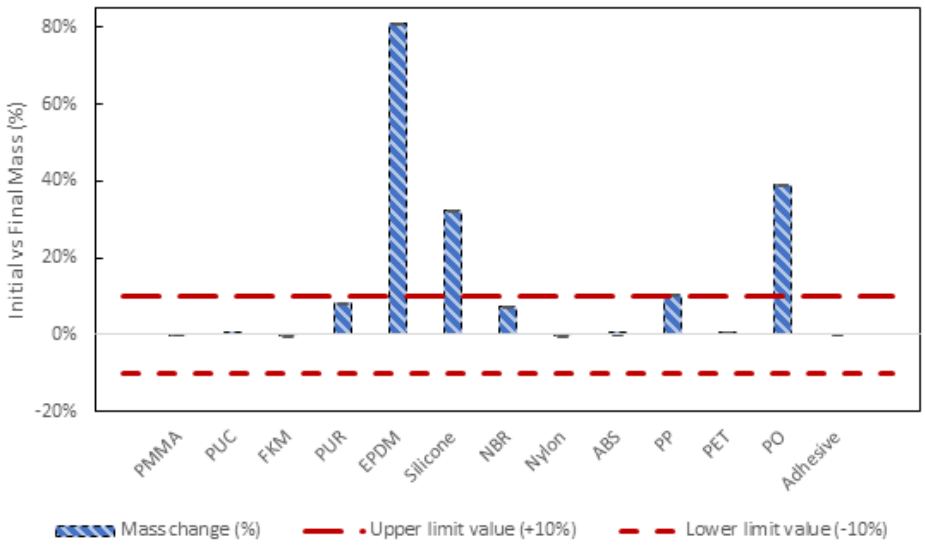

Figure 3. Weight change observed in materials immersed in Synano PP0. Dashed red lines indicate acceptance limit (-10%, +10%). Error bars correspond to the standard deviation from the measurements.

Recording weight before and after immersion allows quantification of fluid uptake by the materials. According to the OCP acceptance criteria, a weight increase above 10% indicates substantial absorption of the dielectric fluid and therefore poor compatibility.

Most tested materials exhibited negligible weight change, indicating minimal interaction with Synano PP0 and good compatibility under the test conditions. NBR and PUR showed moderate increases below the acceptance threshold, suggesting limited but measurable fluid uptake that remains acceptable. PP reached the 10% limit, indicating borderline behavior and suggesting that fluid absorption may become more significant under extended exposure conditions. These observations align with the behavior of PAO-2 fluid.

In contrast, several materials exceeded the acceptance criterion. Silicone and PO showed pronounced weight increases, indicating significant absorption of the immersion fluid. EPDM exhibited the most extreme behavior, with a very large mass increase, clearly indicating strong swelling and incompatibility with the fluid.

Overall, the results confirm that while most materials demonstrate good resistance to fluid uptake, EPDM, PO, and Silicone show clear incompatibility due to excessive absorption, and PP should be treated as a borderline case for long-term applications.

3.4.2 Dimension change

The dimensions of the samples were measured using a digital caliper with precision to the nearest hundredth of a millimeter. Each sample was carefully positioned on top of a working bench and the caliper jaws were gently closed around the sample to ensure accurate readings. The diameter and thickness were recorded once the caliper readings stabilized to provide reliable data for the analysis.

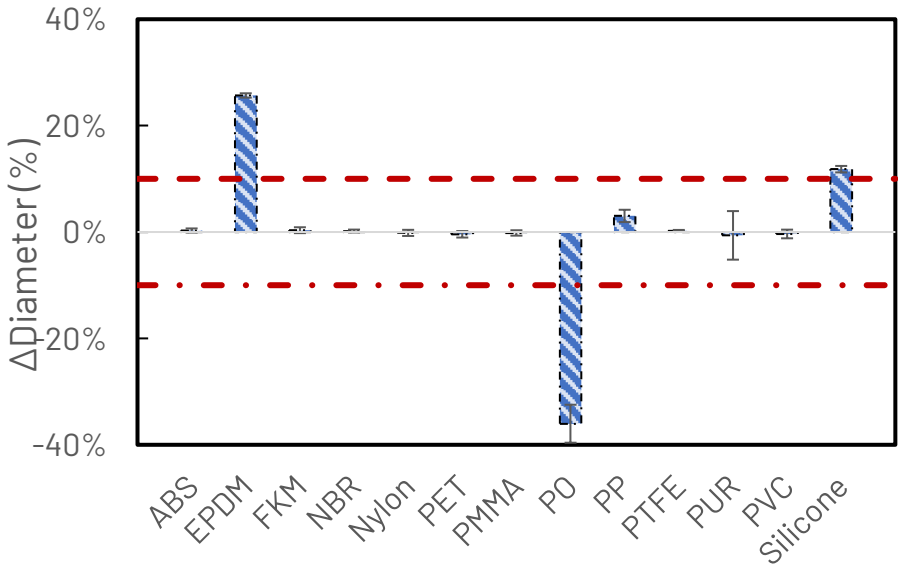

Figure 4. Diameter change observed in materials immersed in Synano PP0. Dashed red lines indicate acceptance limit (-10%, +10%). Error bars correspond to the standard deviation of the measurement.

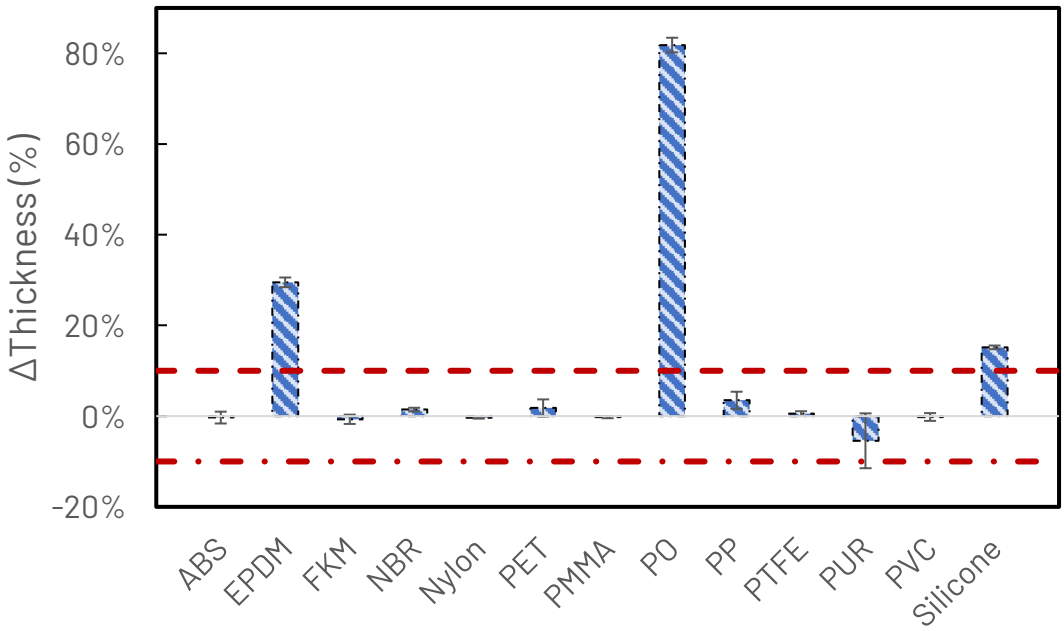

Figure 5. Thickness change observed in materials immersed Synano PP0. Dashed red lines indicate acceptance limit (-10%, +10%). Error bars correspond to the standard deviation of the 6 measurements.

Dimensional measurements provide additional insight into material–fluid interactions. According to OCP acceptance criteria, dimensional variations should generally remain within approximately ±5–10% to ensure structural stability.

Most materials exhibited negligible dimensional changes in both diameter and thickness, confirming good dimensional stability and compatibility with Synano PP0 under the tested conditions.

PP showed minor but measurable increases in both diameter and thickness, remaining within acceptable limits and indicating limited swelling. PUR exhibited small dimensional variations across different measured parameters, all within the acceptable range, suggesting no severe structural degradation despite some fluid interaction.

In contrast, several materials displayed significant dimensional changes exceeding the acceptance criteria. Silicone showed clear expansion in both diameter and thickness, indicating swelling and structural deformation. EPDM also exhibited pronounced increases in both dimensions, consistent with substantial fluid uptake and expansion of the elastomer matrix.

PO demonstrated the most irregular and extreme behavior, with large positive and negative variations across multiple dimensions, including substantial increases in thickness and simultaneous reductions in certain diameters. This combination of expansion and contraction indicates severe structural instability and anisotropic deformation, characteristic of strong material–fluid interaction and incompatibility.

Overall, the dimensional analysis confirms that while most materials maintain structural integrity, EPDM, PO, and Silicone exhibit significant deformation and should be considered incompatible with the tested immersion fluid for applications requiring dimensional stability.

3.4.3 Hardness change

Hardness was measured at six different locations within the samples using a Shore A durometer. Each reading was taken after a 3-second interval using a consistent 9.8 N force. This methodology allowed examination of hardness variations across the sample set, providing insights to variations induced by the immersion in the different dielectric fluids.

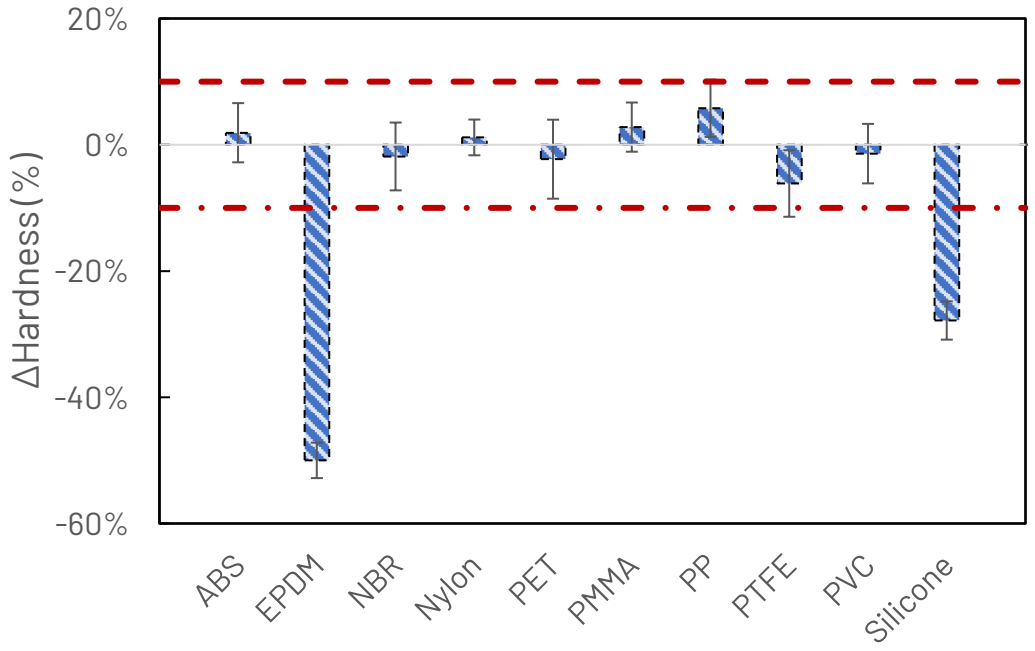

Figure 6. Hardness change observed in materials immersed in Synano PP0. Dashed red lines indicate acceptance limit (-10%, +10%). Black lines correspond to measurement error bars.

Hardness measurements further highlight material–fluid interactions and changes in mechanical properties after immersion. In general, most tested materials exhibited only minor

hardness variations, indicating that their mechanical integrity remained largely unaffected.

Thermoplastics showed limited changes, typically within a narrow range, confirming good stability under the test conditions. PP and PTFE exhibited the largest deviations within this group, but these remained moderate and do not indicate severe degradation.

Elastomeric materials showed more pronounced changes. Silicone exhibited a significant decrease in hardness, indicating softening of the material, likely due to fluid absorption or plasticization effects. EPDM showed the most substantial hardness reduction, reflecting strong interaction with the fluid and a marked loss of mechanical stiffness. NBR showed only minimal hardness variation, suggesting relatively stable behavior compared to other elastomers.

Overall, the results indicate that most materials maintain their hardness after exposure to the fluid, while EPDM and Silicone exhibit clear mechanical degradation and should be considered less suitable where hardness retention is critical.

3.4.4 Breakdown voltage

Maintaining a high value of breakdown voltage (BDV) is pivotal for dielectric fluids' performance. The higher the value, the more insulation the fluid is, as a higher voltage would be required before a spark occurs between two electrodes with a large electric potential difference. BDV tests were performed following the guidelines of the international standard IEC 60156, where BDV values were measured six times using two semi-circle electrodes spaced 2.5 mm from each other. The results plotted in Figure 5 are the average of the 6 measurements with their standard deviation shown as error bars.

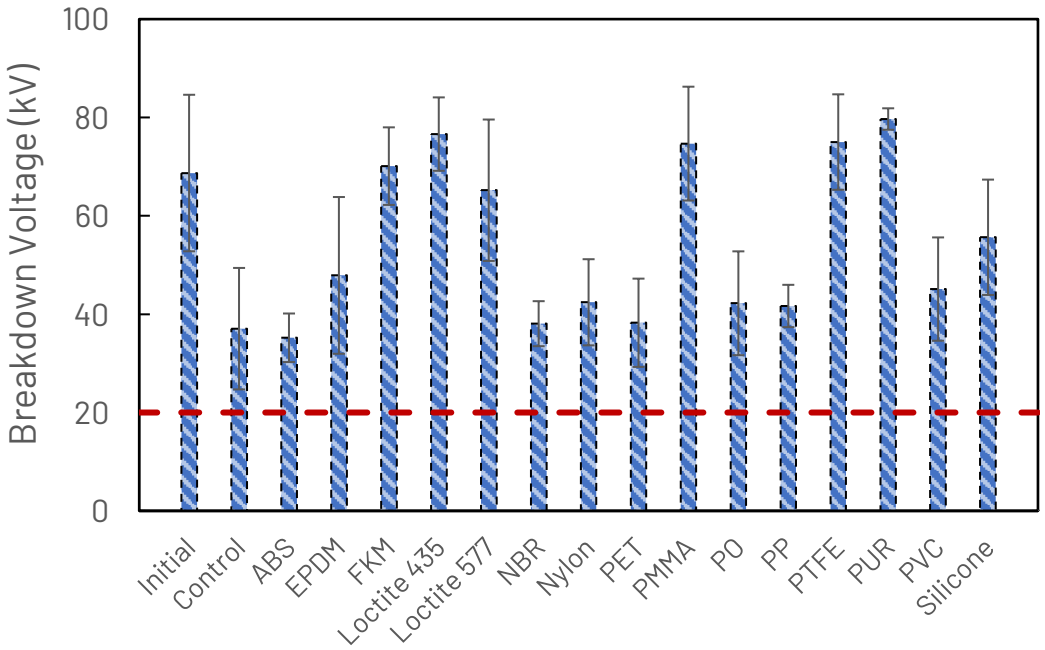

Figure 7. Breakdown Voltage values from Synano PP0 after treatment with each sample. Dashed red line indicates acceptance limit (20 kV). Black lines correspond to standard deviation of the measurement.

The initial breakdown voltage of Synano PP0 was 68.7 kV, while the control sample decreased to 37.1 kV, indicating a baseline reduction due to testing conditions. Following

material exposure, most samples exhibited breakdown voltages within a comparable range (approximately 35–80 kV), suggesting no severe degradation of dielectric performance.

Notably, several materials such as PUR, Loctite 435, PTFE and PMMA resulted in breakdown voltages equal to or higher than the initial value, indicating excellent compatibility and no detrimental contamination of the fluid. FKM and Loctite 577 also maintained high dielectric strength.

Other materials, including Silicone, EPDM, PVC, Nylon, PO, PP, PET, and NBR, showed moderate reductions in breakdown voltage but remained within an acceptable operational range. ABS exhibited the lowest value among the tested materials, though still comparable to the control.

Overall, no material caused a catastrophic drop in dielectric strength. While some reductions were observed, the results do not indicate severe incompatibility, and most materials can be considered compatible with the tested immersion fluid under the evaluated conditions. Moreover, all tested values are well above the ideal values for breakdown voltage as mentioned in section

3.4.5 Dielectric dissipation factor

Dielectric dissipation factor (DDF) provides information on the extent of dielectric losses occurring during operation. Impurities such as water, dissolved insulating resin, additives in formulations and other impurities can also add polarity to the insulating liquid and thereby influence the dielectric dissipation factor.

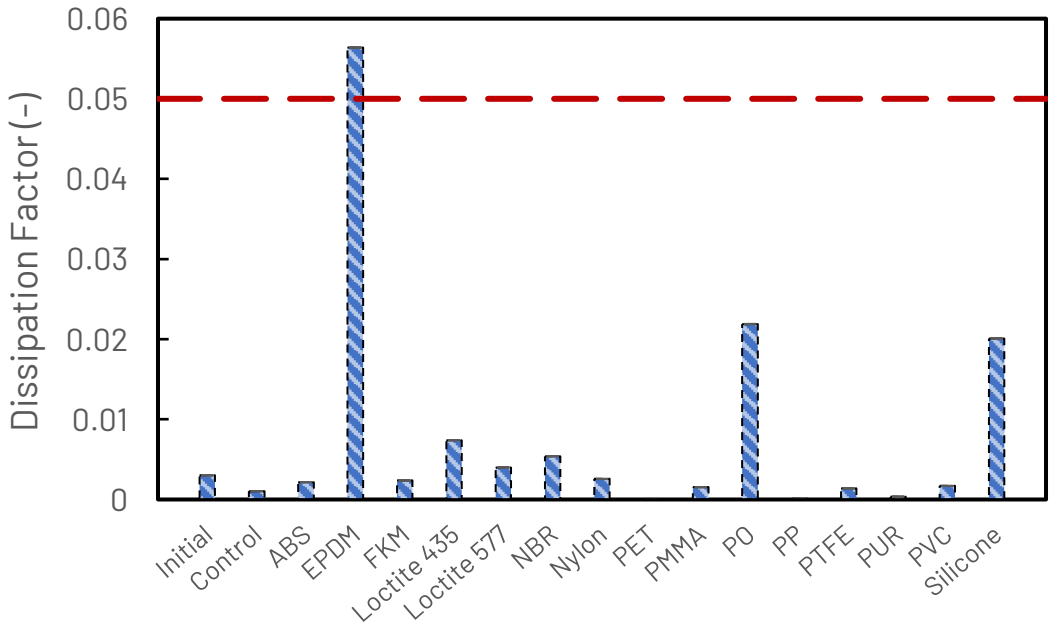

Figure 8. Dissipation factor values from Synano PP0 after treatment with each sample. Dashed red line indicates acceptance limit (0.05). Black lines correspond to measurement error bars.

The dissipation factor of Synano PP0 after material exposure remained low for most samples, generally on the order of 10^{-3} or below, indicating minimal dielectric losses and good fluid stability. The initial value (0.00301) decreased in the control sample (0.00103), suggesting that baseline testing conditions do not inherently increase dielectric losses.

Most materials, including ABS, FKM, Nylon, PMMA, PTFE, PP, PET, PVC and PUR, exhibited dissipation factors comparable to or lower than the initial value. These results indicate that these materials do not introduce significant polar contaminants into the fluid and are therefore electrically compatible under the tested conditions.

However, a subset of materials exhibited noticeably higher dissipation factors. EPDM showed the highest value (0.0564), exceeding the proposed acceptance criterion of 0.05, followed by PO (0.0219) and Silicone (0.0201). NBR (0.0054) and Loctite 577 (0.0040) also exhibited moderate increases. These elevated values suggest the presence of dissolved polar species or extractable additives that increase dielectric losses in the fluid. Except for EPDM, all materials remained below the proposed acceptance criterion, indicating generally acceptable dielectric performance under the conditions evaluated.

Overall, the dissipation factor results indicate that most tested materials maintain good dielectric compatibility with Synano PP0. While **EPDM, PO, and Silicone show a clear trend toward increased dielectric losses**, the magnitude of these changes does not indicate severe contamination. Consequently, no material demonstrates catastrophic incompatibility based solely on dissipation factor, although those with elevated values should be considered more critically for long-term or high-performance applications.

3.4.6 Acidity

The acidity of the samples was measured by measuring the amount of potassium hydroxide (KOH) required to neutralize the acidic components dissolved in the dielectric fluids. The amount of KOH required to neutralize the acidic components was measured three times and the results are shown as the average of those measurements and their standard deviation.

Table 16. Total acid number values of fresh Synano PP0 obtained using the international standard IEC 62021.

	Measurement 1	Measurement 2	Measurement 3
Acidity (mg KOH/g)	0.005	0.006	0.006

Table 17. Standard deviation and acidity mean value of the Synano PP0 acidity measurements determined by the international standard IEC 62021.

	Value
Mean (mg KOH/g)	0.006
St. Dev (mg KOH/g)	0.001

Synano PP0 had an average acidity value of 0.006 mg KOH/g of oil, which positions this single-phase immersion fluid in the lists of fluids with ideal acidity characteristics. Submer Technologies S.L. considers new dielectric fluids with lower acidity values than 0.01 mg KOH/g of oil as ideal for immersion cooling applications (Table 18).

Table 18. Submer Technologies S.L total acid number acceptance criteria for new dielectric fluids using the international standard IEC 62021.

Property	Standard	Ideal	Acceptable	Unacceptable

Acidity value (mg KOH/g oil)	IEC 62021	≤ 0.01	0.01 < x ≤ 0.05	> 0.05

3.5 Thermal Testing Vehicle (TTV) performance analysis

The thermal performance of Synano PP0 was evaluated against the PAO-2 base oil using an Intel LGA7529 thermal test vehicle (TTV) across multiple cooling configurations and power levels. The results consistently indicate that the incorporation of alumina nanoparticles does not produce a measurable impact on system-level thermal performance (**Figures 9 to 11**).

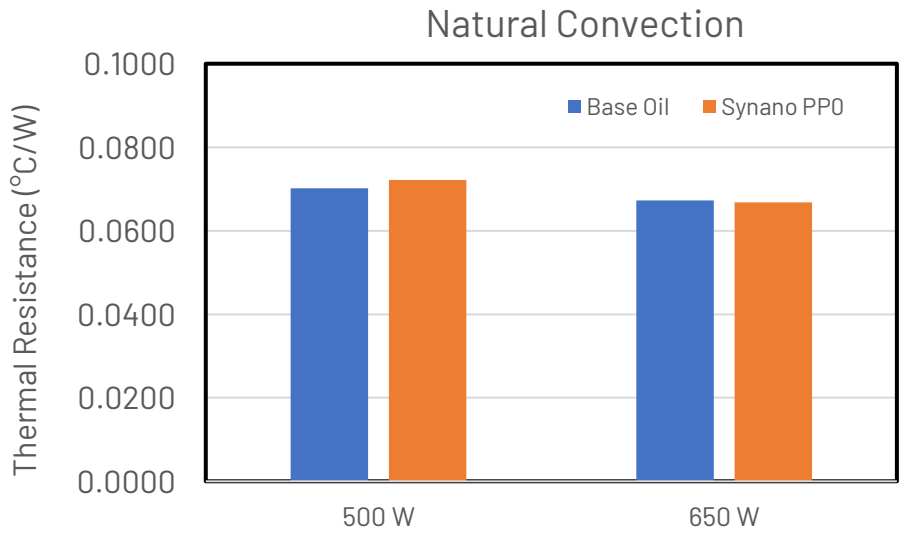

Figure 9. Thermal resistance of base oil and Synano PP0 in natural convection scenarios.

Under natural convection conditions, the measured thermal resistance values for Synano PP0 were very close to those of the base oil. At 500 W, Synano PP0 exhibited a slight increase in thermal resistance (+2.8%), while at 650 W a marginal improvement (–0.8%) was observed. These variations are minor and fall within typical experimental uncertainty,

indicating no meaningful performance deviation between the two fluids in passive cooling conditions.

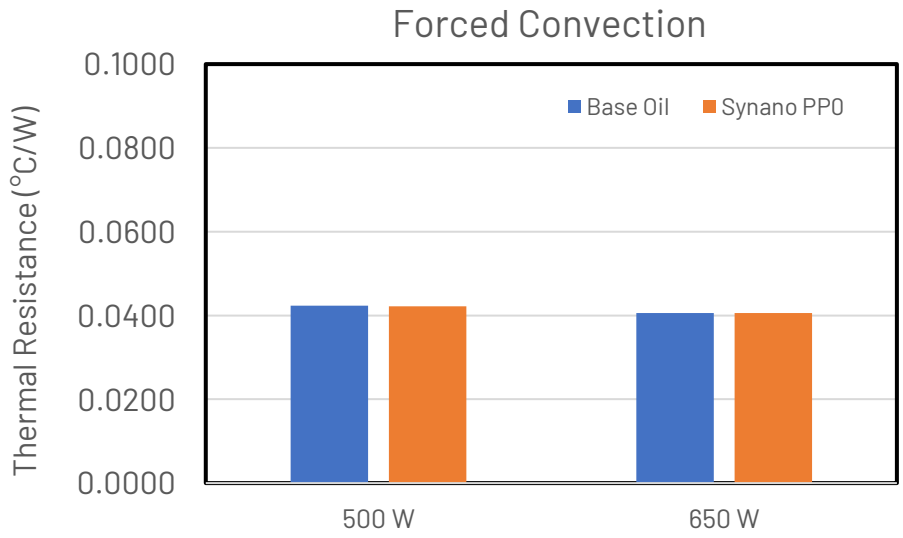

Figure 10. Thermal resistance of base oil and Synano PP0 in forced convection scenarios.

For the forced convection heatsink configuration, both fluids demonstrated nearly identical thermal behavior. Differences in thermal resistance were negligible at both power levels, with deviations of –0.3% at 500 W and –0.1% at 650 W. This confirms that under active airflow conditions, the presence of nanoparticles does not enhance or degrade heat transfer performance at the device level.

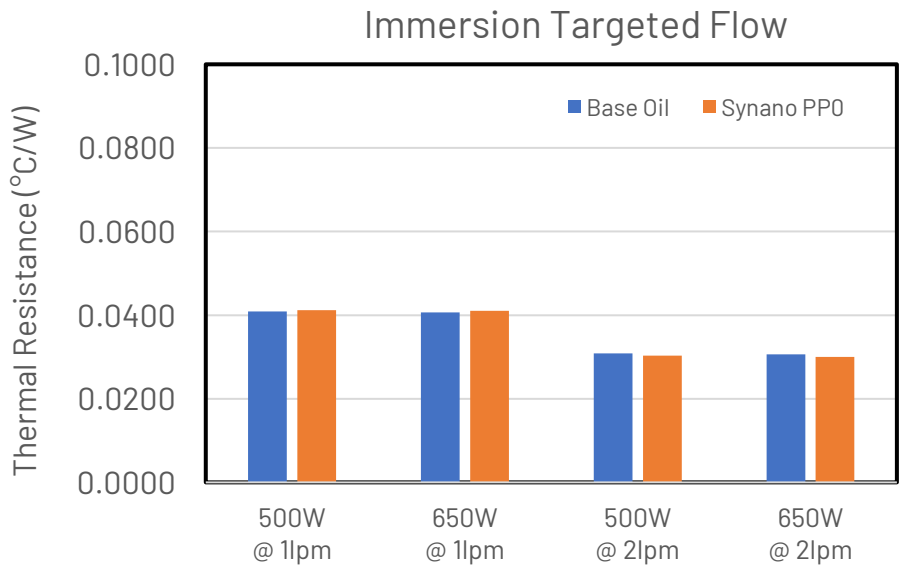

Figure 11. Thermal resistance of base oil and Synano PP0 in immersion targeted flow cooling using a coldplate at 1 and 2 liter per minute.

In the immersion cold-plate (targeted flow) configuration, results similarly showed minimal variation between the two fluids across different flow rates. At 1 L/min, Synano PP0 exhibited a slight increase in thermal resistance (~+0.8%) at both power levels. At higher flow rates (2 L/min), a small reduction in thermal resistance was observed (–1.8% at 500 W and

–2.0% at 650 W). However, these differences remain marginal and do not indicate a consistent or significant performance trend attributable to the nanofluid formulation.

Overall, across all tested configurations, natural convection, forced convection, and targeted flow, the thermal resistance values of Synano PP0 closely match those of the base PAO-2 fluid. The observed variations are minor, non-systematic, and within expected measurement tolerances.

These results demonstrate that, despite the inclusion of alumina nanoparticles, Synano PP0 does not deliver a measurable improvement in heat transfer performance at the TTV level. The thermal behavior remains effectively equivalent to that of the base oil under all tested operating conditions. This suggests that any potential enhancement in intrinsic thermophysical properties (e.g., thermal conductivity) does not translate into system-level performance gains in practical immersion cooling configurations.

4 Conclusions

The validation program demonstrates that Synano PP0 exhibits strong overall performance as a dielectric fluid for immersion cooling applications, meeting or exceeding the majority of acceptance criteria defined by industry standards and internal benchmarks.

From a dielectric standpoint, the fluid shows excellent insulating capability. The breakdown voltage is significantly higher than both minimum and ideal thresholds, with low variability across measurements, confirming reliability and consistency. Complementary electrical properties—including a low dielectric dissipation factor, high volume resistivity, and an appropriate dielectric constant—collectively indicate minimal dielectric losses, high electrical resistance, and stable field behavior. These characteristics confirm that Synano PP0 provides robust electrical insulation suitable for high-performance environments.

In terms of safety, the fluid demonstrates a high flash point well above the required limit, indicating low flammability risk and a substantial safety margin under typical and elevated operating conditions. This supports its suitability for deployment in data center environments where thermal loads can be significant.

Thermochemical analysis shows that Synano PP0 performs in line with conventional hydrocarbon-based immersion fluids. Thermal conductivity values fall within the expected range and show typical temperature dependence, while specific heat capacity is consistent with comparable formulations. Notably, the addition of nanoparticles does not yield a measurable enhancement in thermal conductivity, but the fluid still maintains adequate heat transfer capability for effective thermal management.

Material compatibility results indicate that Synano PP0 is broadly compatible with many common engineering materials, including ABS, PP, PTFE, Nylon, PET, and PMMA, which retained their physical and mechanical integrity after prolonged exposure. However, clear incompatibilities were identified with certain elastomers and polymers, particularly EPDM, PO, and Silicone, which exhibited significant swelling, deformation, and mechanical degradation. Additional materials such as PUR and PVC showed poorer-than-expected compatibility, while others like NBR and FKM demonstrated limited compatibility depending on conditions. Despite these interactions, the fluid's physicochemical and dielectric properties remained largely unaffected after material exposure, indicating good fluid stability.

Across extended testing, including exposure to various materials, Synano PP0 maintained stable dielectric performance and low acidity. The acidity level is well within the ideal range, suggesting minimal degradation and good chemical stability, which are critical for long-term operation.

In summary, Synano PP0 is a high-performing dielectric fluid with strong electrical insulation properties, low flammability risk, and adequate thermophysical characteristics for immersion cooling. While its compatibility with certain materials requires careful consideration in system design, the fluid demonstrates overall reliability, stability, and suitability for deployment in immersion cooling systems when paired with compatible materials.

From a system-level perspective, the thermal evaluation confirms that Synano PP0 performs equivalently to the base PAO-2 fluid across all tested cooling configurations and operating conditions. The addition of alumina nanoparticles does not translate into a measurable improvement in thermal resistance at the TTV level, with all observed variations

remaining within experimental uncertainty. Therefore, any potential enhancement in intrinsic fluid properties does not yield a tangible benefit in practical heat dissipation performance, indicating that Synano PP0 should be considered thermally comparable to conventional base oils in immersion cooling applications.

It is worth noting that the primary objective of developing the PAO-2-based nano-oil was to increase the flash point while maintaining, or preferably improving, its thermal performance. The results demonstrate that the nano-oil achieved a flash point above the target value of 164.8°C, meeting the primary design objective without compromising its thermal behavior. In terms of thermal performance, the incorporation of alumina nanoparticles did not result in a measurable improvement at the chip level, as Synano PP0 exhibited thermal performance comparable to that of the base PAO-2 fluid under the test conditions. Overall, the nano-oil met its primary design objective of achieving the desired flash point while preserving the thermal performance of the base fluid.

5 Annex

Table A1. Values of the physical properties measured on the material probes used in the material compatibility tests shown in section 3.4.

Sample	Weight (%)	Diameter (%)	Thickness (%)	Hardness (%)
ABS	0%	7%	0%	2%
EPDM	81%	0%	26%	-50%
FKM	0%	0%	0%	N/A
Loctite 435	N/A	0%	N/A	N/A
Loctite 577	N/A	39%	N/A	N/A
NBR	7%	0%	1%	-2%
Nylon	0%	39%	0%	1%
PET	0%	10%	0%	-2%
PMMA	0%	0%	0%	3%
PO	39%	8%	2%	N/A
PP	10%	0%	0%	6%
PTFE	0%	32%	0%	-6%
PUR	8%	7%	23%	N/A
PVC	0%	0%	-36%	-1%
Silicone	32%	12%	82%	-28%

Table A2. Values of the physic-chemical properties evaluated on Synano PP0 after exposure to the different materials in section 3.4

Sample	Breakdown Voltage (kV)	Dissipation factor (-)	Color
ABS	35,2	0,00216	< 0.5
EPDM	47,9	0,0564	< 0.5
FKM	70,1	0,00237	< 0.5
Loctite 435	76,6	0,0074	< 0.5
Loctite 577	65,2	0,00400	< 0.5
NBR	38,1	0,0054	< 0.5
Nylon	42,4	0,00257	< 0.5
PET	38,3	0,00006	< 0.5
PMMA	74,7	0,00153	< 0.5
PO	42,2	0,0219	< 0.5
PP	41,7	0,00011	< 0.5
PTFE	75,0	0,00138	< 0.5
PUR	79,7	0,00036	< 0.5
PVC	45,1	0,00170	< 0.5
Silicone	55,6	0,0201	< 0.5

Table A3. Values of the thermal resistance obtained in the TTV tests using different cooling technologies for 500W and 650W thermal loads.

Natural Convection	Base Oil	Synano PP0	ΔThermal resistance (%)
500 W	0.0702	0.0721	2.8
650 W	0.0673	0.0668	-0.8

Forced Convection	Base Oil	Synano PP0	ΔThermal resistance (%)
500 W	0.0423	0.0422	-0.3
650 W	0.0406	0.0406	-0.1

Immersion Cold-plate	Base Oil	Synano PP0	ΔThermal resistance (%)
500W @ 1lpm	0.0409	0.0412	0.8
650W @ 1lpm	0.0407	0.0410	0.8
500W @ 2lpm	0.0309	0.0303	-1.8
650W @ 2lpm	0.0306	0.0300	-2.0

6 Change log

Version	Date (dd/mm/yyyy)	Changes
1.0.0	07/04/2026	Release of the document
1.0.1	21/07/2026	Background section, table number corrections, clarifications in results, clarified conclusions.