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A. Suppan, M. Englert, A. Rahn

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*Ingenieurbüro für technische Kybernetik

**FZK-AG Mol

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ABSTRACT

The articulated boom system (ABS) is an optional part of the basic equipment to maintain in-vessel components of the NET/ITER fusion device during shutdown phases. Due to the high γ-radiation and after-heat of the activated components in-vessel handling equipment is subject of degradation which limits the lifetime of the equipment and thus also its availability due the necessary equipment maintenance. It is the aim of irradiation tests to provide the basis for the qualification of radiation and temperature sensitive equipment components by modification of standard components in collaboration with the suppliers in order to enhance their life expectancy.

Besides sensors, resolvers, electronic and optical components which are not subject of this document, motors and related components are the most sensitive elements and were tested in an extensive program. The results of the experiments leading to a motor radiation hard up to 80 MGy-Si at winding temperatures of 250°C are described in this document.

Bestrahlungstests von Antriebsmotoren für Handhabungssysteme in radioaktiv belasteter Umgebung

ZUSAMMENFASSUNG

Das Vielgelenkarmsystem (ABS) gehört zu den möglichen Komponenten einer Grundausrüstung, um Anlagenteile instandhalten zu können, die innerhalb des Vakuumgefäßes der NET/ITER Fusionsmaschine angeordnet sind. Infolge der hohen γ-Strahlung und Nachwärme der aktivierten Komponenten sind das ABS und seine Bauteile Belastungen ausgesetzt, die ihre Lebensdauer einschränken und wegen ihrer notwendigen Instandhaltung die Verfügbarkeit der Anlage verringern. Es ist das Ziel von Bestrahlungstests, eine Grundlage zur Verbesserung von strahlungs- und temperaturempfindlichen Fernhantierungskomponenten zu schaffen und somit deren Lebensdauer zu erhöhen. Dies erfolgt durch die Modifikation von Standardkomponenten in Zusammenarbeit mit den Herstellern.

Neben Sensoren, Resolvern, elektronischen und optischen Komponenten, die nicht Gegenstand dieses Berichtes sind, zählen Motoren und deren Komponenten zu den empfindlichsten Bauteilen. Sie wurden daher in einem ausgedehnten Versuchsprogramm getestet. Die Ergebnisse der Experimente sind in diesem Bericht beschrieben.

This report has been performed in the framework of the Nuclear Fusion Project of the Forschungszentrum Karlsruhe, Technik und Umwelt, and was supported by the European Communities within the European Fusion Technology Program. The work was carried out in collaboration with CEN/SCK Mol, Belgium

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ABBREVIATIONS

ABS	Articulated Boom System
ABT	Articulated Boom Transporter
EDITH	Experimental Device for In-Torus Handling
EEPU	End-Effector Positioning Unit
IVH	In-Vessel Handling
IVHU	In-Vessel Handling Unit
tbd	to be determined

1 INTRODUCTION

The applicability of in-vessel equipment as an ABS and its subsystems like the articulated boom transporter (ABT) and the end-effector positioning unit (EEPU) /1/ asks for γ-radiation and temperature hard components to fulfil a minimum lifetime of 1000 hours. Motors are such sensitive components and has been tested and modified to fulfil the requirements.

Table 1 shows the NET /2/ and ITER requirements for motors and related components. The requirements differ in the aspired lifetime and thus also in the integral γ-dose.

Table 1: NET/ITER Requirements for Radiation- and Temperature-Hard Components

	NET-Requirements	ITER-Requirements	
		earlier	now
Temperature outside the vacuum vessel	≥20°C	≥20°C	
Temperature inside the vacuum-vessel during maintenance	≤150°C	≤150°C	50°C
Atmosphere	He (tbd) or air (humidity tbd)	He (tbd) or air (humidity tbd)	
Pressure	approx. 1 atmosphere	approx. 1 atmosphere	
Radiation	approx. 30 Kgy/h-Si γ, average energy 1 MeV	approx. 30 KGy/h-Si γ, average energy 1 MeV	
Lifetime	300 hours	1000 hours	3000 hours
Total γ-dose	10 MGy-Si	30 MGy-Si	100 MGy-Si
Contaminated dust	tbd	tbd	
Magnetic field	negligible	negligible	

2 TECHNICAL SPECIFICATION OF MOTORS

2.1 Technical Consideration for the Selection

For the selection of motors different motor principles have been compared with respect to their behavior properties and the specified requirements and environmental conditions, respectively. The best suited type is an AC brushless servo-motor.

The compared motor types were DC brush motors, DC brushless motors, AC brushless (permanent excitation, induction) servo-motors and stepper motors. The selection criteria were:

- Speed range where the torque is almost constant. This is required to achieve almost constant torques over a wide speed range.
- Performance characterized by the ratios power to size, torque to size and power to inertia.
- A high ratio of peak torque versus continuous torque as it is available at brushless motor types reduces a necessary oversizing of the motor. Duration and admissible overloads torques of brushless motors are only limited by the power transistor bridge and the thermal protection logic.
- The compatibility of brushless motors with high temperatures (approx. 250°C winding temperature) is relatively good due to its inside-out design which supports the temperature dissipation. The compatibility with γ-irradiation depends on the selection and has mainly be based on experience available from CERN and additional irradiation tests of base materials.
- At brushless AC servo-motors the motor control is more complex than at other motors due to the needed electronic commutation by means of a brushless rotor position transducer. On the other hand commutation brushes at DC motors require scheduled replacement.

Table 2 gives an overview about the motor properties and the explanation for the selection of AC brushless servo-motors to be modified for the in-vessel equipment.

Table 2: Valuation of Motor Candidates

	Brush-type motor	Brushless DC/AC motor	Induction motor	Stepper motor
• Speed range	++	+++	+++	++
• Power density	++	+++	++	+
• Peak torque	++	+++	+++	-
• Overload behavior	+	++	+++	-
• Environment compatibility	+	++	++	+++
• Thermal performance	-	+++	+	++
• Controller complexity	+++	+	-	++
• Power transmission cables	+++ (2)	++ (4)	++ (4)	- (6)
• Small wiring	+ (0-8)	- (6)	- (6-8)	+++ (0)

2.2 Market Analysis

Based on the specified requirements and following selection of the best suitable motor type only the companies Maccon (Inland-Kollmorgen, Hathaway) and Moog were able and willing to deliver modified motors according our specifications.

After the selection of the best suitable motor type companies were asked to offer such motors taking into account modifications according our design and basic materials specifications. Only two of about 25 companies were able and willing to deliver such motors. Three motors of each of these two companies were ordered. The addresses of the companies are:

Maccon GmbH
Kühbachstraße 9
D-81543 München

Moog GmbH
Hans-Klemm-Straße 28
D-71034 Böblingen

2.3 Technical Description of the Selected Motors

Required motors for the drive units of the ABT are AC brushless servo motors with a continuous stall torque of approximately 22 Nm and a nominal speed of about 2000 rpm. Since the irradiation test rig has a limited space not large enough for ABT motors smaller ones have been selected and tested which are of the same type and fulfill the same environmental requirements. In particular these are the type MT02306 from Maccon and the type D313-L25 from Moog.

Table 3 shows a comparison of both the motor to be applied at the drive units of the ABT and the motor which has been irradiated and tested.

Table 3: Data of ABT Drive Unit Motors and Test Motors

	ABT motor Moog 315-L50	Test motors Moog 315-L25	Test motors MT 02306
Continuous stall torque	22 Nm	2.3 Nm (ΔT=100K)	1.1 Nm (ΔT=100K)
Nominal torque	12 Nm	1.8 Nm	0.9 Nm
Peak torque	60 Nm	6.9 Nm	10.2 Nm
Continuous stall current	17.5 A	4.8 A	3.6 A
Nominal current	9.5 A	3.75 A	2.95 A
Peak current	47.6 A	14.4 A	29.7 A
Continuous no-load speed	2200 rpm	5200 rpm	5000 rpm
Nominal speed	1750 rpm	4200 rpm	2800 rpm
Torque constant	1.45 Nm/A	0.55 Nm/A	0.35 Nm/A
Motor resistance	0.55 Ω	3.78 Ω	3.9 Ω
Motor inductance	5.32 mH	8.32 mH	4.3 mH
Rotor inertia	20.6 kgcm^2	0.66 kgcm^2	0.8 kgcm^2
Mech. time constant	0.54 ms	0.87 ms	2.5 ms
Electr. time constant	9.7 ms	2.2 ms	1.2 ms

For identification purposes the test motors are listed in Table 4 and Table 5.

Table 4: Identification Data of Maccon Motors

KfK-code	Maccon 1	Maccon 2	Maccon 3
Supplier / producer	Hathaway Cooperation, Tulsa, Oklahoma, USA / Maccon GmbH München		
Characteristics	AC brushless servo-motor (electronically		

	commutated three phase motor with permanent magnet excitation)		
Type	HT 02306 / MT 02306		
Serial Nr.	SN 2	SN 3	SN 1
Date code	2/90	2/90	2/90

Table 5: Identification Data of Moog Motors

KfK-code	Moog 1	Moog 2	Moog 3
Supplier / producer	Moog GmbH, Böblingen		
Characteristics	AC brushless servo-motor (electronically commutated three phase motor with permanent magnet excitation)		
Type	D313-L25 (E041, M0-I0-UD31VDC)		
Serial Nr.	D1	D3	D2
Date code	18.9.90	27.9.90	18.9.90

2.4 Cables and Connectors

All single wires and cables are KAPTON insulated and delivered by ISOTEC-KABEL GmbH (earlier: RADOX insulated by SUHNER). The cable covering consists of Kapton foil and glass silk fabric.

Power transmission	4x0.75 mm^2
Resolver signal transmission	6x0.22 mm^2, twisted and shielded in pairs
Brake	2x0.5 mm^2
Thermistor	2x0.22 mm^2

The plug and socket connectors were equipped with a PEEK insulating body (LEMOSA GmbH).

3 SPECIFICATION OF THE TESTS

3.1 Motor Tests Overview

In general three type of tests have been performed to evaluate the temperature and radiation behavior of the motors /3/. Pre-irradiation tests to confirm the basic motor data and to obtain additional reference data for comparison with the data measured at the post-irradiation tests. During the irradiation tests only some additional measurements without loads have been carried out. Post irradiation tests after different integral doses have been performed as qualitative and/or quantitative tests. The

difference of the measured data at pre- and post-irradiation tests should have not exceeded 15%.

Pre-irradiation tests are out-of-pile tests performed prior to the irradiation. The results of these tests serve as basic data for the identification of motor behavior changes caused by irradiation and temperature. Some of these data which determine functionality and behavior of the motors, e.g. insulation, dynamics, efficiency, torque etc. have been provided but only for temperatures of about 20 to 30°C. They are also required for the NET/ITER typical maintenance temperature of 150°C. Therefore, it is necessary to determine them and additional required data in pre-irradiation tests at different temperatures.

Due to the IVH ambient temperature of 150°C (according to the NET/ITER requirements) it have to be taken into consideration that the motor temperature will reach about 250°C during in-vessel operation. Therefore, the pre- and post-irradiation tests should also show the changes of the motor performance due to temperature and prove the temperature resistance of the motors and the related components, as well.

The following data are characterizing motors and are therefore subject of the measurements:

- Characteristic current-torque line
- Characteristic torque-speed line
- No-load speed and no-load current
- Terminal resistance
- Insulation resistance
- Braking torque and current consumption of the fail-safe brake

For detailed information see the report "Gamma Irradiation Tests with Motors for the NET/ITER In-Vessel Handling Equipment" /6/.

Irradiation tests have been performed in a test rig at the BR2 at MOL in responsibility of CEN/SCK. The irradiation conditions are listed in Table 6.

Table 6: Irradiation Conditions

Temperature	150±5°C
Maximum coil temperature	180°C
γ-dose rate	30 KGy/h-Si
Complete motor test consisting of measurement of motor current at different speeds and measurement of speed at different motor torques	1/day
Long run tests consisting of current measurement at 3000 rpm	1/day
Additional measurement consisting of measurement of terminal and insulation resistance	1/week

Post-irradiation tests have been performed in the same way as the pre-irradiation tests. The results of the measurements have been compared with those of the pre-irradiation tests and with the acceptable deviation, defined as 15% of the basic data.

3.2 Test Equipment

Two different test devices were used. The one consisting of a magnetic powder brake in combination with a heating chamber and the data acquisition applied for the pre- and post-irradiation tests. The irradiation tests have been carried out in a test rig inserted at the BR2 at MOL. The test rig has been equipped with a data acquisition for measure and record the irradiation data and results during the in-situ measurements.

The **device for the pre- and post irradiation tests** consists of a magnetic powder brake (shown in Fig. 1) mounted on a frame. The brake can be coupled by means of a clutch with the motor to be tested. The motor itself is surrounded by a heating chamber (shown in Fig. 2) equipped with thermocouples to achieve ambient temperatures up to 200°C. The control and data acquisition system rack is shown in Fig. 3. The motors and the load brake as well are digitally speed and torque controlled. All necessary mechanical, electrical and thermal data are measured and recorded by the data acquisition system.

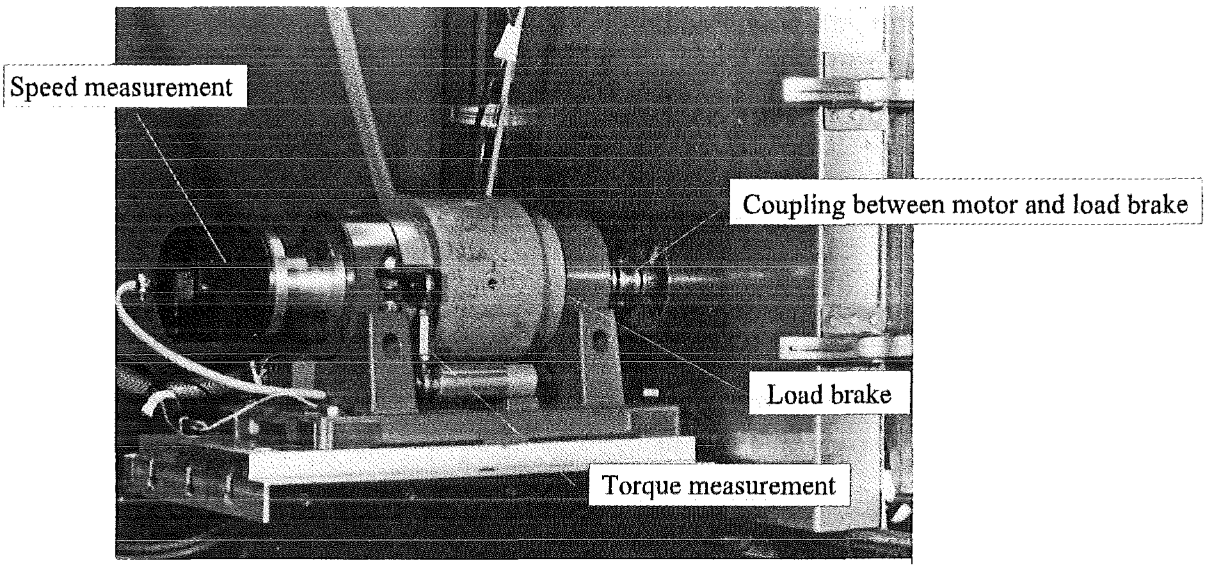

Fig. 1: Magnetic powder brake

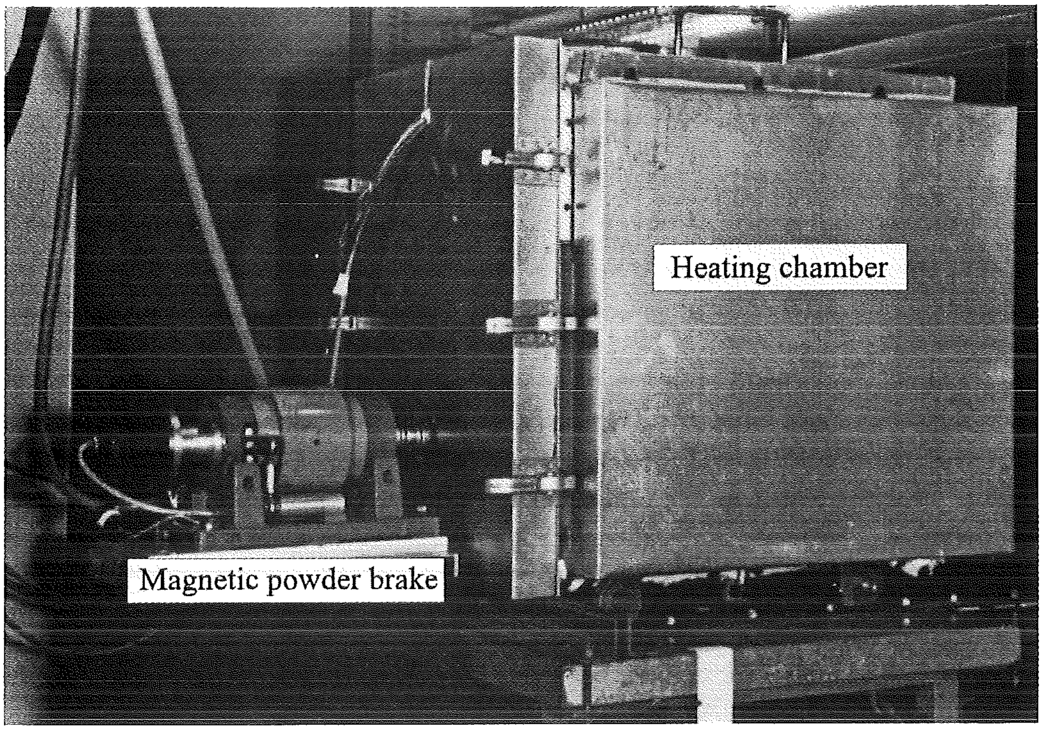

Fig. 2: Arrangement of the equipment for the pre- and post-irradiation tests

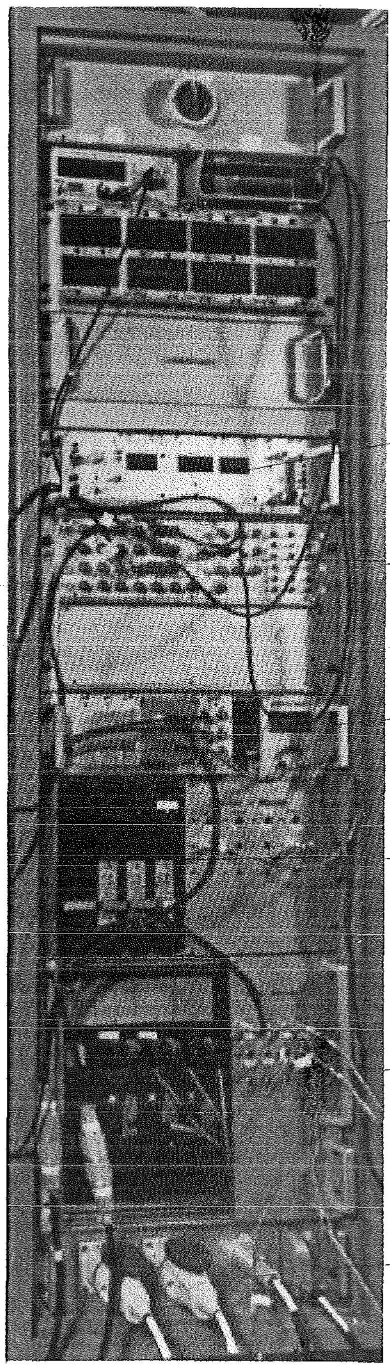

Fig. 3: Control and data acquisition rack

The γ-irradiation facility is located under water in the CMF pool of the BR2-reactor at MOL and is surrounded by 6 spent fuel elements (see Fig. 4/Appendix). The general layout of the test rig is depicted in Fig. 5 (Appendix). The rig is a leak-tight container under controlled atmosphere, containing an inner tube for the heater and the basket for the motors (see Fig. 6/Appendix). It is swept by Nitrogen. The temperature is controlled by thermocouples. Instrumentation-, power- and gas lines routed in two flexible hoses provide the link with the control equipment. The calculated γ-dose rate is measured directly by RED PERSPEX dosimeters which are located at different levels inside a dummy rig. The measurement has been performed before the start of motor irradiation.

The arrangement of the motors inside the basket during the irradiation and the online measurements is shown in Fig. 7 with two test motors and in Fig. 8 with only one motor.

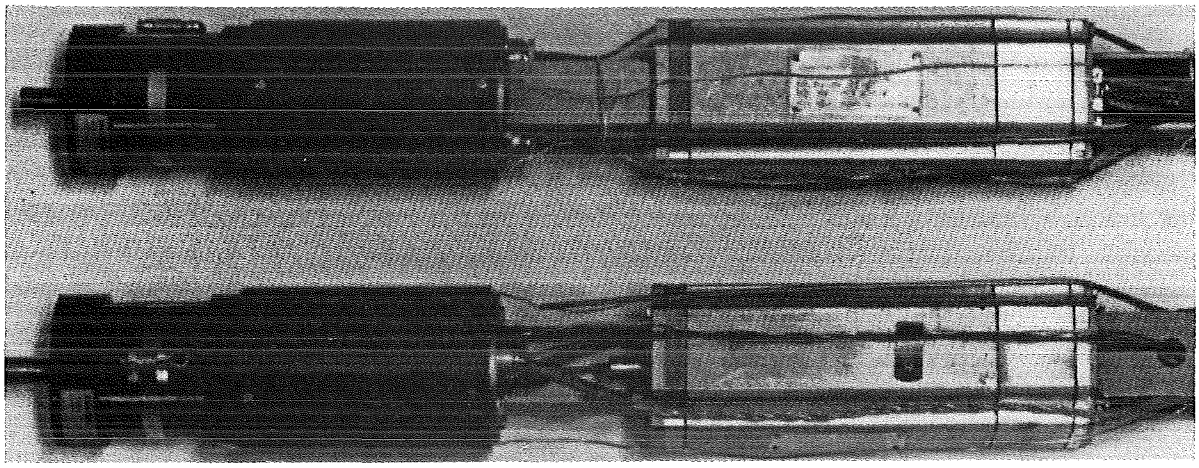

Fig. 7: Arrangement of two motors inside the basketduring the irradiation

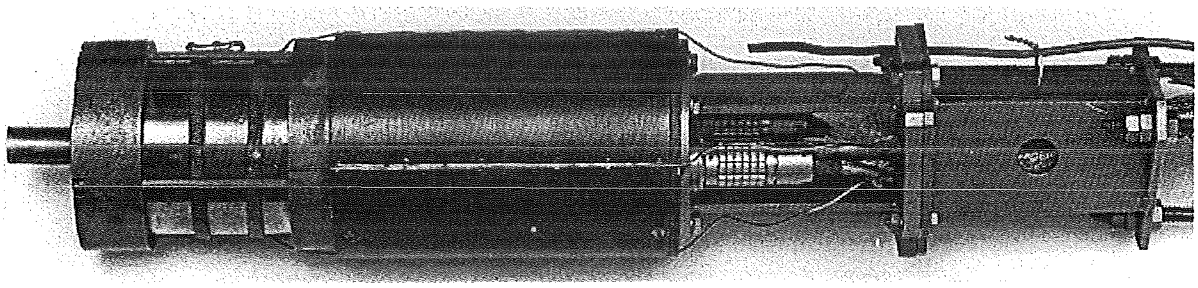

Fig. 8: Arrangement of one motor inside the basketduring the irradiation

For further informations see /6/, /7/, /8/, /10/, /11/, /12/.

4 TEST RESULTS

4.1 Pre-Irradiation Tests

During the whole test period difficulties with the fail-safe brakes happened at all motors due to temperature effects. The Moog 3 motor failed completely by sticking of a bearing.

From time to time the fail-safe brakes could not be unlocked. This might be caused by adhering of rotor and stator (temperature effect).

At Moog motors problems occurred by adjusting of the air gap for the brakes. The reason was that the thermal expansion of the aluminium motor housing has been twice the expansion of the steel rotor shaft. Since the stator of the brake has been coupled with the motor housing rigidly, the air gap of the brake changed with the motor temperature. Therefore, dependent on the motor temperature a safe locking and unlocking of the brake, respectively has not been possible. Improvement is possible by changing the arrangement of the brakes and/or changing the material of the motor housing.

At the high temperature tests the Moog 1 motor failed due to an irreversible expansion of a bearing outer ring caused by a microstructure change of the material at a temperature of 250°C. The variation was sufficient to stick the bearing's outer ring (a steel socket shrinked in the aluminum housing). The bearing balancing movement in axial direction, necessary with respect to the different thermal expansion of the aluminum motor housing and expansion of the steel shaft, was not possible any more. Consequently, the motor has been deformed mechanically and caused a damage of the bearing. The problem can be solved by using special high temperature bearings with less thermal expansion.

Table 7 shows the history of the pre-irradiation tests of the motors.

Table 7: History of Pre-Irradiation Tests

Date	Moog 1	Moog 2	Moog 3	Maccon 1	Maccon 2	Maccon 3
10/90	Start of pre-irradiation tests	Start of pre-irradiation tests	Start of pre-irradiation tests	Start of pre-irradiation tests	Start of pre-irradiation tests	Start of pre-irradiation tests
11/90		Fail-safe-brake failure (temporarily)	Winding failure, irreparable, **End of Test**		Fail-safe brake failure, transportation to Maccon	
12/90	Bearing and fail-safe brake failure, transportation to Moog					
01/91					Delivery of repaired motor, continuation of motor tests	

02/91	Delivery of repaired motor, continuation of motor tests					
03/91	End of pre-irradiation tests	End of pre-irradiation tests		End of pre-irradiation tests	End of pre-irradiation tests	End of pre-irradiation tests

Due to several problems with the motors under high temperature conditions, not all specified measurements have been carried out.

Because of unsuitable fail-safe-brakes, the Maccon motors were only tested up to maximum motor temperature of 180°C during the pre-irradiation tests.

The major results of the pre-irradiation tests are listed in the following Table 8. For further informations see /4/.

Table 8: Major Results of the Pre-Irradiation Tests

	MOOG 1	MOOG 2	MOOG 3	MACCON 1	MACCON 2	MACCON 3
Continuous Stall Torque at an ambient temp. of 25°C and ΔT=100K	2.3 Nm	2.4 Nm	2.55 Nm	1.22 Nm	not measured	1.09 Nm
Continuous Stall Torque at an ambient temp. of 100°C and ΔT=100K	2.25 Nm	2.35 Nm	1.95 Nm	not measured	not measured	not measured
Continuous Torque at 3000 UPM at an ambient temp. of 25°C and ΔT=100K	2.05 Nm	1.95 Nm	2.1 Nm	0.76 Nm	not measured	0.93 Nm
Continuous Torque at 3000 UPM at an ambient temp. of 100°C and ΔT=100K	1.85 Nm	1.75 Nm	1.7 Nm	not measured	not measured	not measured
Rated Power at an ambient temp. of 25°C and ΔT=100K	840 W	710 W	780 W	250 W	not measured	290 W
Rated Power at an ambient temp. of 100°C and ΔT=100K	700 W	630 W	660 W	not measured	not measured	not measured
Torque Constant at 150°C	not measured	0.53 Nm/A	0.52 Nm/A	0.32 Nm/A	0.29 Nm/A	0.31 Nm/A
Insulation of motor windings	> 2 GΩ	> 2 GΩ	> 2 GΩ	> 2 GΩ	> 2 GΩ	> 2 GΩ
Insulation of resolver windings	> 2 GΩ	> 2 GΩ	> 2 GΩ	> 2 GΩ	> 2 GΩ	> 2 GΩ

4.2 1st Irradiation Campaign

For implementation of the irradiation tests the motors have been transported to CEN/SCK, Mol on March 1991.

At the Mol experiment F2-1 during the 1st irradiation campaign the Maccon 3 motor has been irradiated. From the irradiation beginning a frictional and temperature increase has been observed which became significant after an irradiation time of 41 hours and an integral dose of 1.4 MGy-Si. After this partial blockage of the motor which was caused by a motor bearing the irradiation tests have been continued with a modified program up to 3.5 MGy-Si. No electrical effects have been detected.

The history of the MOL F2-1 experiment is shown in Table 9 /7/.

Table 9: History of the MOL F2-1 Experiment

Date	Moog 1	Moog 2	Moog 3	Maccon 1	Maccon 2	Maccon 3
23/04/91						Start of irradiation
25/04/91						Partial blockage of the motor during on-line measurements
28/04/91						End of irradiation tests at 3.5 MGy-Si **End of Test**

Within the frame of the 2nd irradiation campaign at the Mol experiment F2-2 the Moog 1 motor and the Maccon 1 motor have been irradiated. After an irradiation time of 22 hours and an integral dose of 0.8 MGy-Si a total blockage of the Maccon motor happened. It has been observed that the frictional resistance of the motor increased and finally the motor blocked due to a sticking of a bearing. It can be stated that neither the brake nor an electrical defect has been the reason for the blockage. The Moog motor showed a constant behavior during 178 hours of irradiation and up to an integral dose of 5.9 MGy-Si. Then a blockage happened. Current and temperature increased. The blockage was neither caused by the brake nor by an electrical defect but by released fixing screws of the motor resolver inside the motor housing. The released screws blocked the rotor of the fail-safe-brake mounted at the end of the motor shaft. The rotor of the brake has been mechanically damaged due to this fact. Fig. 9 shows the damaged dismantled rotor.

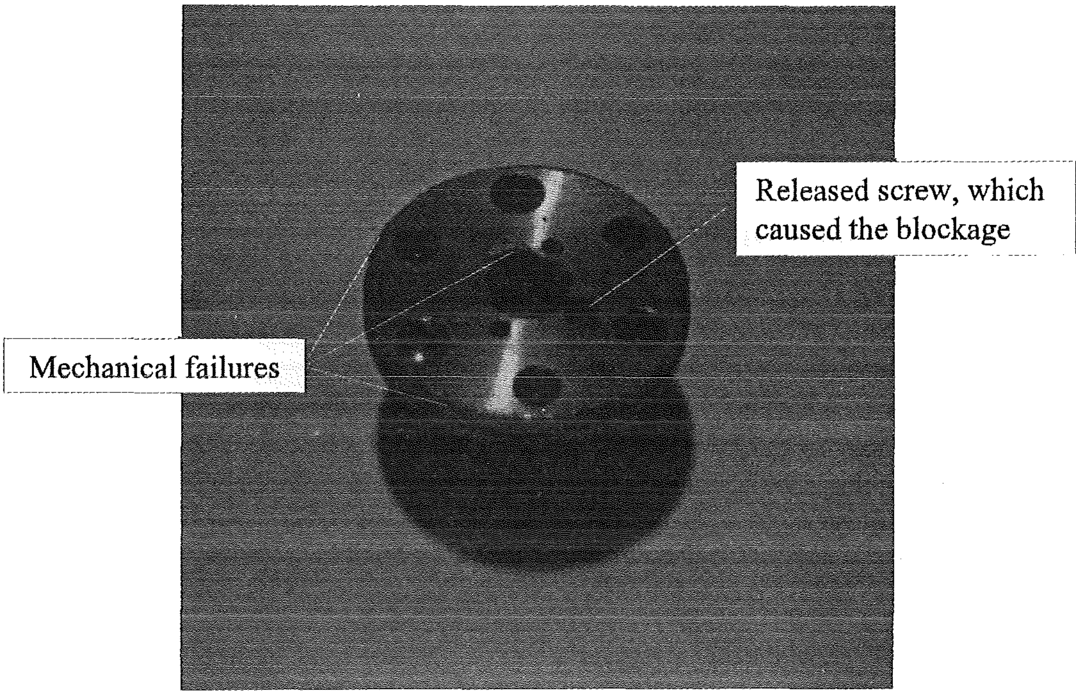

Fig: 9: Damaged rotor of the fail-safe-brake of the Moog motor

The history of the Mol F2-2 experiment is shown in Table 10 /8/.

Table 10: History of the Mol F2-2 Experiment

Date	Moog 1	Moog 2	Moog 3	Maccon 1	Maccon 2	Maccon 3
16/05/91	Start of irradiation			Start of irradiation		
17/05/91				Total blockage of the motor at 0.8 MGy-Si		
23/05/91	Total blockage of the motor at 5.9 MGy-Si					
24/05/91	End of the F2-2 irradiation at 6.4 MGy-Si			End of the F2-2 irradiation at 6.5 MGy-Si **End of Test**		

After a qualitative examination of the Moog 1 motor and dismantling the fail-safe-brake the irradiation has been continued during the Mol experiment F2-2/2 up to an integral dose of 10 MGy-Si. The motor was blocked all the time. A lower coil resistance pointed

to a short circuit. Basic materials have been irradiated together with the motor.

The history of the MOL F2-2/2 experiment is shown in Table 11 /10/.

Table 11: History of the MOL F2-2/2 Experiment

Date	Moog 1	Moog 2	Moog 3	Maccon 1	Maccon 2	Maccon 3
04/03/92	Start of irradiation					
03/92	Total blockage during the irradiation					
26/03/92	End of the F2-2/2 irradiation at 10 MGy-Si End of Test					

4.3 Qualitative Post-Irradiation Tests

Corresponding to the previous motor defects the irradiation tests MOL F2-1, MOL F2-2, MOL F2-2/2 and the qualitative post-irradiation tests, as well showed the **weak points of the motors /5/**. Up to now, none of the three irradiated motors could finish the irradiation campaigns without any defects.

In particular the weak points which caused several defects were:

- The brake due to temperature sensitivity (insulation material, cable outlet)
- Cables with respect to temperature and γ-irradiation
- Lubricants due to temperature and γ-irradiation sensitivity
- Ball bearings with respect to temperature
- Cable outlet and cable bushing

The electrical components like motor winding and resolver winding showed a good condition. The measured terminal and insulation resistances corresponded to the values measured before irradiation.

At the cable connections the insulation material was broken. The ball bearings were destroyed because of unsuitable lubricants (Shell APL 701 grease, Graphite dry lubricant).

In Fig. 10 and Fig. 11 the crucial cable outlets of the motor`s stator windings and the fail-safe-brake, respectively are shown.

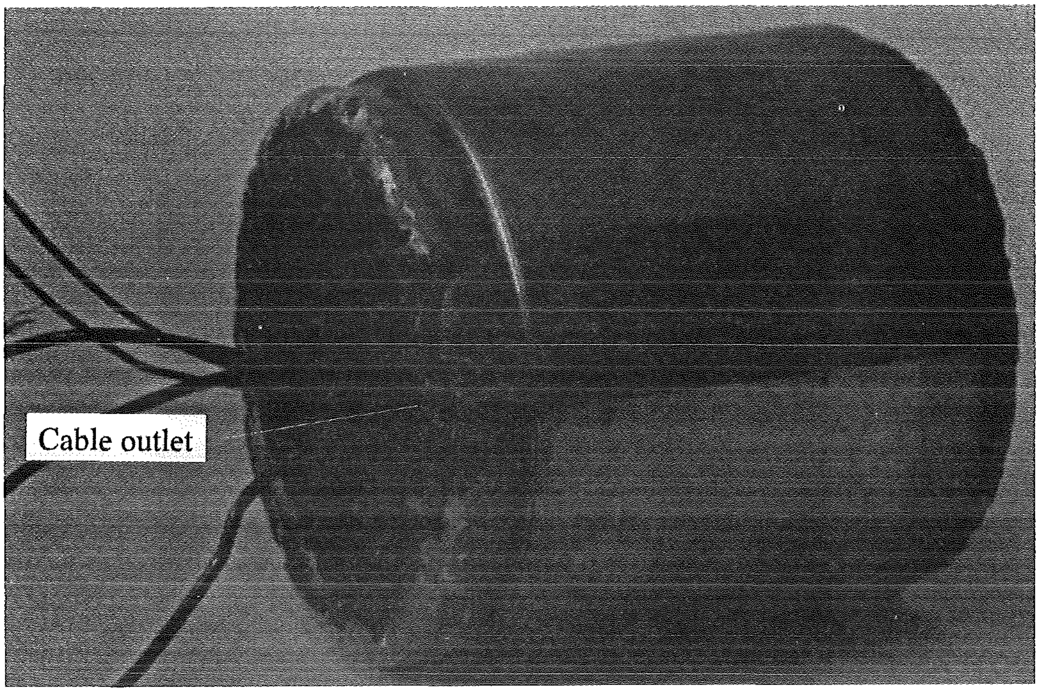

Fig. 10: Crucial cable outlet of the motor`s stator winding

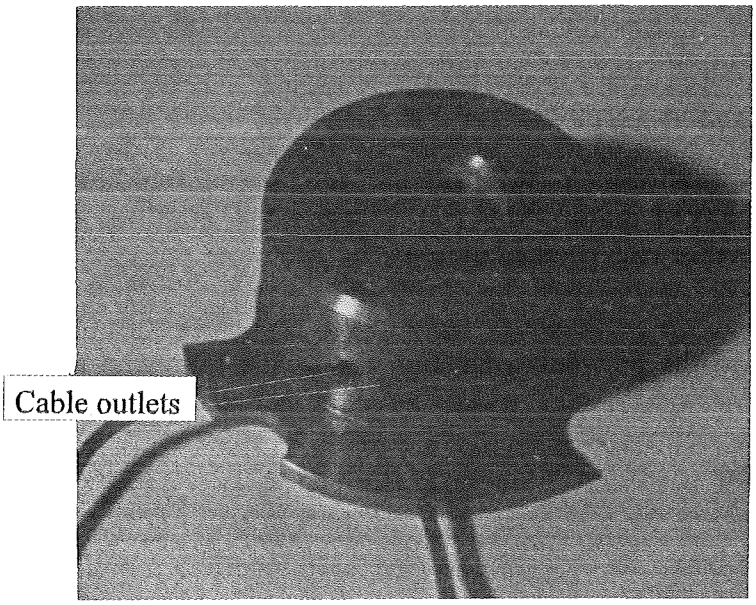

Fig. 11: Crucial cable outlet of the fail-safe-brake

Fig. 12 shows a failed ball bearing, which has been destroyed due to a unsuitable grease.

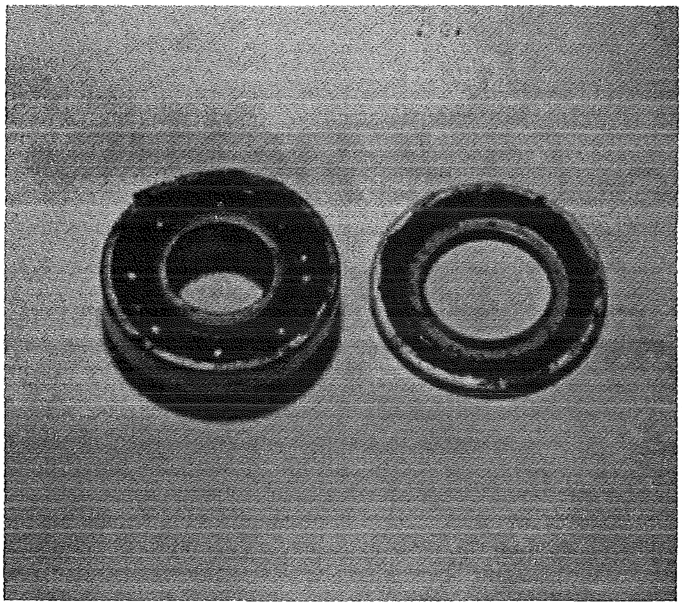

Fig. 12: Failed ball bearing due to unsuitable lubricant

4.4 Modification of Motors

According to the qualitative post-irradiation tests the motors have been modified. Moog delivered one changed motor (Moog 2), Maccon two modified motors (Maccon 2 and Maccon 3) for further radiation campaigns.

In consideration of the previous irradiation results the following modifications have been performed:

4.4.1 Moog Motor

- At the fail-safe-brake the cable outlets have been modified as well as the inlets and outlets at the windings and the motor housing.
- The connection cables of the motor stator, brake and resolver have been substituted by KAPTON cables, exclusively.
- The previous ball bearing has been substituted by high temperature bearings which do not need lubricants (changing the motor housing and the rotor shaft due to the new ball bearings).
- The previous resolver (Litton) has been replaced by another one without rotor winding (Admotec) with KAPTON insulated wiring.

4.4.2 Maccon Motor

- Modified motor stator with KAPTON insulated connection cables and LEMO plugs with PEEK insulation at the cable outlets of the motor housing.
- The connection cables of the motors and resolvers have been substituted by KAPTON cables.
- The previous lubricant of the motor bearing has been substituted by a high temperature and radiation resistant grease.
- The lubricant of the resolver bearings have been replaced by a dry lubricant.
- The rebuilding of the motor was done without fail-safe-brake.

4.5 Irradiation of modified motors up to 10 MGy-Si

4.5.1 Performance of the MOL F2-3 Experiment

After modification of the motors with respect to the previous irradiation experiments and their results one modified Maccon (Maccon 2) and one modified Moog (Moog 2) motor were irradiated during the MOL F2-3 irradiation campaign. The aim of this experiment was to reach a total γ-dose of 10 MGy-Si at both motors. **After an irradiation time of 505 hours the Moog motor reached a total γ-dose of 10.2 MGy-Si and the Maccon motor 10.4 MGy-Si.**

The history of the MOL F2-3 experiment is shown in Table 12 /11/.

Table 12: History of the MOL F2-3 Experiment

Date	modified Moog 2	modified Maccon 2	modified Maccon 3
05/05/94	Start of irradiation	Start of irradiation	
26/05/94		Short circuit at the motor winding	
26/05/94	End of the F2-3 irradiation at **10.2 MGy-Si**	End of the F2-3 irradiation at 10.4 MGy-Si End of Test	

4.5.2 Results of the MOL F2-3 Experiment

The Moog 2 motor showed a very good behaviour during the MOL F2-3 experiment up to a total gamma dose of 10 MGy-Si. At a gamma dose of 5.6 MGy-Si a grounded resolver coil was detected but this failure had no influence to the motor operation. **No problems occured during this irradiation campaign.**

The Maccon 2 motor showed an excellent operation behaviour during the irradiation tests up to gamma dose of 10 MGy-Si until a few minutes before reaching the end of this irradiation campaign, when a short circuit at the motor windings occured. The defective part was the crucial **cable outlet** of the motor stator. **The resolver has shown a good condition during the whole campaign.**

4.5.3 Performance of the MOL F2-3/1 Experiment

After the failure of the Maccon 2 motor during the MOL F2-3 irradiation campaign the second modified Maccon motor (Maccon 3) has been irradiated during the further MOL F2-3/1 experiment. The aim of this experiment was to reach a total γ-dose of 10 MGy-Si, as well. **After an irradiation time of 407 hours the Maccon 3 motor reached a <u>total γ-dose of 12 MGy-Si.</u>**

The history of the MOL F2-3/1 experiment is shown in Table 13 /11/.

Table 13: History of the MOL F2-3/1 Experiment

Date	modified Moog 2	modified Maccon 2	modified Maccon 3
03/06/94			Start of irradiation
20/06/94			End of the F2-3/1 irradiation at **12.0 MGy-Si**

4.5.4 Results of the MOL F2-3/1 Experiment

The Maccon 3 motor showed a very good operation behaviour during this irradiation campaign up to a <u>total γ-dose of 12 MGy-Si</u>. The online measurements during the irradiation have shown only small changes. During the whole irradiation campaign the operation behaviour of the motor was almost constant.

<u>4.6 Quantitative Post-Irradiation Tests</u>

The Maccon 3 motor has passed through the post-irradiation test program without any critical failure. One solder point inside the motor housing was broken several times but it was easyly to repair. **To avoid these soldered connections** should be taken into account for the redesign of the motor.

The measurement of the insulation resistances of the Maccon motor showed no significant change for the worse. All measured values were situated in acceptable ranges. The lubrication of the ball bearings is in a very good condition. Taking into account the results of the post-irradiation tests and the following qualitative examinations **the Maccon motor is situated in an excellent condition** considering the total γ-dose of 10 MGy-Si and the high temperature operations as well.

The Moog 2 motor passed through the whole irradiation test program (10 MGy-Si) but it failed during the post-irradiation tests. The failure was caused by a local overtemperature inside the motor winding which caused a short circuit between two stator windings /13/. The event of a local overtemperature inside the Moog motor will be rather possible than at the Maccon motor because of the higher power density of the Moog motor. **A failure caused by gamma irradiation will be ruled out** in all probability because both motor winding and resolver were irradiated before during component tests up to 30 MGy-Si without any critical changes. Because of the failure the whole post-irradiation test program couldn`t be carried out.

In addition to the short circuit between two motor windings the insulation resistance of the resolvers`s rotor winding was almost damaged. But following tests have shown that this had no influence on the motor`s operation behaviour.

The **high temperature ball bearings** of the Moog motor which need no lubricant showed **no sign of wear and tear**. The rotor friction was nearly the same than before irradiation.

The **fail safe brake showed also an excellent condition**. The braking torque and the current consumption have shown no changes. To lock and unlock the brake at low and high temperatures was possible without problems all the time.

The post-irradiation tests have **confirmed the reversible temperature dependent losses** due to the reduction of magnetic flux. The increasing of the motor temperature caused a flux reduction of about 2.2% per temperature rise of 50K. This was confirmed by measuring the torque constant, which has been reduced by increasing the motor temperature. The measurements at both motors gave the same result. Furthermore the reduction of the torque constant will influence the maximum continuous torque of the motor and the continuous output power as well, which has been reduced at higer motor temperatures.

A reduction of the torque constant due to the gamma irradiation was not established at the Maccon motor. On the other hand the torque constant of the Moog motor was decreased by about 5%.

The major results of the post-irradiation tests after 10 MGy-Si are listed in Table 14 /13/.

Table 14: Major Results of the Post-Irradiation Tests after MOL F2-3 and MOL F2-3/1

	modified MOOG 2	modified MACCON 2	modified MACCON 3
Continuous Stall Torque at an ambient temp. of 25°C and ΔT=100K	2.1 Nm	failed during MOL F2-3	1.06 Nm
Continuous Stall Torque at an ambient temp. of 100°C and ΔT=100K	failed during the post-irradiation tests	failed during MOL F2-3	1.07 Nm
Continuous Torque at 3000 UPM at an ambient temp. of 25°C and ΔT=100K	1.7 Nm	failed during MOL F2-3	0.86 Nm
Continuous Torque at 3000 UPM at an ambient temp. of 100°C and ΔT=100K	failed during the post-irradiation tests	failed during MOL F2-3	0.82 Nm
Rated Power at an ambient temp. of 25°C and ΔT=100K	590 W	failed during MOL F2-3	265 W
Rated Power at an ambient temp. of 100°C and ΔT=100K	failed during the post-irradiation tests	failed during MOL F2-3	265 W
Torque Constant at 150°C	0.49 Nm/A	failed during MOL F2-3	0.32 Nm/A
Insulation of motor windings	50KΩ – 1GΩ	failed during MOL F2-3	4 - 700 MΩ
Insulation of resolver windings	5KΩ – 1GΩ **End of Test**	failed during MOL F2-3	> 2 GΩ

For further detailed informations see /13/.

4.7 Irradiation up to 30 MGy-Si

4.7.1 Performance of the MOL F2-3/2 Experiment

The aim of this experiment MOL F2-3/2 was to reach a total γ-dose of 30 MGy-Si. After an irradiation time of 767 hours (total: 1173 hours) the Maccon motor reached a total γ-dose of 33 MGy-Si.

The history of the MOL F2-3/2 experiment is shown in Table 15. For further informations see /11/, /12/.

Table 15: History of the Mol F2-3/2 Experiment

Date	modified Moog 2	modified Maccon 2	modified Maccon 3
15/09/94			Start of irradiation at a total γ-dose of 12.0 MGy
17/10/94			End of the F2-3/2 irradiation at **33.0 MGy-Si**

4.7.2 Results of the MOL F2-3/2 Experiment

The Maccon 3 motor showed an excellent operation behaviour during these irradiation tests up to γ-dose of 33 MGy-Si. At one of the resolver coils a higher terminal resistance was measured at a total gamma dose of 20 MGy-Si, but it didn`t influence the motor behaviour.

4.8 Quantitative Post-Irradiation Tests

The Maccon motor has passed through the post-irradiation test program without any critical failure. One solder point inside the motor housing was broken several times during the MOL F2-3/1 post-irradiation tests but not during the MOL F2-3/2 tests. To avoid these soldered connections should be taken into account for the redesign of the motor.

The post-irradiation tests have confirmed the reversible temperature dependent losses due to the reduction of magnetic flux. The increasing of the motor temperature caused a flux reduction of about 2.2% per temperatur rise of 50K. This was confirmed by measuring the torque constant, which has been reduced by increasing the motor temperature. Furthermore, the reduction of the torque constant will influence the maximum continuous torque of the motor and the continuous output power as well, which has been reduced at higer motor temperatures.

A reduction of the torque constant due to the gamma irradiation was not established at the Maccon motor but the maximum continuous output power and stall torque were decreased by about 10% comparing the pre- and the post-irradiation measurements.

The measurement of the insulation resistances of the Maccon motor showed no significant change for the worse. All measured values were situated in acceptable ranges. The lubrication of the ball bearings is in a very good condition. Taking into account the results of the post-irradiation tests of MOL F2-3/1 and MOL F2-3/2 and the following qualitative examinations the Maccon motor is situated in a excellent condition considering the total gamma dose of 33 MGy-Si and the high temperature operations as well.

The major results of the post-irradiation tests after 33 MGy-Si are listed in Table 16.

Table 16: Major Results of the Post-Irradiation Tests after MOL F2-3/2

	modified MOOG 2	modified MACCON 2	modified MACCON 3
Continuous Stall Torque at an ambient temp. of 25°C and ΔT=100K	failed during Post-Irradiation Tests of MOL F2-3	failed during MOL F2-3	1.0 Nm
Continuous Stall Torque at an ambient temp. of 100°C and ΔT=100K	failed during Post-Irradiation Tests of MOL F2-3	failed during MOL F2-3	1.02 Nm
Continuous Torque at 3000 UPM at an ambient temp. of 25°C and ΔT=100K	failed during Post-Irradiation Tests of MOL F2-3	failed during MOL F2-3	0.75 Nm
Continuous Torque at 3000 UPM at an ambient temp. of 100°C and ΔT=100K	failed during Post-Irradiation Tests of MOL F2-3	failed during MOL F2-3	0.83 Nm
Rated Power at an ambient temp. of 25°C and ΔT=100K	failed during Post-Irradiation Tests of MOL F2-3	failed during MOL F2-3	240 W
Rated Power at an ambient temp. of 100°C and ΔT=100K	failed during Post-Irradiation Tests of MOL F2-3	failed during MOL F2-3	270 W
Torque Constant at 150°C	failed during Post-Irradiation Tests of MOL F2-3	failed during MOL F2-3	0.32 Nm/A
Insulation of motor windings	failed during Post-Irradiation Tests of MOL F2-3	failed during MOL F2-3	> 1 GΩ
Insulation of resolver windings	failed during Post-Irradiation Tests of MOL F2-3	failed during MOL F2-3	> 1 GΩ

For further informations see /14/.

<u>4.9 Irradiation up to 100 MGy-Si</u>

4.9.1 Performance of the MOL F2-3/3 Experiment

The aim of this experiment MOL F2-3/3 was to reach a total γ-dose of 100 MGy-Si at the MACCON 3 motor and at some components of the failed MOOG 2 motor.

4.9.2 Results of the MOL F2-3/3 Experiment

MACCON motor:
The motor was operating online up to a γ-dose of 80 MGy-Si. This dose was reached after an irradiation time of 3200 hours. A short circuit has stopped the online measurements. Furthermore no weighty irradiation effects were found. Following the motor was irradiated without online operation up to a total γ-dose of 100 MGy-Si during an irradiation time of 4538 hours.

MOOG motor:
The motor, which failed during the post-irradiation tests of MOL F2-3 (10 MGy-Si) due to an overtemperature effect was irradiated without online operation. A second short circuit was established at a γ-dose of 56 MGy-Si. The motor components were irradiated up to a total γ-dose of 62 MGy-Si during an irradiation time of 3870 hours.

4.10 Qualitative Post-Irradiation Tests

MACCON motor:
No quantitative post-irradiation tests were possible due to the motor defect, which occured during the irradiation campaign MOL F2-3/3 at a total γ-dose of 80 MGy-Si. The Kapton insulated wires and cables and the Peek insulated connectors have been in a good condition. The short circuit occured inside the windings. The insulation resistance against the houses (motor, resolver) was sufficiently high. The lubricant of the ball bearings was partly vaporized.

MOOG motor:
No problems with the Kapton insulated wires and cables and the Peek insulated connectors, as well. The short circuit occured inside the motor housing between the windings. The fail-safe-brake, the thermistor (NTC) and the grease free ball bearings have been in a very good condition. The insulation material of the winding wires should be modified concerning total γ-doses of 100 MGy-Si.

For further informations see /15/, /16/.

5 COMPARISON OF PRE- AND POST-IRRADIATION RESULTS

5.1 Results after 10 MGy-Si

5.1.1 Moog Motor

Due to a motor failure which occured during the post-irradiation tests under high temperature conditions it was not possible to carry out the whole test program. Nevertheless, conclusions based on the measurements which have been carried out and thus a comparison with the results of the pre-irradiation tests are possible.

The post-irradiation tests confirmed the temperature dependent losses of the motor due to the reduction of magnetic flux and the increased ohmic resistance (copper losses) /13/.

Due to irradiation effects the torque constant K_T and the maximum continuous stall torque have been reduced by about 5% and 12%, respectively. The maximum continuous output power of the motor decreased by about 17% due to irradiation effects.

The main results of the post-irradiation measurements compared with the measurements during the pre-irradiation tests are listed in the following Table 17. For further informations see /4/, /13/.

Table 17: Test Results before and after Irradiation of the Moog motor up to 10 MGy-Si

	Before Irradiation	After Irradiation at a total dose of 10 MGy-Si	Deviation [%]
Torque Constant K_T [Nm/A] at			
50°C	0.54	0.51	-5
100°C	0.53	0.50	-5
150°C	0.53	0.49	-7
200°C	0.52	0.48	-7
250°C	--	0.47	--
No-load speed [rpm] at			
50°C	5440	4900	-10
100°C	5510	4900	-11
150°C	5610	4950	-11
200°C	5690	5400	-6
250°C	--	5440	--
Continuous Stall Torque [Nm] at an ambient temp. of 25°C and ΔT=100K	2.4	2.1	-12
Continuous Stall Torque [Nm] at an ambient temp. of 100°C and ΔT=100K	2.35	--	--
Continuous Torque [Nm] at 3000 rpm at an ambient temp. of 25°C and ΔT=100K	1.95	1.7	-13
Continuous Torque [Nm] at 3000 rpm at an ambient temp. of 100°C and ΔT=100K	1.75	--	--
Rated Power [W] at an ambient temp. of 25°C and ΔT=100K	710	590	-17
Rated Power [W] at an ambient temp. of 100°C and ΔT=100K	630	--	--
Insulation of motor	> 2GΩ	50KΩ – 1GΩ	--

windings			
Insulation of resolver windings	> 2GΩ	5KΩ – 1GΩ	--

5.1.2 Maccon Motor

The Maccon motor has passed through the post-irradiation test program without any critical failure. Some problems with the soldered connections inside the motor housing occured during the tests but the broken solder points were easyly to repair and therefore, these events didn`t influence the test program.

The main results of the post-irradiation measurements compared with the measurements during the pre-irradiation tests are listed in the following Table 18. For further informations see /4/, /13/.

Table 18: Test Results before and after Irradiation of the Maccon motor up to 10 MGy

	Before Irradiation	After Irradiation at a total γ-dose of 12 MGy-Si	Deviation [%]
Torque Constant K_T [Nm/A] at			
50°C	0.34	0.33	-2
100°C	0.33	0.32	-2
150°C	0.32	0.32	0
200°C	--	0.31	--
250°C	--	0.30	--
No-load speed [rpm] at			
50°C	5350	5100	-4
100°C	5380	5250	-2
150°C	5410	5300	-2
200°C	--	5300	--
250°C	--	5400	--
Continuous Stall Torque [Nm] at an ambient temp. of 25°C and ΔT=100K	1.09	1.06	-3
Continuous Stall Torque [Nm] at an ambient temp. of 100°C and ΔT=100K	--	1.07	--
Continuous Torque [Nm] at 3000 rpm at an ambient temp. of 25°C and ΔT=100K	0.93	0.86	-7
Continuous Torque [Nm] at 3000 rpm at an ambient temp. of 100°C and ΔT=100K	--	0.82	--

Rated Power [W] at an ambient temp. of 25°C and ΔT=100K	290	265	-8
Rated Power [W] at an ambient temp. of 100°C and ΔT=100K	--	265	--
Insulation of motor windings	> 2GΩ	4 - 700 MΩ	--
Insulation of resolver windings	> 2GΩ	> 2GΩ	--

5.2 Results after 30 MGy-Si

Only the Maccon 3 motor was tested after a total γ-dose of 30 MGy-Si. No further post-irradiation tests and examinations, respectively were carried out up to a γ-dose of 80 MGy-Si.

The qualitative examination during the post-irradiation tests showed **no significant changes** compared with the condition after a total γ-dose of 10 MGy-Si (MOL F2-3/1). Only the terminal resistance of one resolver winding has changed to a few higher values, but this fact didn't influence the motor operation.

The insulation of all components were in a good condition. The main performance data compared with the measured data before irradiation and after a total γ-dose of 10 MGy-Si are listed in the following Table 19:

Table 19: Test Results before and after Irradiation of the Maccon motor up to 30 MGy

	Before Irradiation	After Irradiation at a total γ-dose of 12 MGy-Si	After Irradiation at a total γ-dose of 33 MGy-Si
Torque Constant K_T [Nm/A] at			
50°C	0.34	0.33	0.33
100°C	0.33	0.32	0.32
150°C	0.32	0.32	0.31
200°C	--	0.31	0.3
250°C	--	0.30	--
No-load speed [rpm] at			measured with coupled load brake
50°C	5350	5100	3940
100°C	5380	5250	3920
150°C	5410	5300	4070
200°C	--	5300	4090
250°C	--	5400	--
Continuous Stall Torque [Nm] at an ambient temp. of 25°C and ΔT=100K	1.09	1.06	1.0
Continuous Stall Torque [Nm] at an ambient	--	1.07	1.02

temp. of 100°C and ΔT=100K			
Continuous Torque [Nm] at 3000 rpm at an ambient temp. of 25°C and ΔT=100K	0.93	0.86	0.75
Continuous Torque [Nm] at 3000 rpm at an ambient temp. of 100°C and ΔT=100K	--	0.82	0.83
Rated Power [W] at an ambient temp. of 25°C and ΔT=100K	290	265	240
Rated Power [W] at an ambient temp. of 100°C and ΔT=100K	--	265	260
Insulation of motor windings	> 2GΩ	4 - 700 MΩ	50-2000 MΩ
Insulation of resolver windings	> 2GΩ	> 2GΩ	>1GΩ

6 SUMMARY

The aim of the motor irradiation program was to get irradiation hardened servo motors used for in-vessel handling devices. During several γ-irradiation campaigns two types of brushless AC-servo motors were irradiated under online motor operation conditions and online measurements. Pre- and post-irradiation tests were carried out to find out the influence of γ-irradiation and high temperature on the motor performance and the used materials, respectively.

The motors and related components should fulfil the NET and the ITER requirements for radiation resistance up to a total γ-dose of 10 MGy-Si and 30 MGy-Si, respectively. The motors should also fulfil the temperature requirements of 250°C maximum continuous winding temperature.

The first irradiation tests and the motor defects which occured, respectively showed the weak points of the used motors. Based on these previous test results the motors have been modified corresponding to the damaged components, which were axamined in detail.

The NET irradiation requirements of 10 MGy-Si has been reached by a Moog and a Maccon motor, as well. The corresponding post-irradiation tests showed, that the motor performance has been slightly reduced due to irradiation and temperature. The temperature dependent losses seem to be reversible but the losses due to irradiation are irreversible.

The ITER requirements of a γ-dose of 30 MGy-Si was reached by a Maccon motor. The post-irradiation tests have confirmed the irradiation and temperature dependent losses measured during the previous post-irradiation tests. Still after a total γ-dose of 33 MGy-Si the motor showed a good operation behaviour. During the further irradiation up to a total γ-dose of 100 MGy-Si online operation was possible up to a total dose of 80 MGy-Si without any critical irradiation effects.

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APPENDIX

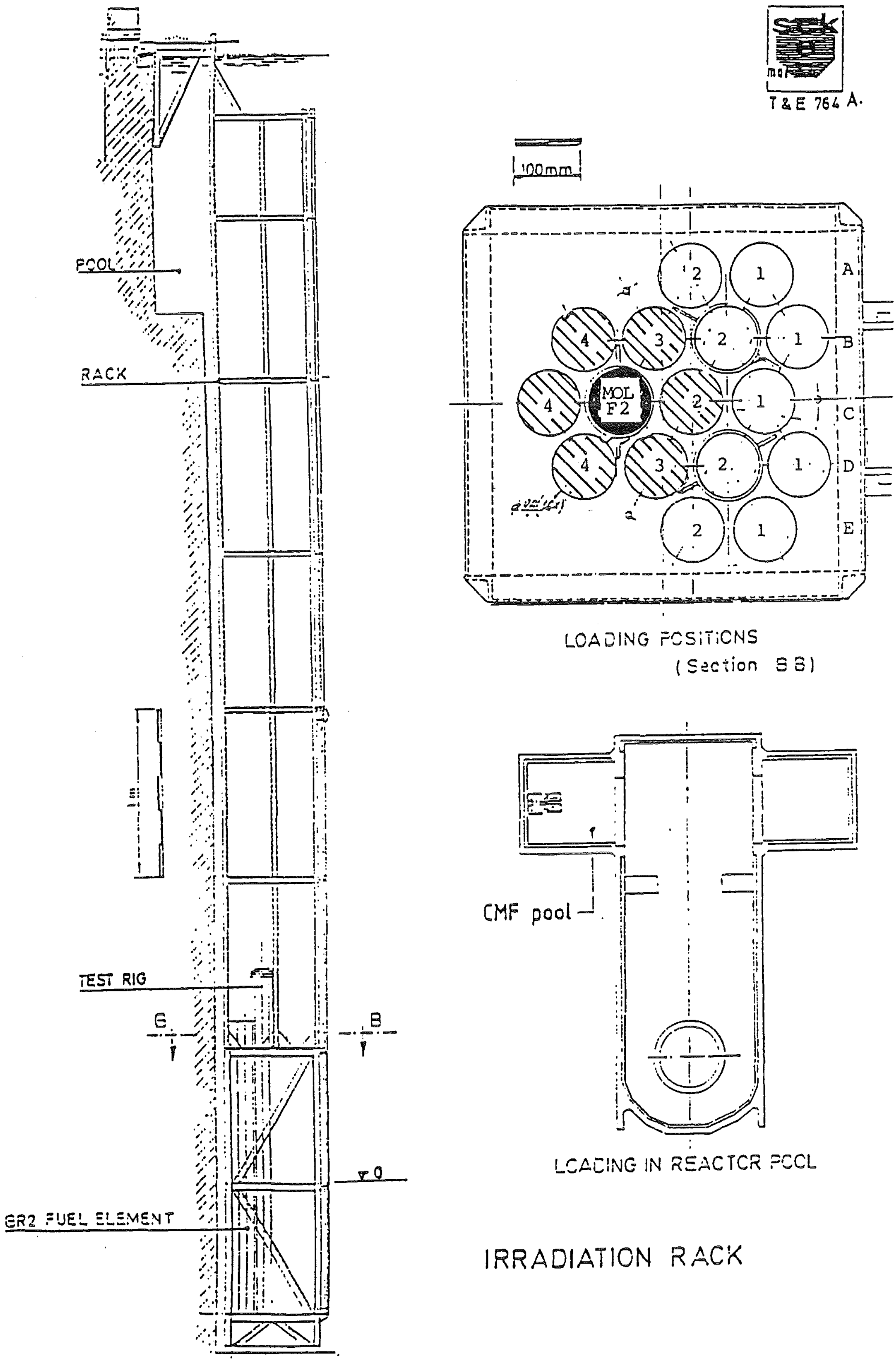

Fig. 4: Irradiation rack in the CMF pool of the BR2 reactor at SCK/CEN, Mol

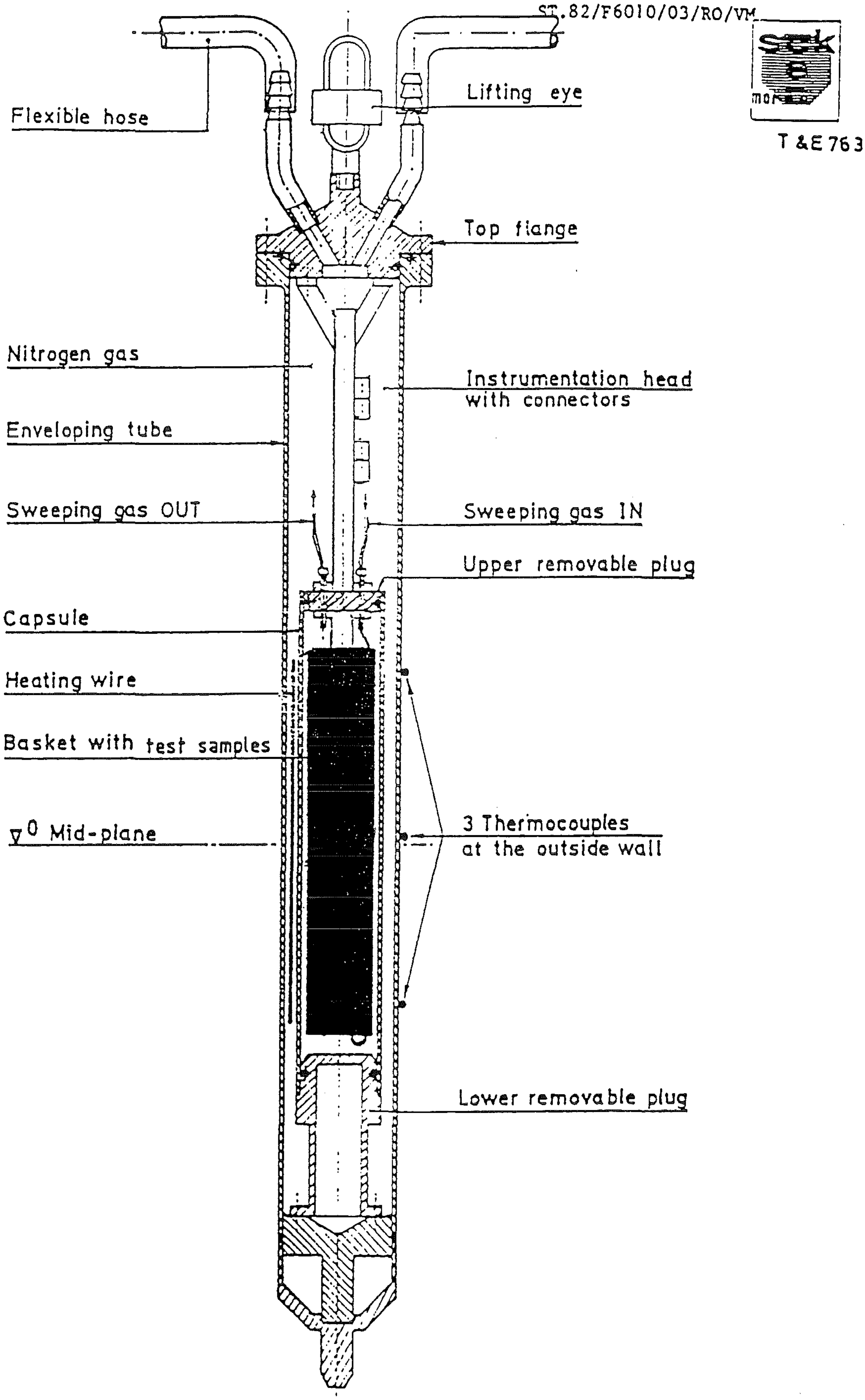

Fig. 5: General lay-out of the test rig for γ-irradiation

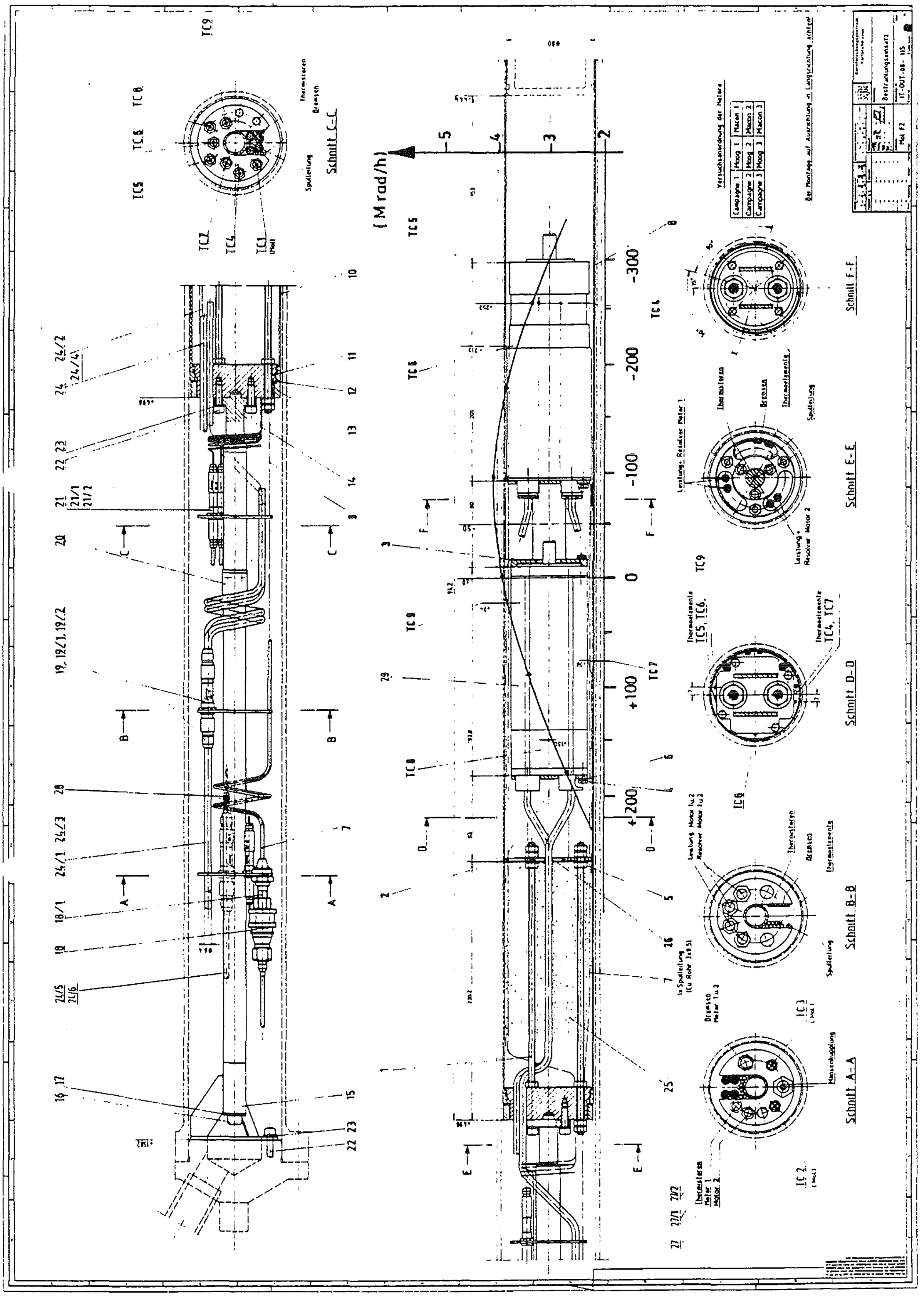

Fig. 6: Drawing of the motor basket