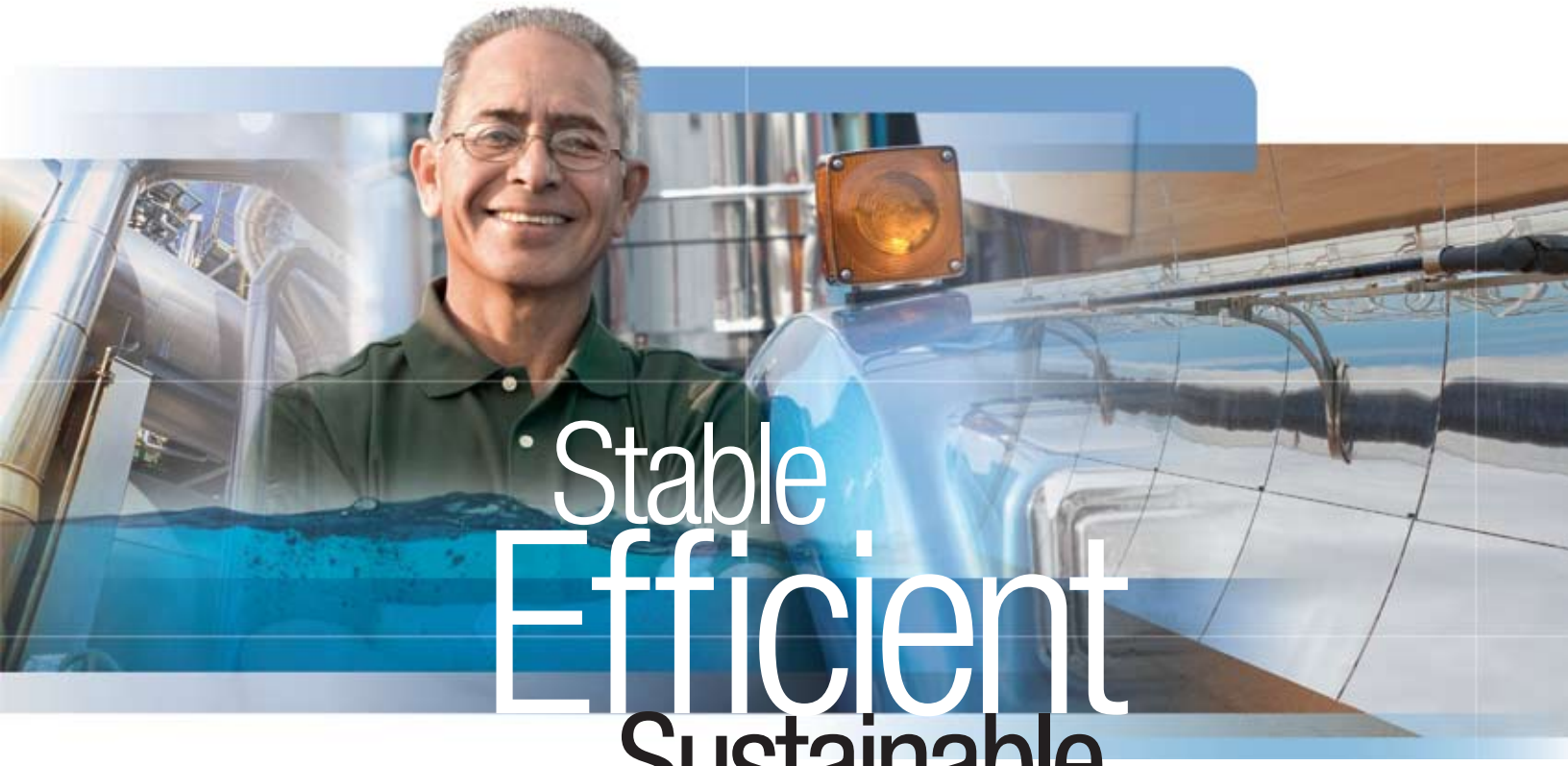
3M™ Novec™ Fluids
For Organic Rankine Cycle Systems



Stable Efficient Sustainable

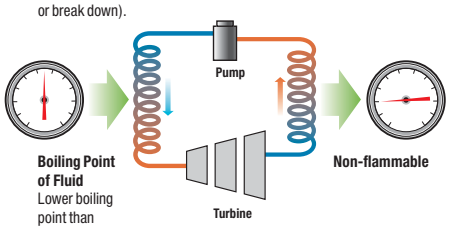
Environmentally sustainable working fluids
for Organic Rankine Cycle (ORC) Systems

3M

Critical considerations for choosing the right working fluid

Thermal Stability of Fluid
Fluid must remain stable at maximum cycle temperature (does not decompose or break down).

Environmental factors
will ensure sustainable system ODP, GWP, Toxicity.



Boiling Point of Fluid
Lower boiling point than heat source temperature to ensure vaporization.

Non-flammable

Molecular Weight of Fluid
High Molecular Weight reduces turbine rpm and component size.

3M™ Novec™ 649 Fluid showed insignificant changes in purity during tests carried out in sealed glass ampules at temperatures ranging from 200–300°C for durations between 120 hours and 30 days. The extreme thermal stability of Novec 649 fluid makes it particularly well-suited for recovering energy from high temperature sources such as internal combustion engines and industrial processes.

Products with other boiling points are available or under development. Contact your 3M sales representative for details.

Engineered for stable, predictable performance

Increased fuel demand, rising costs and the need to reduce greenhouse gases and other pollutants have spurred the development of technologies enabling more efficient use of all forms of power.

In particular, there has been growing interest in the *Organic Rankine Cycle* (ORC), which uses low-grade waste heat or heat from geothermal, solar, or other heat sources to generate useful mechanical or electrical energy. ORC is being evaluated for its ability to increase the efficiency of a wide range of systems, from automotive engines to power plants and general industrial processes.

A critical element in the development of practical ORC systems is the fluid used to absorb heat from the primary energy source. This fluid is converted to a vapor, which drives a turbine before condensing and being re-routed to the heat source.

A number of factors must be taken into consideration when choosing the optimal working fluid for an application incorporating an Organic Rankine Cycle. Among these are:

- **Performance** – In general, the thermal efficiency of a Rankine cycle improves as the difference between the heat source and sink temperatures increases. However, the actual performance of any given system will depend on the thermodynamic properties of the chosen working fluid. The thermophysical properties of the fluid will have implications on component sizing, cost and overall system design.
- **Stability** – The fluid should offer long-term thermal stability at the expected maximum cycle temperature. It should also be non-corrosive, to protect the integrity of coils, seals and other system components.
- **Safety** – The fluid should be nonflammable and low in toxicity
- **Long-Term Sustainability** – As environmental regulations become more stringent, factors such as low global warming potential and a short atmospheric lifetime will help ensure the viability of a fluid, both today and at the time of decommissioning.

3M™ Novec™ Fluids – The sustainable solution for ORC working fluids

3M has developed two high-performance working fluids that are particularly suited to the unique requirements of ORC applications: **3M™ Novec™ 649 Fluid and 3M™ Novec™ 7000 Engineered Fluid**. Both are from the Novec family of low global warming materials, designed to deliver safe, effective and sustainable solutions in a wide range of applications.

Novec fluids offer proven heat transfer performance, with properties that include:

- Good materials compatibility
- Low toxicity
- Nonflammable
- Zero Ozone Depletion Potential
- Low Global Warming Potential

Typical Physical Properties

		Novec 649	Novec 7000
Boiling Point	°C (°F)	49 (120.2)	34 (93.2)
Pour Point	°C (°F)	-108 (-162)	-122 (-188)
Molecular Weight	g/mol (lb/lbmol)	316	200
Critical Temperature	°C (°F)	169 (336)	165 (329)
Critical Pressure	MPa (psia)	1.88 (273)	2.48 (360)
Vapor Pressure	kPa (psia)	40 (5.8)	65 (9.4)
Heat of Vaporization	kJ/kg (BTU/lb)	88.0 (37.8)	142 (61.0)
Liquid Density	kg/m^3 (lb/ft^3)	1600 (99.9)	1400 (87.4)
Coeffcient of Expansion	K^{-1} (°F^{-1})	0.0018 (0.0010)	0.0022 (0.0012)
Kinematic Viscosity	cSt	0.4	0.32
Absolute Viscosity	cP	0.64	0.45
Specific Heat	J/kg-K (BTU/lb-°F)	1103 (0.263)	1300 (0.311)
Thermal Conductivity	W/m-K (BTU/hr-ft-°F)	0.059 (0.034)	0.075 (0.043)
Surface Tension	mN/m	10.8	12.4
Solubility of Water in Fluid	ppm by weight	20	~60
Dielectric Strength, 0.1" gap	kV	>40	~40
Dielectric Constant@1kHz	–	1.8	7.4
Volume Resistivity	Ohm-cm	10^{12}	10^{8}

Environmental and Safety Properties and Exposure Guidelines

	Novec 649	Novec 7000	HFC 245fa
Ozone Depletion Potential	0	0	0
Global Warming Potential[1]	1	420	1030
Atmospheric Lifetime (years)	0.014	4.1	7.6
Flashpoint	None	None	None
Flammability Range in Air	None	None	None
Exposure Guidelines (ppm) 8 hr. time-weighted average	150	75	300
Acute Inhalation Toxicity (ppm) 4 hr LC_{50} [Rat]	>100,000	>100,000	>200,000

[1] IPCC 2007 Intergovernmental Panel on Climate Change Method 100 Year (ITH)

Novec 649 Thermodynamic Properties

Temperature (°C)	P (Bars)	ρ_L (kg/m^3)	ρ_v (kg/m^3)	H_L (kJ/kg)	ΔHvap (kJ/kg)	H_v (kJ/kg)	S_L (kJ/kgK)	S_v (kJ/kgK)
-40	0.01	1766	0.164	0.00	109	109	0.00	0.47
-20	0.04	1718	0.605	21.6	105	127	0.09	0.50
0	0.13	1665	1.768	43.4	101	144	0.17	0.54
20	0.33	1608	4.331	65.4	96.1	161	0.25	0.58
40	0.73	1546	9.269	88.4	90.2	179	0.33	0.61
60	1.45	1480	17.89	111	85.0	196	0.40	0.65
80	2.63	1408	32.21	134	78.8	212	0.46	0.68
100	4.45	1329	55.33	157	71.3	229	0.53	0.72
120	7.11	1239	92.82	182	61.8	244	0.59	0.75
140	10.8	1125	157.0	209	48.9	258	0.66	0.77
160	16.0	929	292.9	240	27.7	268	0.73	0.79

Novec 649 fluid has been shown to exhibit very good thermal stability in laboratory tests inside sealed glass ampules. Contact 3M Technical Service for more information.

Novec 7000 Thermodynamic Properties

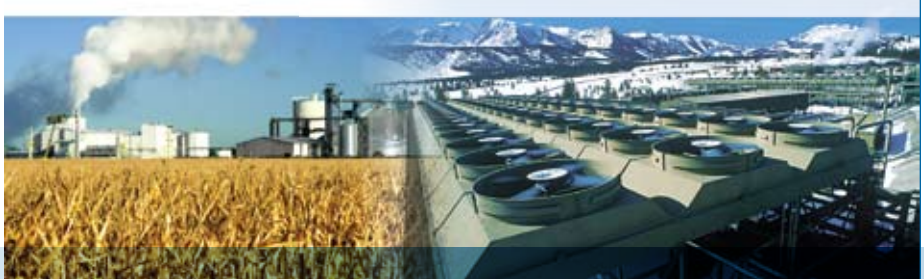
Temperature (°C)	P (Bars)	ρ_L (kg/m^3)	ρ_v (kg/m^3)	H_L (kJ/kg)	ΔHvap (kJ/kg)	H_v (kJ/kg)	S_L (kJ/kgK)	S_v (kJ/kgK)
-40	0.03	1585	0.265	3.25	159	162	0.01	0.69
-20	0.09	1536	0.845	24.3	152	176	0.10	0.70
0	0.24	1483	2.175	46.2	145	191	0.18	0.72
20	0.57	1428	4.840	68.9	138	207	0.26	0.74
40	1.19	1372	9.705	92.3	130	223	0.34	0.76
60	2.25	1311	18.03	117	122	238	0.42	0.78
80	3.98	1246	31.71	142	113	254	0.49	0.81
100	6.62	1173	53.81	168	101	269	0.56	0.83
120	10.5	1089	90.01	195	87.8	283	0.63	0.85

Materials Compatibility

3M™ Novec™ Fluids are compatible with a wide variety of materials used in ORC equipment. Most of the materials commonly considered "hard" plastics will perform well with Novec fluids. In addition, all metals, hard polymers and variety of inexpensive elastomers can be used. Elastomers should be limited to those that are not heavily plasticized. 3M engineers can assist you with recommendations and testing on specific compounds.

In addition to these two featured products, Novec fluid products are available in a wide range of boiling points, to meet your specific design requirements. Contact your 3M representative for more details.

Early ORC systems have used commercial refrigerants for decades (*Heat Recovery Systems* CHP Vol 13, No. 5 pgs 409-418). 3M now offers improved fluids with low environmental impact and excellent stability and performance.



Novec Fluids vs. HFCs: Designing for long-term viability

For several years, hydrofluorocarbons (HFCs) have been utilized as working fluids in commercial ORC systems. Although current environmental regulations allow the use of these materials in this application, the high global warming potential of HFCs is the "achilles heel" for ORC technology which, ultimately, is sold on the basis of its energy savings and climate impact. HFCs, due to their climate impact, are targeted for emission reduction by the Kyoto protocol and European regulations, making it likely they will be subject to future production phase-down schedules. For this reason their incorporation into a climate-sensitive technology such as ORC is a contradiction that 3M™ Novec™ Fluids can help resolve. Because they are more sustainable for the long term, Novec fluids are well suited as working fluids for an evolving ORC technology intended to save energy for our future generations.

For example, 3M™ Novec™ 649 Fluid (C_6-fluoroketone) is a non ozone-depleting material with a global warming potential of 1 – the same as naturally-occurring carbon dioxide. It also has a very short atmospheric lifetime of only 5 days.

Novec 649 fluid, like all Novec fluids, is also nonflammable and has an excellent toxicological profile – helping to ensure the health and safety of both workers and end-users.

As technologies with low climate impact, such as C_6-fluoroketone, become available, they are likely to increase regulatory pressures on HFCs, potentially limiting the useful life of systems based on these compounds. Companies will have to decide whether it is worth the risk to invest in designs based on HFCs, a currently acceptable alternative subject to regulatory attention, rather than choosing a sustainable technology with low climate impact.

Even though ORC is considered a "non-emissive" application, factors such as leakage, spills, equipment damage and eventual decommissioning/disposal must be taken into account when evaluating the sustainability of a working fluid. The regulatory community generally works from the assumption that a pound produced is a pound emitted and policy reflects that assumption. Although no one can predict what will happen in the future, current regulatory activity is undeniably moving toward reducing greenhouse gases – a critical consideration for engineers concerned about the long-term viability of their systems.

An experienced global partner

For over 50 years, 3M has been providing high performance heat transfer fluids used in a number of critical military, aerospace and electronics manufacturing applications. As a 3M customer, you can put that experience to work for you, with design assistance, testing services and technical support that can help reduce your costs and optimize system performance.

Heat Transfer Seminar/Design Assistance

Given free of charge at qualifying customer sites, this seminar teaches appropriate design procedures by discussing material compatibility, sources of leakage, pumping, component selection, environmental issues and more. The content of these seminars can be tailored to the specific interests of the audience. 3M has conducted seminars at numerous customer locations.

Compatibility Testing

3M engineers can evaluate parts with advanced testing methods to help you determine if a component or material is suitable in your design.

On-Site Consultations

Working side-by-side with equipment designers and end users, 3M engineers frequently help customers tighten-up equipment and optimize system performance.

Analytical Services

3M has state-of-the-art analytical resources which are used to help answer customer questions.

3M Novec fluid products are commercially available and supported by 3M technical service specialists around the world. To arrange for a free Novec fluid sample, or to request more information, contact us at 800-810-8513 in the U.S., or at one of our global locations listed below.

The 3M™ Novec™ Brand Family

The Novec brand is the hallmark for a variety of patented 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, lubricant deposition and several specialty chemical applications.

3M™ Novec™ Engineered Fluids ▪ 3M™ Novec™ Aerosol Cleaners ▪ 3M™ Novec™ 1230 Fire Protection Fluid ▪ 3M™ Novec™ Electronic Coatings ▪ 3M™ Novec™ Electronic Surfactants

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