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M Cooke, P Butcher, M Huguet¹, J Last, C Sborchia¹.

JET Joint Undertaking, Abingdon, Oxon, OX14 3EA.

¹, ITER Naka Joint Work Site, Naka, Japan.

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Organic Cooling Fluids for the JET Toroidal and Divertor Field Coils

M. Cooke, P. Butcher, M. Huguet*, J. Last, C. Sborchia*
JET Joint Undertaking, Abingdon, Oxon, OX14 3EA, UK
*ITER Naka Joint Work Site, Naka Japan

ABSTRACT

When the inter-turn electrical fault was found on the JET toroidal field coil 3.1 a series of studies were carried out to find an alternative cooling fluid to demineralised water with a high intrinsic electrical resistivity. The initial selection examined the physical characteristics of the fluids and ruled out all but three organic compounds. This paper describes the further tests and studies which were carried out to assess the performance and suitability of these organic cooling fluids. The plant implications including storage vessels, vent pipework, pump mechanical seals vapour detection scheme and leak detection are examined together with the waste management and the environmental aspects of using organic cooling fluids.

INTRODUCTION

The proposed change in the Toroidal Field coil cooling fluid for one with a high intrinsic electrical resistivity required the fluid to meet the needs of a high power electrical coil in a radiation environment. The fluid must fulfill the following parameters:

- High intrinsic electrical resistivity.
- Non-flammable, the open cup auto ignition temperature must be well in excess of 350°C. The vacuum vessel operates at this temperature and any risk of fire cannot be tolerated.
- The fluid must withstand the radiation level produced by the JET machine without breaking down, polymerisation or the formation of ions.
- Good heat transfer characteristics to avoid long pulse repetition times.
- The fluid shall be non-toxic and non-carcinogenic.
- The boiling point shall be in the range to give single phase flow at reasonable pressures.
- The viscosity and density shall be such that the existing pumping plant and heat exchangers can be retained.

COOLING FLUIDS

The table below lists the basic physical characteristics of the fluids considered.

When the control parameters are applied to each fluid the conventional heat transfer fluids (silicone liquids, glycols, synthetic oil and mineral oil) are ruled out because of the possibility of fire and auto ignition of a fluid spill on a hot vacuum vessel.

TABLE 1: CHARACTERISTICS OF HEAT TRANSFER FLUIDS

	Density Kg/l	Boiling Point °C	Auto Ignition Temp °C	Viscosity Cst	Thermal Conductivity W/m.k
Water	1	100	-	0.88	0.598
CFC113	1.55	47.7	-	0.41	0.064
C ₆ F ₁₄	1.682	58.2	-	0.39	0.0653
C ₂ Cl ₄	1.62	121	-	0.5	0.06
Glycol	1.113	200	180	20	0.16
HCFC 141b	1.236	32	550	0.35	0.104
Mineral Oil	0.88	190	150	16	0.147
Silicone	0.92	200	62	3	0.105

The non CFC replacement refrigerant for Trichlorotrifluoroethane CCl₂F-CClF₂ (CFC113), namely HCFC 141b, is an aggressive solvent which would not pass the compatibility tests and the vapour is flammable.

The fluids considered suitable for further testing were the three organic cooling fluids C₆F₁₄ perfluorocarbon, CFC113 and C₂Cl₄ perchloroethylene.

COMPATIBILITY STUDIES

All fluids under consideration were subjected to tests for compatibility with the materials which are part of the Toroidal Field cooling loop. The materials tested included, brazed copper joint, EPDM hose, Hypalon hose, epoxy glass, nitrile gaskets and viton gaskets for which the following tests were carried out:

- Absorption and physical dimension change.
- Extraction and change in weight.
- Electrical properties of residue fluid.
- Chemical properties of residue fluid.

The tests with perchloroethylene showed that there was a much larger extraction and absorption than the other fluids and the epoxy glass samples cracked and delaminated (see Fig. 1). It was concluded that any contact of the perchloroethylene with the TF coil insulation could cause serious damage and this fluid was for this reason considered to be not suitable.

The results of the studies with CFC113 showed that the original EPDM hose material had a greater absorption than the Hyperlon hose. It was therefore recommended that the hose material be changed from EPDM to Hyperlon. The results of absorption, extraction and electrical properties of all samples with CFC113 were acceptable and the fluid was considered to be compatible. The results with C₆F₁₄ indicated that the loss tangent was adversely effected when in contact with epoxy glass, hyperlon hose and the brazed copper joint. The resistivity was however only slightly lower than the original stock fluid.

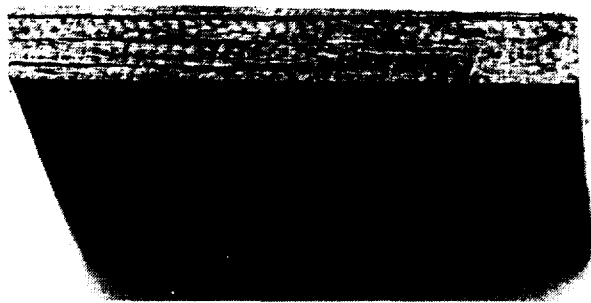


Fig. 1: Compatibility of Epoxy Glass with Perchloroethylene

IRRADIATION STUDIES

Samples of the three organic fluids were γ irradiated to the equivalent dose of the active phase of JET 1.5Mrad for C_6F_{14} 1Mrad for CFC113 and 0.73Mrad for perchloroethylene. The difference in levels is due to a weighting factor which has been applied for the elemental composition of each fluid.

The samples were tested under two separate conditions. The first tests were carried out with sealed glass containers, with air above the fluid and with and without copper pieces present. The second tests were carried out with sealed glass containers with nitrogen above the fluid and with copper pieces present. In addition the samples were subjected to much higher radiation levels i.e. 60Mrads to check for signs of breakdown or polymerisation.

After irradiation the samples were checked for signs of polymerisation, the formation of copper, chlorine or fluorine ions, the composition of the breakdown gases or compounds and any change in physical properties i.e. viscosity, thermal conductivity resistivity.

TABLE 2: IRRADIATION RESULTS

Fluid	With Cu	Irrad time/ mins	dose rate/ kGy/h	Dose/ kGy	[F-]/ $\mu\text{g/g}$	[Cl-]/ $\mu\text{g/g}$	[Cu]/ $\mu\text{g/g}$
Samples Sealed With Air							
C_6F_{14}	Yes	9850	3.45	906.20	260	<1	<=0.005
C_6F_{14}	Yes	340	2.45	22.21	110	<1	0.006
C_6F_{14}	No	9850	2.76	724.96	280	15	<0.005
C_6F_{14}	No	340	2.47	22.39	130	<1	<0.005
C_2Cl_4	Yes	28	2.45	1.83	2	5	5.3
C_2Cl_4	Yes	170	2.45	11.11	<1	130	n.m
C_2Cl_4	No	28	2.47	1.84	2	130	<0.005
C_2Cl_4	No	170	2.47	11.20	<1	200	<0.005
CFC113	Yes	9850	2.47	648.79	110	100	0.62
CFC113	Yes	242	2.45	15.81	110	70	0.15
CFC113	No	9850	2.74	719.71	130	70	<0.005
CFC113	No	242	2.47	15.94	110	100	<0.005
Samples Sealed With Nitrogen							
CFC113	Yes	180	3.04	9.12	4	20	<0.002
C_6F_{14}	Yes	180	3.04	9.12	3	0.5	<0.002
C_2Cl_4	Yes	180	3.52	10.56	2	15	1.4

The analysis of the results indicated the following:

- None of the fluids broke down even when the samples were subjected to the higher level 60Mrads.
- Polymerisation did not occur with either CFC113 or C_6F_{14} however small signs of precipitation or polymerisation did occur with perchloroethylene. This was thought to be due to the stabiliser compound added to the fluid.
- With air or oxygen above the sample there were signs of copper oxide forming on the copper samples. This observation reinforced the decision to use nitrogen as the pressurisation gas in vessels and pipework.
- The irradiation did not effect the viscosity, thermal conductivity or resistivity of the fluids.
- There were no measurable quantities of copper chlorine or fluorine ions as a consequence of the irradiation.
- Without the presence of oxygen or water the breakdown products take the form of free radical carbon, chlorine or fluorine atoms.

ACTIVATION CALCULATIONS

The activation of the three organic fluids was calculated using a neutron flux model of the JET machine. The calculations allowed for the quantity of fluid within the coils during a ten second energy pulse, a total neutron production of 10^{24} neutrons for the whole D-T operation phase and 10^{20} neutrons for D-D operation.

During the non-active phase of the machine access to the cooling plant for maintenance of the equipment in the basement will not require any controls from Health Physics. Unless there is a leak of coolant then the area around the leak will be a controlled area.

The basement plant room will be equipped with γ monitors and in the active phase access will normally be allowed 24 hours after the last pulse when the radiation level due to the activation of CFC113 would be $10\mu\text{Sv/h}$ or for C_6F_{14} $14\mu\text{Sv/h}$. In the event of a leak or other emergency, access immediately after a pulse can be considered for short durations only (controlled entry) since the dose rate would be 160mSv/h with CFC113 or 560mSv/h with C_6F_{14} .

A sample of CFC113 was taken at the end of the last operating campaign and the radioactivity measured. The results showed a reduced activity compared with the calculations by a factor 4.4. Measurements of β emission were also made on the inside surface of the stainless steel pipework to assess the plating out of activity on the oxide surface layer. The measurements indicated that 25% of the activity was plated out on the surface of the pipework.

A test was carried out to find what proportion of the activity would be held in the molecular sieve of the system drier. A test rig was manufactured including a small drier with the same molecular sieve materials as the system drier. The active fluid was circulated in the test rig for a time corresponding to a year of operation. The results indicated a reduction in activity by a factor of 4.7.

A further experiment was carried to see if the activation products P^{32} and S^{35} etc.would remain on the floor of the

TABLE 3: PREDICTED ACTIVATION AND HALF LIFE

Iso- tope	Production Reaction	1/2-Life	Gamma Rays (MeV)	Activity at Shutdown (Bq/g)		Gamma-Ray Dose-rate (μ Sv/h)		Activity at Shutdown (Bq/g)		Gamma-ray Dose-rate (μ Sv/h)		Activity at Shutdown (Bq/g)		Gamma-ray Dose-rate (μ Sv/h)	
				CFC113				Perfluorocarbon C ₆ F ₁₄				Perchloroethylene C ₂ Cl ₄			
				D-T	D-D	D-T	D-D	D-T	D-D	D-T	D-D	D-T	D-D	D-T	D-D
Be ¹⁰	C ¹³ (n,d)	2.5 x 10 ⁶ y	-	1.5, -3	-	-	-	4.7, -3	-	-	-	1.2, -3	-	-	-
C ¹⁴	C ¹³ (n, γ)	5.7 x 10 ³ y	-	3.3, -3	6.7, -7	-	-	1.0, -2	2.1, -6	-	-	2.6, -3	5.4, -7	-	-
F ¹⁸	F ¹⁹ (n,2n)	110m	0.51	4.3, 5	-	1.2, 5	-	2.0, 6	-	5.6, 5	-	-	-	-	-
P ³²	Cl ³⁵ (n,2n)	14.3d	-	6.4, 5	2.0	-	-					6.9, 5	1.8	-	-
P ³³	Cl ³⁷ (n,na)	25d	-	3.4, 3	-	-	-					3.8, 3	-	-	-
S ³⁵	Cl ³⁵ (n,p)	88d	-	1.1, 6	1.7, 2	-	-					1.2, 6	1.8, 2	-	-
Cl ³⁶	Cl ³⁵ (n, γ)	3.1 x 10 ⁵ y	0.51	6.4, 1	6.7, -3	-	-					6.9, 1	7.2, 3	-	-
Cl ³⁸	Cl ³⁷ (n, γ)	37m	2.1	1.0, 5	2.1, 1	4.3, 4	8.4					1.1, 5	2.3, 1	4.6, 4	9.4

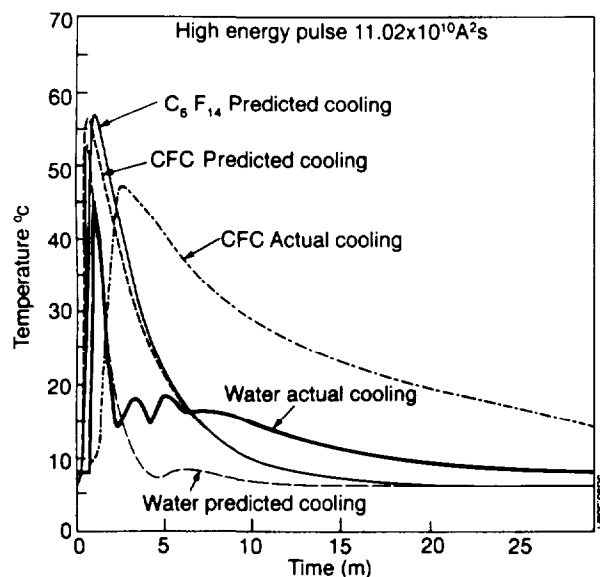
Note: 1.5, -3 = 1.5 x 10⁻³

Torus Hall when evaporation occurred of any CFC113 spill. A small quantity of CFC113 was heated in a flask and then recondensed in a liquid N₂ cold trap. After total evaporation the results showed that the level of S³⁵ was reduced by a factor 4. The result confirmed that the radioactive activation products would not become airborne.

COOLING PERFORMANCE

The predicted cooling performance of water CFC113 and , C₆F₁₄ for a typical high energy TF pulse (67kA current 12 second flat top, energy 106 10⁹A²s) are shown below together with the actual curves for demineralised water and CFC113 cooling.

The CFC113 cooling flow rate is less than that for water. This was brought about by the necessity to keep the absorbed power the same when the fluid was changed and the pump impeller was ground to the new pump duty point.



Predicted and Actual Cooling Curves

PLANT CONSIDERATIONS

The use of an organic fluid necessitated mechanical design changes to ensure a totally sealed closed loop system with storage vessels, drainage vessel and expansion tank. The vent pipe from each vessel and the crown distribution pipes on the top of the machine are linked together to ensure the transfer of vapour during any draining or filling operation without any release to the atmosphere.

To give the maximum integrity to the system, all valves were kept to a minimum and the pipework was fully welded. The most vulnerable item, the hoses connecting the manifolds to the coils, were changed to "Hyperlon" material after the compatibility tests indicated that EPDM was not suitable and connected with hydraulic screw connectors in preference to the Rafix push-on connectors. The shaft seals on the main circulating pumps were changed to a double carbon silicon carbide seal with the interspace filled with a heat transfer oil. The oil has a pressure 1 bar gauge greater than the pump discharge pressure to ensure no leakage of CFC113 to the plant room atmosphere. The individual pumps for the divertor coils are magnetically coupled sealless units and the control valves have bellows shaft seals to reduce further the possibility of a leak.

The control system was designed with relay logic and the supplies connected to a uninterruptible power supply. Should a leak occur at a hose or joint the system automatically drains into the storage vessels. The drainage sequence is initiated by either a very low level switch in the expansion vessel or an individual CFC113 reading above 2000ppm on the analyser panel. The liquid from the spill would be collected in the floor drainage system and then pumped to a separate storage vessel. After a clean up operation the vapour remaining would be released to the atmosphere. However a cryogenic trap in the Torus Hall cell and basement ventilation discharge duct, is currently under design for installation during the next shutdown. When commissioned any CFC113 vapour from a spill together with the atmospheric water vapour would be condensed and piped to a storage vessel.

ENVIRONMENTAL ASPECTS

All organic fluids have an impact on the environment either as a greenhouse gas or are ozone depleting.

The production of CFC chemicals has been the subject of world wide discussions and recommendation for many years because of the ozone depletion properties. The current recommendations follow the Montreal, London and Copenhagen protocols which state that production should stop by the year 2000. Recent EEC directives have brought this date forward to 1997 and the UK has declared an earlier date of 1st January 1994. Although production will cease all existing stocks and user applications are considered in environmental terms to have been released into the atmosphere.

The fluids considered are all greenhouse gases and because of their inert nature remain in the atmosphere for many years. The lifetime in the atmosphere for CFC113 is 111 years and for C₆F₁₄ perfluorocarbon is up to 2000 years. There are no recommendations or legislation on the use of chemicals that are greenhouse gases. However, the recent proposal by the EEC to introduce a carbon tax to reduce greenhouse gas emission and also the fact that global warming and greenhouse gases was on the agenda of the Earth summit does mean it will become a major environmental issue. Some major chemical manufacturers no longer produce perfluorocarbons because of the global warming potential.

WASTE MANAGEMENT

At the completion of the active phase all fluid will be drained from the coils and pipework into the main 63m³ storage vessel. Assuming the neutron production will be 10²² neutrons and allowing a plating out factor of 10 the CFC113 would contain two prominent isotopes Cl³⁶ at a level of 6.4 x 10⁻³Bq g⁻¹, half life 3 x 10⁵ years and S³⁵ at a level of 1.1 x 10³Bq g⁻¹, half life 88 days.

The activity prohibits the re-use of the fluid as a feed stock for a different compound and the final waste management route will be disposal by high temperature incineration. In order to achieve the activation level at which the disposal company has a license to operate of 11Bq g⁻¹ it will be necessary to store the fluid on site for approximately two years. This delay would not occur with the use of the perfluorocarbon C₆F₁₄ as the activation level is below 11Bq g⁻¹ in a matter of hours.

FLUID SELECTION

The compatibility studies showed that perchloroethylene was not a suitable fluid because of the high extraction and eventual cracking of epoxy glass. Also there were signs of polymerisation of this fluid when irradiated.

The remaining two fluids which were studied in detail CFC113 and C₆F₁₄ have similar physical properties, radiation tolerance, and heat transfer abilities. They both have an impact on the environment although there is no current legislation on the future use of perfluorocarbon compounds

there is however a limit on the manufacture of CFC compounds of the 1st January 1994.

The activation products of CFC113 have a much longer half live than C₆F₁₄ and the concern of an activated CFC vapour release to the atmosphere must be accomodated in the plant design. Perfluorocarbon has a higher storage tank surface radiation dose rate than CFC113 which may restrict immediate access to the plant room in the event of a fault. The purchase cost of CFC113 was £1 kg⁻¹ when supplied to JET for the non-active phase. The cost to change to perfluorocarbon C₆F₁₄ for the active phase would be an additional £1.3 x 10⁶ assuming the circuit volume was reduced to 38m³ with pipework size changes and route modifications and the current cost of C₆F₁₄ of £20 kg⁻¹.

The final selection was made for the active phase to use CFC113 for which there is now operational experience and install the necessary plant modifications to condense any activated vapour that may be released.

CONCLUSIONS

The use of CFC113 as a coolant for the TF coils has shown that reasonable cooling efficiency has been achieved with a fluid with a high intrinsic electrical resistivity. There have been no operational restrictions with the new coolant and an interpulse time of between 15 to 25 minutes has been achieved for standard pulses. For high energy pulses 106.10⁹ A²s current of 67kA and a 12 second flat top a interpulse time of 24 minutes was maintained for consecutive pulses. This interpulse time is very similar to that for demineralised water since the cooldown time for high energy pulses is determined by the capacity and control sequence of the chiller plant on the primary site water rather than the thermal properties of TF coolants.

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