Performance, sustainability, safety.

It is a fast-moving and often complex environment for buyers of heat transfer solutions. Fortunately there is no longer a need to trade-off performance for sustainability and safety. This white paper examines how 3M is helping businesses achieve many objectives with 3M thermal management fluids.

3M™ Novec™ Engineered Fluids are commercialised via the Electronics Materials Solutions Division at 3M. The division has developed a wide variety of solutions, which enable next generation technology in semiconductor, electronic devices, battery materials, signal management and data centres. 3M's diversity in electronics provides a broad understanding of our customers' needs and the expertise to create solutions that address multiple challenges and markets.

Novec fluids are an example of a technology used across multiple applications, including heat transfer, cleaning, electronics coatings, carrier solvents, clean fire extinguishing and more. Within heat transfer applications, customers can potentially use Novec fluids for semiconductor thermal management (chillers, tools and test equipment), gross leak testing and other electronics applications that require thermal management, and low temperature heat transfer (pharmaceutical & chemical industry).

Novec Engineered Fluids: the chemistry

Based on 3M proprietary segregated hydrofluoroether (HFE) and fluoroketones (FK) chemistries, Novec fluids have many properties contributing to their diverse use. They are non-flammable, dielectric and exhibit a wide operating temperature range (-120°C to 168°C), which makes them suitable for many heat transfer applications, both single and phase change processes. They also have very low surface tension and viscosity. 3M continues to innovate in thermal management, adding more products with different boiling points to meet evolving customer needs.

Sustainability

In 1996, Novec engineered fluids – a new class of sustainable chemistries – were introduced as replacements for ozone-depleting substances such as CFCs and HCFCs, and greenhouse gases such as HFCs.

Novec fluids have low Global Warming Potential (GWP) when compared with other chemistries such as hydrofluorocarbons (HFCs). They also have an Ozone Depletion Potential of zero meaning they have no effect on stratospheric ozone.

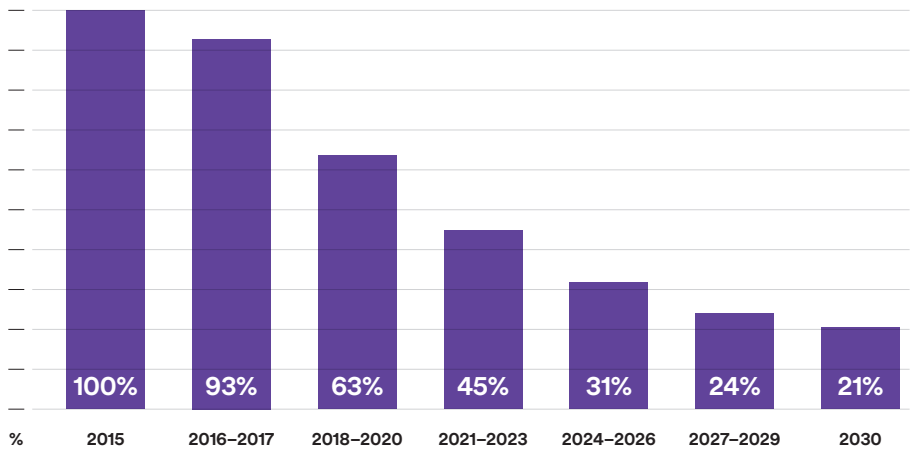
The environmental profile of Novec engineered fluids has led to wide acceptance for commercial use by regulatory agencies in the United States, Canada, Japan, Korea, Taiwan, Australia, Europe, the Philippines and China.

F-Gas Regulation II

In Europe 3M™ Novec™ Engineered Fluids are not listed in Annex I of the F-Gas II Regulation (EU 517/2014), meaning they are not restricted or banned for use within the EU, whereas HFCs are restricted as follows:

- HFC phase down from 2015-2030 – volume related quota
- HFCs are banned from certain applications

By 2030 only 21% of the HFC volume put on market between 2009 and 2012 will remain.



In addition to the European F-Gas Regulations, more recent amendments have been made to the Montreal Protocol, to seek global phase out of HFCs.

The Novec engineered fluids family consists of sustainable alternatives to both HFCs and Perfluoropolyether (PFPE), in HFE and FK chemistries.

3M has established over the years a cooling heritage with its 3M™ Fluorinert™ Electronic Liquid range, a portfolio of electronics coolants which demonstrate good heat transfer characteristics with high dielectric strength and excellent materials compatibility. More recently 3M has introduced the Novec brand products which have the same properties with superior environmental profile.

Indeed, Novec and Fluorinert products share similar properties as shown in the following tables.

Typical electrical properties of Novec engineered fluids family:

Dielectric strength (0.1" gap)	>25 kV
Volume resistivity	10^8 ohm-cm
Dielectric constant, 100 Hz – 10 MHz	1.8 – 7.4

Typical electrical properties of Fluorinert FC range:

Dielectric strength (0.1" gap)	>40 kV
Volume resistivity	10^{15} ohm-cm
Dielectric constant, 100 Hz – 10 MHz	1.8 – 2

Heat transfer processes

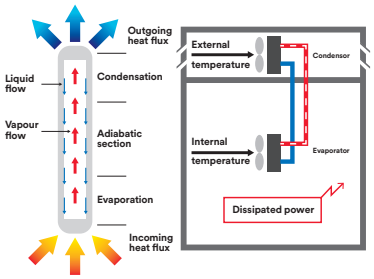
Let's focus hereafter on thermodynamics properties of 3M™ Novec™ 7500 Engineered Fluid vs 3M™ Fluorinert™ FC 3283 to emphasise their similar characteristics:

Properties	Units	FC-3283	Novec 7500 Engineered Fluid
Boiling point	°C	128	128
Freezing point	°C	-50	-100
Density	kg/m^3	1820	1614
Surface tension	mN/m	15	16.2
Dynamic viscosity	cP	1.4	1.24
Specific heat	J/kg K	1100	1128
Latent heat of vapourisation	kJ/kg	78	89
Dielectric strength	kV/0.1"	>40	>25

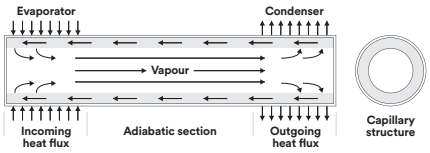
Passive processes

While the heat dissipation requirements of many electronics have become increasingly demanding, there is a wider range of options available than ever before (both passive and active processes) thanks to 3M™ Novec™ Engineered Fluids.

Thermosyphon (gravity)



Heat Pipes (capillary)



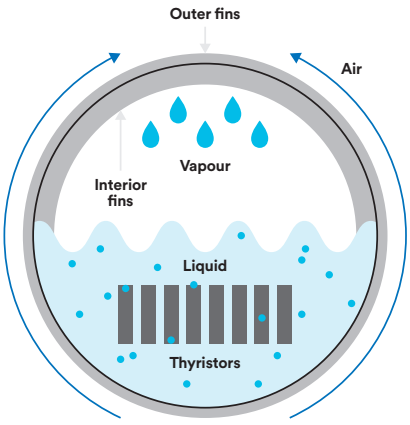
How does it work?

A thermosyphon is a passive, 2-phase (liquid to vapour in the evaporator and condensation in the condensor), gravity assisted device. It consists of a hermetic enclosure with a saturated fluid inside that is free of any non condensable gas.

Heat pipes (capillary)

- Liquid-vapour cooling is performed through a closed loop
- Capillary forces make the fluid move through
- Thermal dissipation around 800W

Two phase immersion process



Two phase immersion cooling

Water or water/glycol cooling mixtures are popular in some applications where dielectric properties are not required. However, as soon as water is introduced, the components to be cooled need to be within a sealed unit, in order to prevent any risk of damage. This can limit the cooling efficiency since there is no direct contact with components.

Immersion cooling with oil based fluids is another alternative which works well for many applications, but its flammability prohibits its use in many applications. Plus, due to the typically low coefficient of thermal expansion in combination with high viscosity of oils, the convective properties are less favourable and a pump is more likely to be required to efficiently remove the heat from components. Also, the nature of oils makes repairs a messy process, not to mention the danger of exposing the application to flammable fluids should a leak occur.

How does two phase immersion cooling work?

Step 1 = Heat by convection in the liquid phase

Step 2 = Vapourisation of the fluid to evacuate heat

Step 3 = Condensation of the vapours along the exchange surface

As electronics have become increasingly sophisticated, the power they need to process has also multiplied. Consider high speed computers, powertrains, batteries for electric and hybrid cars as just a few examples of advanced electronics… all areas where cooling of components is becoming an increasing focus area for design and test engineers.

This has led to a rise in the popularity of liquid immersion cooling, a technique which is more cost-effective than air-cooling, effectively removing heat without risk of damage to components.

3M™ Novec™ Engineered Fluids are an alternative to water or oil based cooling systems that can be used for a broad range of potential applications.

The evolution of electronics minituarisation leads to increasing dissipated power densities. In many cases these elevated power densities cannot be evacuated by traditional air cooling. Fortunately there is a wide range of options available within the Novec product family to meet even the most demanding cooling requirements.

Active processes

Immersion forced convection

In this configuration, the liquid is pumped directly over the battery cells and the heat is then rejected through an external heat exchanger.

This system enables direct cooling of battery cells with no heat transfer loss. Moreover, the uniform cooling due to the fluid circulating between the cells improves battery life time as well as charge/discharge rates. But the real advantage of this solution is safety, from the immersion of the cells into a non-flammable fluid. Offering intrinsic fire protection, this solution enables the use of higher density battery packs as thermal runaway propagation is prevented.

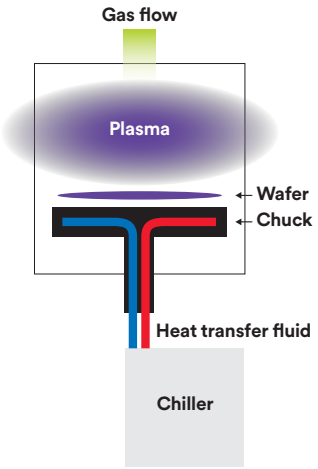
The two main heat transfer fluid choices available today are deionized (DI) water and fluorinated liquids. Although DI water is less expensive than fluorinated liquids, its disadvantages quickly offset any apparent cost savings.

For example, at operating levels above 1 Mohm-cm, DI systems may require stainless steel chillers costing 40%-50% more than comparable copper chillers. Above 60°C, DI water is highly corrosive – even to stainless steel. Ion-exchange bed filters to produce DI water are expensive and require periodic maintenance to sustain the high degree of purity necessary for volume resistivity and high dielectric strength. Finally, DI systems cannot operate above 80°C because of the temperature limits of DI filters.

Fluorinated liquids, in comparison, have several advantages.

Novec fluids have high dielectric strength, and due to their chemical inertness, will not damage electronic equipment or wafers in the event of a leak or other failure. A properly designed, tight system utilising 3M™ Fluorinert™ Electronic Liquids or Novec engineered fluids can have very low operating costs – which means customers can dedicate resources to running the system, rather than maintaining it.

Illustration = Heat transfer application in semiconductor manufacturing



Example:
Plasma etch thermal management

Thermal management issues are becoming increasingly important to electronics and semiconductor manufacturers. New designs put more demands on the dielectric fluids used to maintain the correct temperature. Environmental factors play an ever increasing role in fab or plant operating decisions. And cost remains an important issue.

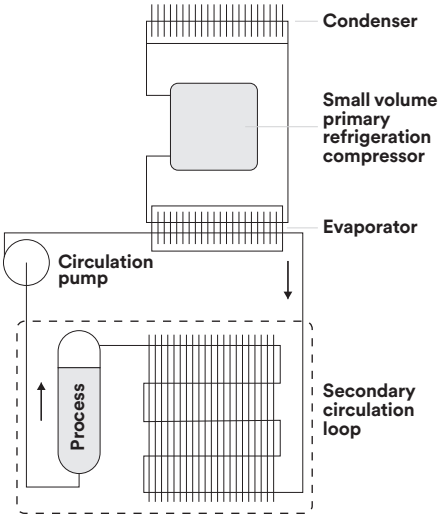
In short, selection of a heat transfer fluid for semiconductor and electronics equipment can no longer be an afterthought. Long-term, high performance solutions are needed.

3M™ Novec™ Engineered Fluids exhibit a very wide operating temperature range due to a unique combination of very low pour point and viscosity. The low viscosity means Novec fluids require very low pumping energy at low temperature in forced convection heat transfer applications. As a result, the shear forces in the pump are extremely low so that there is little or no temperature rise in the pump. Also, the low viscosity allows for small diameter piping since there is only a very small pressure drop in the loop.

Using a fluid with a boiling point close to the application operating temperature can improve heat transfer performance. To avoid pump and chiller wear it's important to use a fluid with low viscosity.

- The viscosity of a fluorinated fluid increases with boiling point, resulting in decreased heat transfer coefficients and increased pumping power.

Illustration: Low temperature heat transfer = cold storage



Novec fluids are ideal for heat transfer applications at low temperatures (down to -120°C). In this application, Novec engineered fluids are used in a secondary loop which transfers heat from the process to a primary refrigerant cycle. The unique set of properties (low freezing temperature, low viscosity and low surface tension) makes the Novec fluids easy to pump at very low temperature. The secondary loop works at low pressure, greatly reducing the risk of fluid loss.

Novec fluids are non-flammable, and this gives them an advantage over other substances used in cold storage such as methylene chloride, mineral oils or silicone oils. Typical low temperature applications are found in tissue storage, freeze-drying, pharmaceutical and chemical processes, etc.

3M has the thermal management fluids and technical support to meet specific customer needs – even at very low temperatures – and help improve reliability and lower overall operating cost.

Materials compatibility

When selecting a heat transfer fluid, materials compatibility is as important as the thermal performance. 3M™ Novec™ Engineered Fluids are generally compatible with the materials in the following table (users should evaluate parts containing some plastics and elastomers for long-term compatibility. Contact 3M to discuss your compatibility testing requirements.)

Metals	Plastics	Elastomers
Aluminium	Epoxy	Polysulphide
Copper	Nylon	Chlorosulphonated
Carbon steel	PTFE	EPDM
302 Stainless steel	Polyethylene	Buna-S*
Brass	Polypropylene	Butyl rubber*
Zinc	Polyester	Natural rubber*
Molybdenum	Phenolic	
Tantalum		
Titanium		
Tungsten		
Cu/Be alloy C 172		
Magnesium alloy AZ31B		

*Minor volume swell

In general, Novec Engineered Fluids are compatible with:

- All common metals and their alloys.
- Most rigid polymers as those contain little or no plasticisers. Best examples are polyethylene and polypropylene.
- Elastomers with little or no plasticisers like EPDM or butyl rubber.

If any fluid absorption occurs, it can lead to volume swell, as well as potential fluid loss by diffusion.

Novec fluids can occasionally extract plasticisers from polymeric materials. This extraction process leaves the polymer more brittle. The dissolved plasticiser can eventually redeposit in other areas.

The severity of these effects often depends on the specific function of the polymer in the system. It is therefore not easy to publish a full list of compatible/non compatible materials. Also, any polymer contains a number of additives that will vary between manufacturers. Those additives can influence the compatibility behaviour.

Fluorinated elastomers e.g. fluorocarbon, PTFE, DuPont™ Kalrez® will swell significantly. The same effect will be observed in most silicones.

Thus, during system design, the compatibility between the fluids and plastic and elastomeric materials should be tested.

Selection of heat transfer fluids

Balancing the demand for thermal management performance with worker safety and low environmental impact has never been more important. 3M recognises customers' need for a long-term heat transfer fluid with low greenhouse gas emissions and has meticulously engineered the solution – a comprehensive portfolio of 3M™ Novec™ Engineered Fluids. Customers can reduce greenhouse gas emissions by up to 99 percent in their application by replacing perfluorocarbon (PFC) or perfluoropolyether (PFPE) heat transfer fluids with Novec fluids.

Properties	Unit	3M™ Novec™ Engineered Fluids							
		7000	649	7100	774	7200	7300	7500	7700
Boiling point	°C	34	49	61	74	76	98	128	167
Pour point	°C	-122	-108	-135	-78	-138	-38	-100	-50
Molecular weight	g/mol	200	316	250	366	264	350	414	528
Critical temperature	°C	165	169	195	195	210	243	261	290
Critical pressure	MPa	2.48	1.88	2.23	1.71	2.01	1.88	1.55	1.41
Vapour pressure	kPa	65	40	27	15.7	16	5.9	2.1	<0.1
Heat of vapourisation	kJ/kg	142	88	112	90	119	102	89	83
Liquid Density	kg/m^3	1400	1600	1510	1660	1420	1660	1614	1797
Coefficient of expansion	K^{-1}	0.0022	0.0018	0.0018	0.0015	0.0016	0.0013	0.0013	0.0011
Kinematic viscosity	cSt	0.32	0.40	0.38	0.52	0.41	0.71	0.77	2.52
Absolute viscosity	cP	0.45	0.64	0.58	0.87	0.58	1.18	1.24	4.54
Specific heat	J/kg-K	1300	1103	1183	1130	1220	1140	1128	1040
Surface tension	mN/m	12.4	10.8	13.6	12.3	13.6	15.0	16.2	18
Solubility of water in fluid	ppm by weight	~60	20	95	20	92	67	45	14
Solubility of fluid in water	ppm or ppb by weight	<5 ppm	-	12 ppm	-	<5 ppm	<295 ppb	<4 ppb	<1 ppb
Dielectric strength range, 0.1" gap	kV	>25	>40	>25	>40	>25	>25	>25	>25
Dielectric constant @ 1kHz	-	7.4	1.8	7.4	1.9	7.3	6.1	5.8	6.7
Volume resistivity	Ohm-cm	10^8	10^{12}	10^8	10^{12}	10^8	10^{11}	10^8	10^{11}
Global warming potential[a]		530	<1	297	<1	57	310	100	436

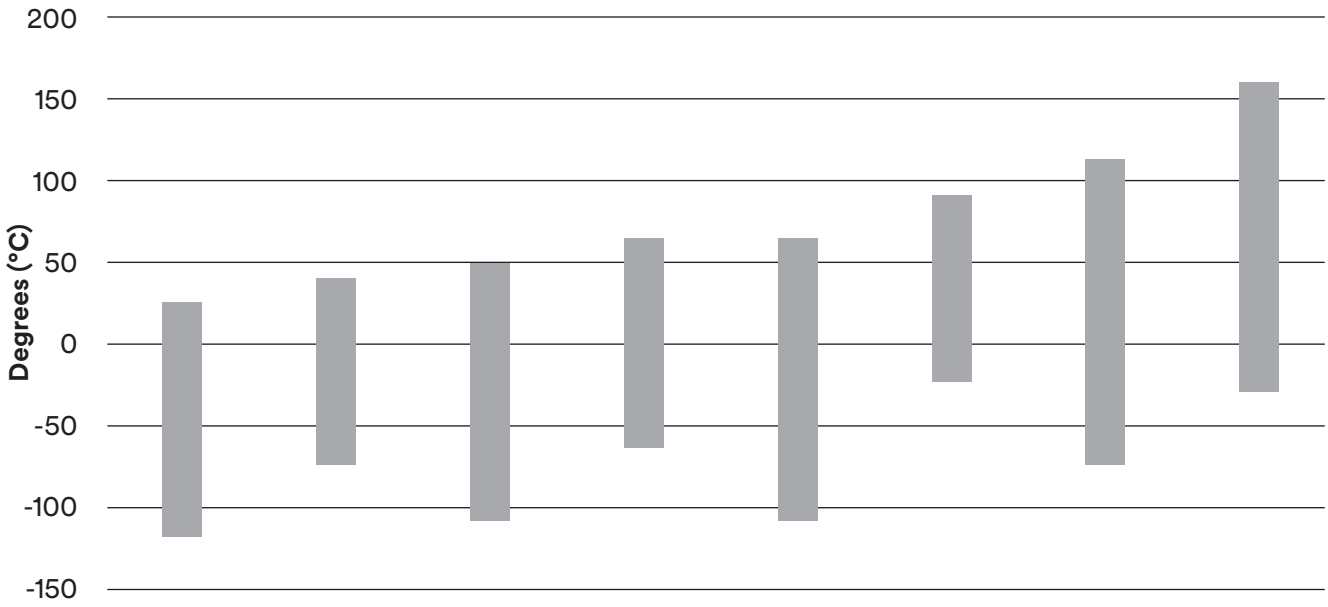
Not for specification purposes. All values @ 25°C unless otherwise specified.

[a] GWP-100 year ITH, CO_2 = 1.0, per IPCC 2013, with the exception of Novec 7100 fluid, which notes IPCC 2007.

Heat transfer applications using 3M™ Novec™ Engineered Fluids

Recommended Operating Temperature Range for Pumped Single Phase Systems*. Maximum recommended operating temperature is typically 10 degree C below boiling point, minimum recommended operating temperature is determined by viscosity (around 15-20 cSt). A wider operating range is possible depending on the specific customer application.

Operating temperature range



	3M™ Novec™ 7000 Engineered Fluid	3M™ Novec™ 649 Engineered Fluid	3M™ Novec™ 7100 Engineered Fluid	3M™ Novec™ 774 Engineered Fluid	3M™ Novec™ 7200 Engineered Fluid	3M™ Novec™ 7300 Engineered Fluid	3M™ Novec™ 7500 Engineered Fluid	3M™ Novec™ 7700 Engineered Fluid
Maximum	25	40	50	65	65	85	115	155
Minimum	-120	-75	-105	-60	-105	-30	-75	-30

*For two phase systems, contact your 3M technical service representative.

Safety

Novec engineered fluids offer a wider margin of safety than other alternative fluids and don't require any specific handling conditions in standard use. 3M™ Novec™ 7100 Engineered Fluid and 3M™ Novec™ 7500 Engineered Fluid are classified as 750 ppm and 100 ppm (parts per million) respectively in terms of exposures limits.

For fluoroketones, 3M™ Novec™ 649 Engineered Fluid has an exposure guideline of 150 ppm.

Flammability

Novec engineered fluids are non-flammable in their liquid phase thanks to the absence of a flash point. Under normal operating conditions, Novec fluids are non-flammable even when exposed to a direct flame or an electrical arc.

Summary: considerations in evaluating heat transfer fluids

In lower-voltage and power environments, traditional air cooling and thermal interface materials (TIMs) still have a role to play, but they often do not have the ability to remove heat efficiently or quickly enough in today's more sophisticated electronics world.

Dielectric heat transfer fluids can be used in both single phase and two phase applications, but regardless of process, their desirable properties include:

1 Excellent thermo-physical properties – heat transfer fluids remove heat by convection so factors such as the coefficient of thermal expansion, high density, low viscosity and low surface tension are beneficial. For two-phase applications, high latent heat of evaporation is also an advantage.

2 Direct contact – a high dielectric strength makes fluids good insulators and suitable for direct contact with power electronic systems.

3 Temperature range – this depends on the application, but typically a low freezing point is desirable, while the atmospheric boiling point is chosen in relation to the upper operating temperature.

4 Longevity – chemical and thermal stability for the lifetime of the component or device being cooled.

5 Good materials compatibility.

6 Non-corrosive behaviour with electronic components.

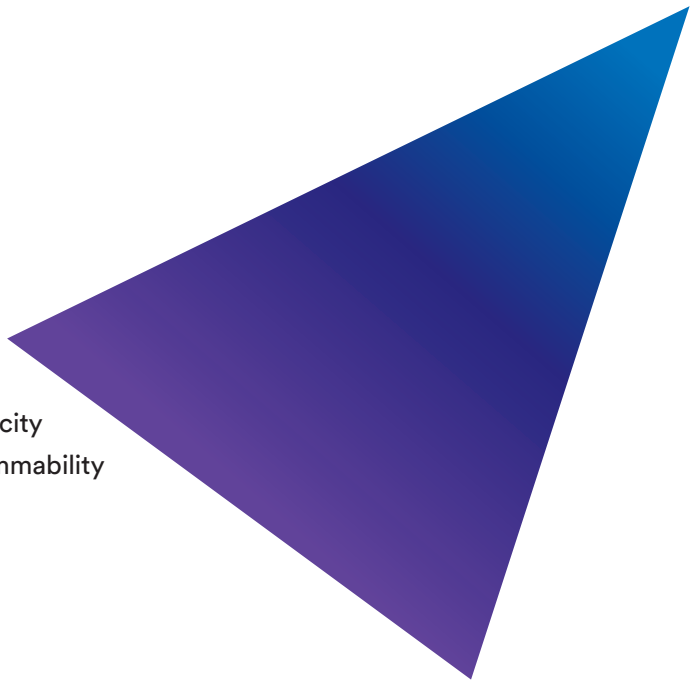
7 Cost of ownership – across the lifetime of the component or device it is supporting, including requirements for ancillary equipment as part of the cooling process.

8 Sustainability – 3M™ Novec™ Engineered Fluids are not subject to any current or forthcoming environmental, health and safety legislation or restrictions.

9 Zero flammability.

The growing influence of market regulations and the awareness of organisations' environmental footprint are important considerations in heat transfer solutions. Fortunately customers no longer have to compromise between performance, high margin of safety and sustainability. Novec fluids strike a balance between all these demands. 3M continues to innovate and commercialise additional fluids in the Novec family that meet our customers' demanding and evolving needs in thermal management.

3M™ Novec™ Engineered Fluids – the right balance on performance, safety and environment



Performance

- compatibility
- high density, low viscosity
- evaporate without residue
- wide boiling point fluids range

Safety

- stability
- low toxicity
- non flammability

Environment

- zero ozone depletion
- short atmospheric lifetime
- low global warming impact
- low water solubility

The 3M™ Novec™ brand family

The Novec brand is the hallmark for a variety of proprietary 3M products. Although each has its own unique formula and performance properties, all Novec products are designed in common to address the need for safe, effective, sustainable solutions in industry-specific applications. These include precision and electronics cleaning, heat transfer, fire protection, protective coatings, immersion cooling, advanced insulation media replacement solutions and several specialty chemical applications.

3M™ Novec™ Engineered Fluids ■ 3M™ Novec™ Aerosol Cleaners ■ 3M™ Novec™ 1230 Fire Protection Fluid ■ 3M™ Novec™ Electronic Grade Coatings ■ 3M™ Novec™ Electronic Surfactants ■ 3M™ Novec™ Insulating Gases

UK
3M Electronics Materials Solutions Division
0800 032 0841

Germany
3M Germany
49 2131 140

Belgium
3M Belgium
32 3 250 7521

Czech Republic
3M Czech Republic
420 2 61380111

3M East
41 4179 94040

France
3M France
33 1303 16161

Israel
3M Israel
972 9 9561490

Spain
3M Spain
34 91 3216000

Russia
3M Russia
7 495 7847474

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3M Hungary
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Electronics Materials Solutions Division
3M United Kingdom PLC, 3M Centre, Cain Rd, Bracknell RG12 8HT, United Kingdom
0800 0320841
www.3M.co.uk/novec

J344361.