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The NET Articulated Boom: Preliminary Investigations and Justification for a Full Scale Prototype

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Preliminary Investigations and Justification for a Full Scale Prototype

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Abstract

The articulated boom system is the favourite in-vessel handling system for NET which will be used to maintain or replace in-vessel components during short term interventions. The testbed EDITH is the prototype of this system and is the logical step between the proof of principle of the system, which is already performed by the JET articulated boom, and the operational equipment for NET. EDITH is required to demonstrate that maintenance of plasma facing components can be carried out with the anticipated reliability and time. To achieve this aim EDITH is based on the experience of the JET boom and will be constructed in full scale, supplemented by a full scale mock-up. A further goal of EDITH is to allow the testing of boom components and subassemblies.

In this paper the results of preliminary investigations for the boom are summarized, the need of the testbed EDITH and a full scale mock-up is discussed and both EDITH and the mock-up are described.

Der NET In-Vessel Transporter:
Vorläufige Untersuchungen und Begründung für einen Prototyp im Maßstab 1:1

Zusammenfassung

Der In-Vessel Transporter ist das favorisierte Hantierungssystem für NET, das benützt werden soll, um während kurzzeitiger Interventionen In-Vessel Komponenten zu warten oder auszutauschen. Der Teststand EDITH ist der Prototyp dieses Systems und stellt den logischen Schritt zwischen dem Nachweis des Funktionsprinzips, wie er am JET-Vielgelenkarm erbracht wurde, und dem späteren NET-Transporter dar. Mit Hilfe des Teststandes soll gezeigt werden, daß die Instandhaltung der nahe dem Plasma angeordneten Komponenten mit der erforderlichen Zuverlässigkeit und in angemessener Zeit durchführbar ist. Um dieses Ziel zu erreichen basiert EDITH auf den Erfahrungen, die mit dem JET-Vielgelenkarm gemacht wurden. EDITH und ein Mockup werden im Maßstab 1:1 erstellt. Darüber hinaus ermöglicht EDITH das Testen von Transporterkomponenten und -baugruppen.

In diesem Bericht sind die Ergebnisse der vorläufigen Untersuchungen zusammengestellt, die Notwendigkeit des Teststandes EDITH und des Mockups im Maßstab 1:1 diskutiert und das Mockup beschrieben.

Abstract

Preface

Work documented in this report was performed within the frame of the Nuclear Fusion Project of the Kernforschungszentrum Karlsruhe GmbH. and is supported by the European Fusion Technology Programme.

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Abbreviations

ABS articulated boom system
ABT articulated boom transporter
CU control unit
DHD divertor module handling device
EDITH experimental device for in-torus handling
EE end-effector
EEPU end-effector positioning unit
MSSM master-slave servomanipulator
HLCS high level control system
ITER International Thermonuclear Experimental Reactor
IVC in-vessel component
IVHS in-vessel handling system
IVT in-vessel transporter
IVTS in-vessel teleoperation system
IVVS in-vessel vehicle system
IVVT in-vessel vehicle transporter
JET Joint European Torus
LLCS low level control system
MS bay maintenance and storage bay
MMI man-machine interface
NET Next European Torus
NRWS NET remote handling work station
POP proof of principle
RH remote handling
TARM telescopic articulated remote mast
TBD to be determined
TBU to be updated
TFTR tokamak fusion test reactor at Princeton
TU transfer unit
US ultra-sonic sensor
VV vacuum vessel
WU work unit
WUIF work unit interface flange

1. Introduction

1.1 Objective of this Document

Objectives of this document are

- to summarize the preliminary investigations on an articulated boom transporter (ABT) for in-vessel handling in NET,
- to justify a full scale experimental device for in-torus handling (EDITH) in a full scale mock-up to demonstrate the performance of sophisticated handling operations and to perform integral tests of single components,
- to describe EDITH and its integration in the European Technology Programme,
- to identify areas and critical issues where future actions are required for the boom and in particular also for EDITH.

1.2 NET In-Vessel Operation Requirements

Basis of the investigations for the articulated boom transporter as part of the basic equipment for in-vessel operations are the technical specification for NET/ITER in-vessel transporters /1/, the document "Divertor Maintenance Using IVHU" /2/ and the document "Definition of Requirements for the Design of Prototype Divertor Handling Equipment" /3/. A short summary is given below. Dimensions and arrangement of the NET device are shown in Figure 1, Figure 2 and Figure 3.

The following maintenance tasks and operations will be carried out by the in-vessel teleoperation system (IVTS):

Scheduled:

- Protective armour tiles replacement
- Radio frequency launchers replacement (TBD)
- Divertor modules replacement
- Inspection of first wall components and of vacuum vessel (VV)
- Dust vacuum cleaning (TBD)

Unscheduled:

- Active control coils replacement
- Leak detection
- Leak repairs (TBD)
- Debris recovery

Besides the requirement for the application of an ABS for the handling of in-vessel components through the equatorial maintenance ports the ABS may also be useful and possibly be required to support blanket handling acting as a transporter for vision systems

/4/ and/or geometry measurement systems and/or to support directly the withdrawal/insertion of blanket segments.

Replacement of divertor modules is the most demanding operation due to size and weight of the divertor modules and to the limited dexterity of the divertor module handling device (DHD). Therefore this task is the driving factor for the investigation and design of the ABT. The modules can be arranged poloidally or radially to the torus. Investigations about the suitability of both options are ongoing at NET. Therefore, for the ABT investigations the radial and poloidal segmentation of divertor modules has to be taken into account. The data of the divertor modules are listed in Table 1, those about the ABT in Table 2 and data about the environmental conditions in Table 3 and Table 4.

	Radial Segmentation	Poloidal Segmentation
Number of divertor modules	32 upper/32 lower ones	32 upper/32 lower ones
Width of one module (mm)	745/1202	1861/2394
Length of one module (mm)	3462	1657 (3350 for the inboard module including coolant supply)
Height of one module (mm)	approx. 600	approx. 670
Weight of one module (kg)	approx. 1000	approx. 1000

Table 1. Maximum dimensions and weights of divertor modules

Number and reach of ABTs	2 x 90° at full load capacity, alternative 1 or 2 x 180° at reduced load capacity
Number of entry ports available for ABT	2
Additional entry ports for insertion and withdrawal of components and equipment	2
Size of entry ports	H = 3400 mm, W = 1300 mm

Table 2. Technical data for ABT-design

Temperature	+20 to +150°C
Atmosphere	He (TBU) or Air (humidity TBD)
Pressure	approx. 1 atmosphere
Radiation	3×10^6 rad/h γ, negligible α and β
Contaminated dust	TBD
Magnetic field	negligible

Table 3. Environmental conditions during ABT operation

Temperature	0 to +40°C
Atmosphere	He (TBU) or Air (humidity TBD)
Pressure	approx. 1 atmosphere
Radiation	negligible (TBU)
Contaminated dust	negligible
Magnetic field	negligible (TBU)

Table 4. Environmental conditions during ABT maintenance and storage

1.3 Preselection of the Articulated Boom Concept

Out of several design options for an IVTS two solutions were identified which may have the capabilities to fulfill the Net requirements. One is a teleoperation system based on an articulated boom. The other one is an in-vessel vehicle system on boom rails. The proof of principle for the ABT has been already demonstrated by JET /5/ and TFTR /6/.

Based on the experience from the JET boom during the last years, the performance of conceptual studies and several discussions in expert and working groups a system with similar features was preselected by the NET Team for the NET machine. The reasons for this decision were mainly:

- Practical experience at JET has been gained during in-vessel handling of equatorial limiters, belt limiters and radio-frequency antennae. All these interventions have been performed satisfactorily in manual control mode and under direct operator viewing. In mock-up trials, some assembly operations have been tried in teach-repeat mode.
- Based on the practical experience components like actuators were improved which give the basis for further consequent development.
- This system is independent from the NET device.
- Technology used is state of the art with exception of the radiation resistance of several components. This is being investigated separately in collaboration with CEN/SCK MOL.

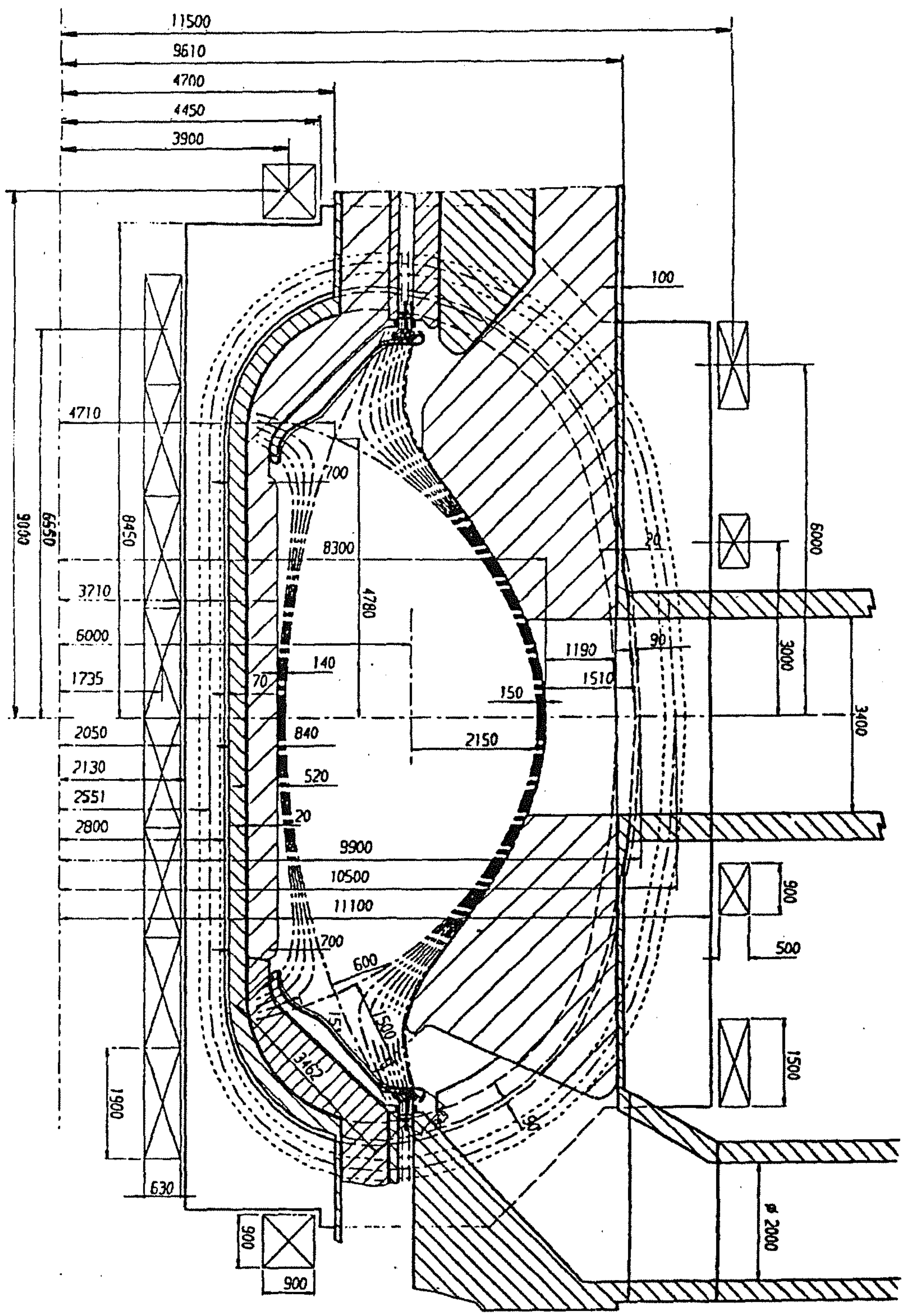


Figure 1. NET Machine Cross Section

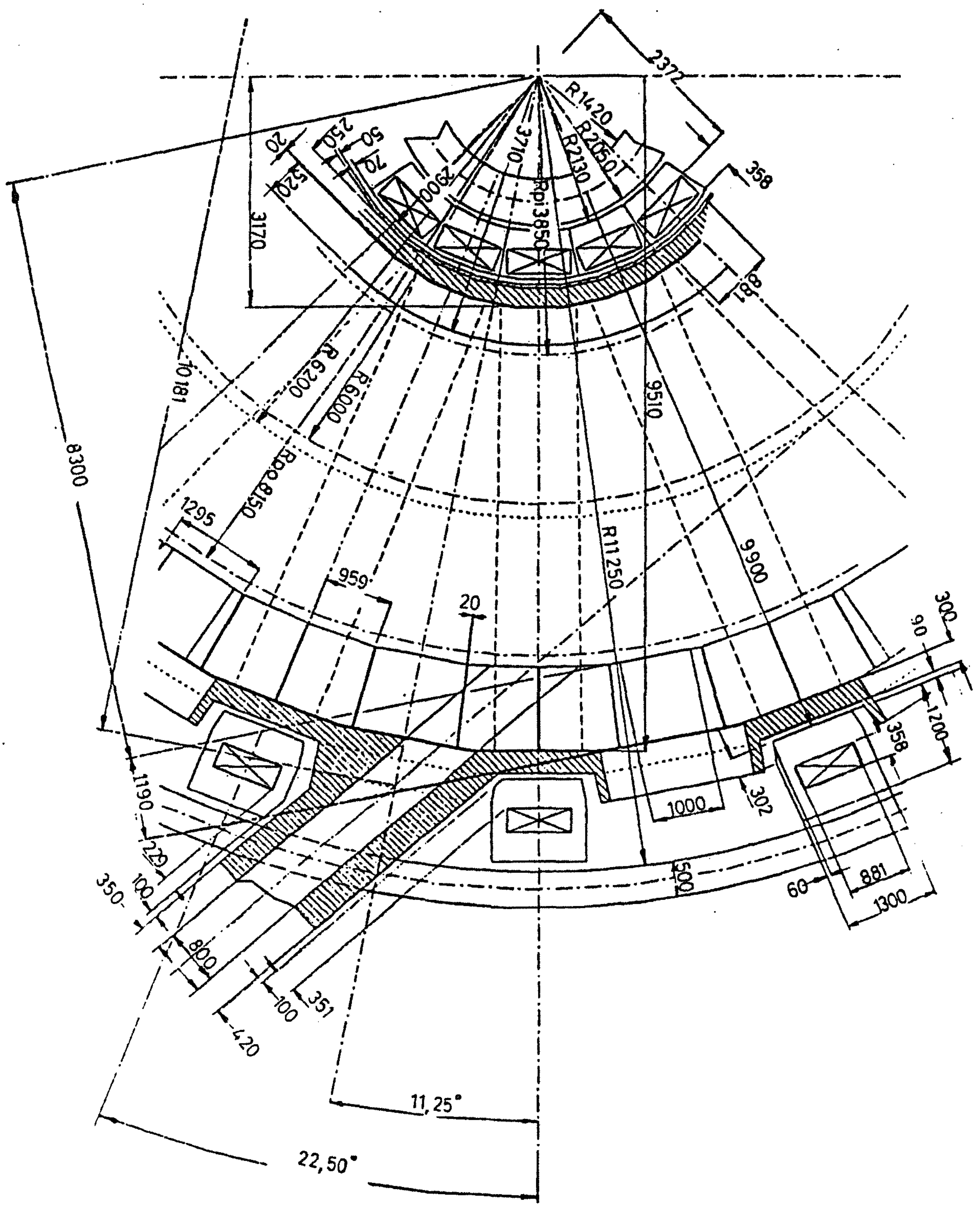


Figure 2. NET Machine Equatorial Cross Section

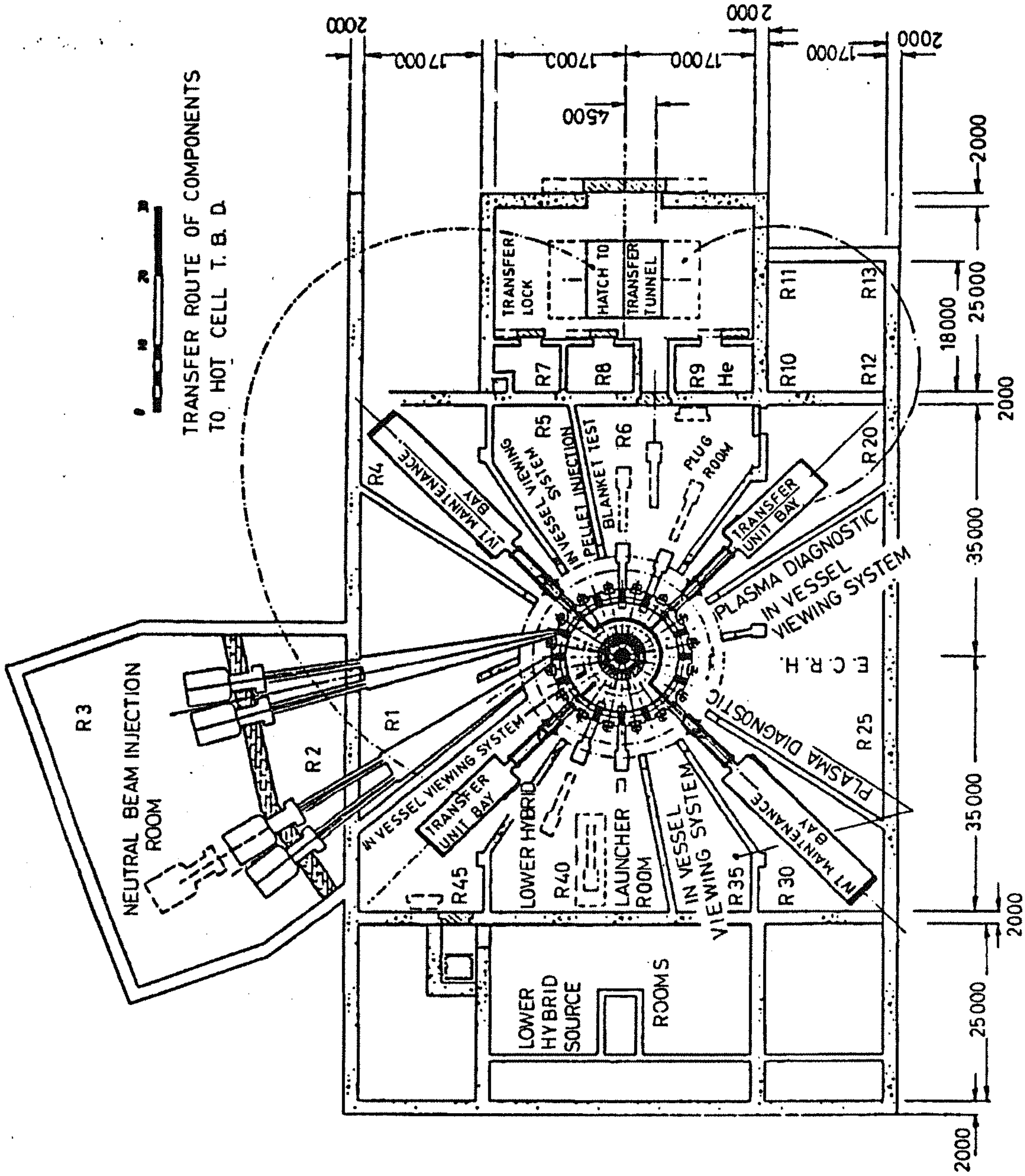


Figure 3. Schematic Layout of Maintenance and Storage Bays

1.4 NET Position with Respect to In-Vessel Transporters

Scheduled and unscheduled maintenance tasks for in-vessel components (IVC) can be subdivided in long-term and short-term operations. Typical short-term operations are the replacement of one or two divertor plates or single protective armour tiles or leak detection in case of a failure, while long-term operations are e.g. the scheduled routine replacement of all divertor plates. As discussed in maintenance working groups and decided by the NET Team the articulated boom system (ABS) is foreseen to be used especially for short-term operations. As discussed in maintenance working groups it was stated by NET /7/,

> that ABS and IVVS complement one another, i.e. the boom would be used for short term interventions because of its relative ease of deployment, whereas the vehicle would be used for the longer term tasks because its faster operating time would compensate for the longer set-up period.

In the same meeting NET concluded the discussion as follows /7/:

> In-Vessel Handling Unit in the form of a boom type manipulator was essential. The question remaining was wether the reach of +/-180° was required. Because of the availability of the JET boom a "Proof of Principle" was not required, therefore the next step should be a prototype such as that proposed by KfK.

The need for providing an articulated boom technical solution to in-vessel maintenance problems was restated by NET and approved by the Remote Handling Expert Group during the Remote Handling Expert Group Meeting on February 21, 1990 /8/:

> It is restated that, according to the technical evidence available today, the articulated boom remains the favourite option for limited intervention (main reason is that opening of one port only is sufficient).

2. ABT Investigations

2.1 Overview

As shown in Figure 4 which presents a preliminary option of the ABS arrangement the system is composed of the following main subassemblies:

- Carrier
- Cantilever arm
- Articulated boom transporter
- Work unit interface
- Work units

The carrier is movable on rails radially to the torus and is housed in the maintenance and storage bay (MS bay) which is connected with the torus of the NET device via a tunnel. The length of this tunnel (TBD) and the thickness of the biological shield of the device determine the length of the cantilever arm (9.5m TBU) which is attached to the carrier and connects carrier and ABT. The tip of the boom is equipped with an end-frame where the different work units (WU) can be attached remotely.

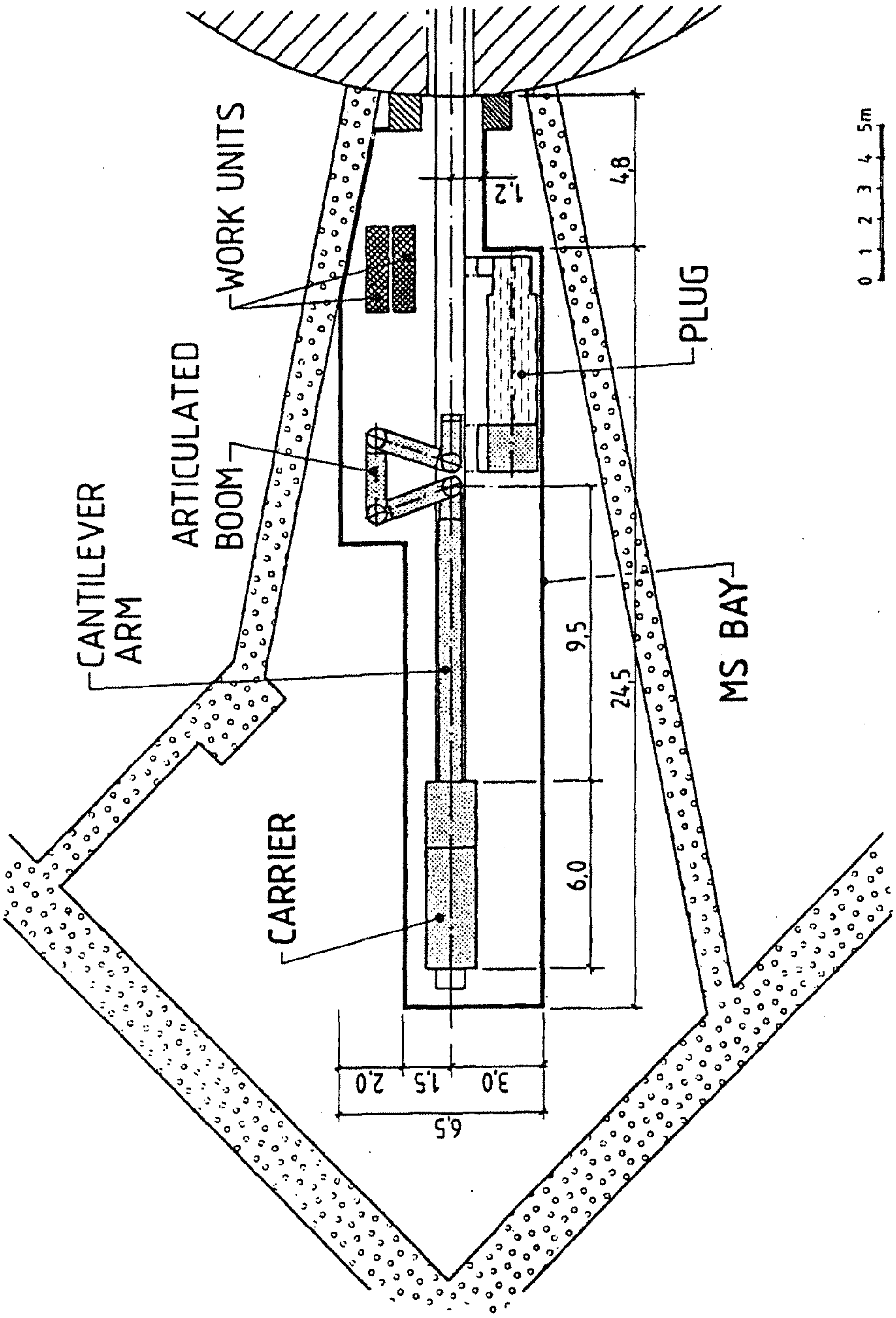


Figure 4. Preliminary ABS - Arrangement

2.2 Overall Dimensions and Performance to Comply with RDD

Figure 5 shows the ABS in a simplified form. Details of the ABT can be seen also as examples on the drawings concerning ED'TH (/9/) as these are prototypical for the operational equipment.

The kinematics of the ABS (transporter and ABT) is shown in Figure 6. The ABT is composed of the four links B1 to B4. The links are connected by the yaw joints Z1 to Z4. The end-frame is integrated into the link B4 and has two additional joints, the pitch joint Z5 and the rotation joint Z6. The pitch joint and the rotation joint serve to align the end-frame vertically in order to compensate the deflection of the ABT, e.g. during the remote engagement of WUs or performing maintenance tasks. In addition, the rotation joint is required to make possible to turn the end-frame by 180°, thus allowing to reach with an attached WU the upper and lower regions of the torus. The data of the ABT link joints are given in Table 5.

Number of yaw joints	4
Range of operation for yaw joints	±120°
Drive of yaw joints	1 coaxial drive unit for the joints Z2 to Z4, 2 coaxial drive units for the joint Z1
Number of rotation joints	1
Range of operation for the rotation joint	±180°
Drive of the rotation joint	2 cyclo drives actuating one common spur wheel gear
Number of pitch joints	1
Range of operation for the pitch joint	±5°
Drive of the pitch joint	2 spur wheel gears actuating one planetary spindle

Table 5. ABT - Technical data concerning link joints

The links have box cross section. Their height is stepwise reduced from link B1 to B4. The dimensions of the links are listed in Table 6, the weights are given in "Structural analysis".

Link Nr.	Link length (mm)	Width (mm) x Height (mm) / Wall thickness (mm)
B1	2450	600 x 1930 / 8
B2	2450	600 x 1871 / 6
B3	2450	600 x 1825 / 5
B4	1535	600 x 1730 / 15 (front plate)

Table 6. ABT - Technical data concerning the links

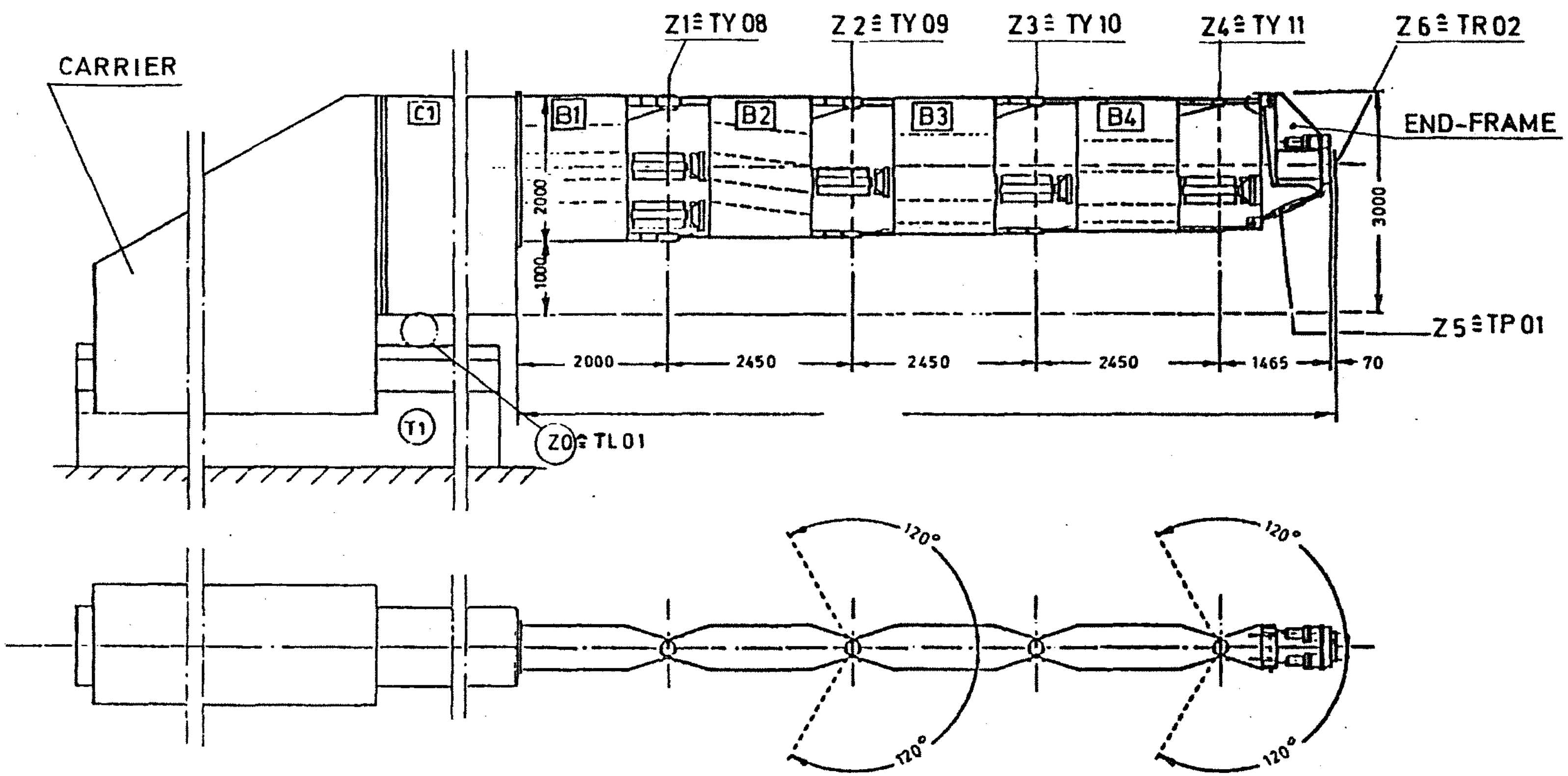


Figure 5. Articulated Boom System

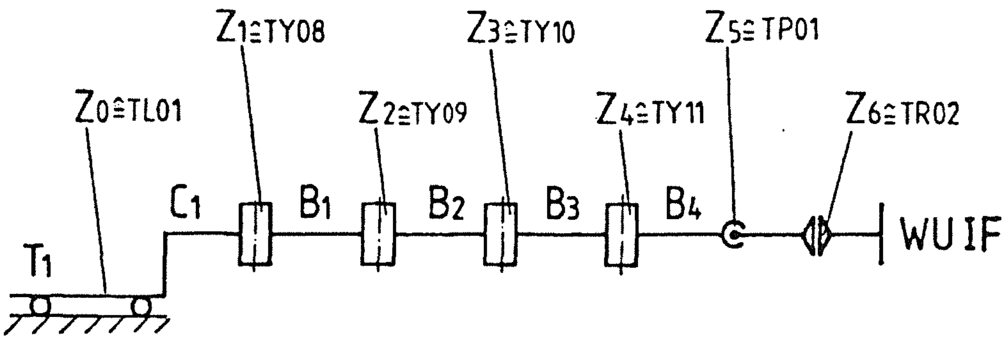


Figure 6. ABT - Kinematics

2.3 Summary of ABT Requirements Resulting from Work Unit Investigations

Up to now there are two different WUs foreseen. One multi-purpose unit on the basis of existing electrical master-slave manipulators (MSSM) and another special one for the handling (withdrawal and insertion) of divertor modules. Additional ones may be possible, e.g. for the handling of protection tiles or antennae but are not yet defined and will probably be less demanding than the (DHD) due to the fact that the divertor modules handling is the most sophisticated task with respect to size, weight and arrangement of the divertor modules at the top and bottom of the torus. Therefore, the requirements for the ABT caused by the WUs result from the DHD. The DHD, like other WUs, will be remotely attached to the ABT outside the torus in the MS bay, but their detachment may also be possible inside the torus. Figure 7 on page 12 shows the conceptual design of the DHD without the gripper for the divertor modules. /11/

The total weight of the DHD and the divertor module which was taken into account for the stress analysis and dimensioning of the ABT was 3900kg (weight of WU 2900kg). The weight is based on preliminary investigations of the DHD performed by KfK and presents a conservative estimation.

Figure 8 shows the kinematics of the DHD. The main components are the trolley (DT01), the slide (DT02), the upper pitch joint (DP01), the rotation joint (DR01) and the yaw or lower pitch joint (DY01). These four degrees of freedom are not sufficient for the handling of the modules. Two additional degrees of freedom, a swivelling round a vertical axis will have to be performed by the Z4-yaw joint of the ABT, a linear movement radially to the torus requires a combined motion of the ABT yaw joints Z4, Z3 and Z2. The integration of these two degrees of freedom into the DHD would not be very useful as the complexity and weight of the WU would be increased. The requirements for the control system caused by the DHD are implemented in "NET In-Vessel Operation Requirements".

The kinematics of the manipulator unit is presented as an example in Figure 9 and will be analysed further. Compared with standard MSSMs the manipulator needs additional joints. These are for the vertical movement the trolley (MT01) and the slide (MT02), for rotation the joint (MR01) plus the shoulder joints (MP01) and (MP05). These additional links are taken into account in the ABS control system.

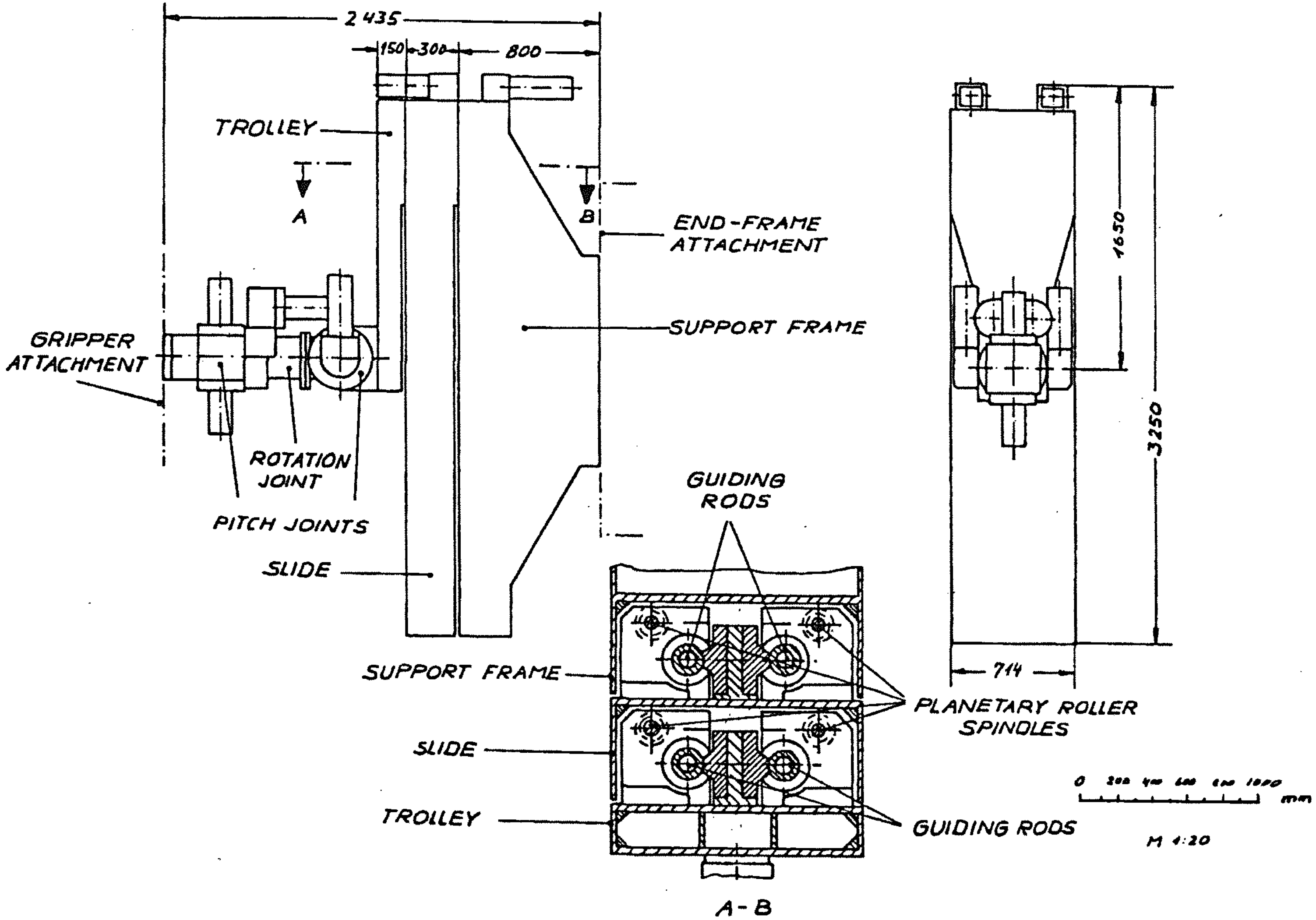


Figure 7. Divertor Handling Device

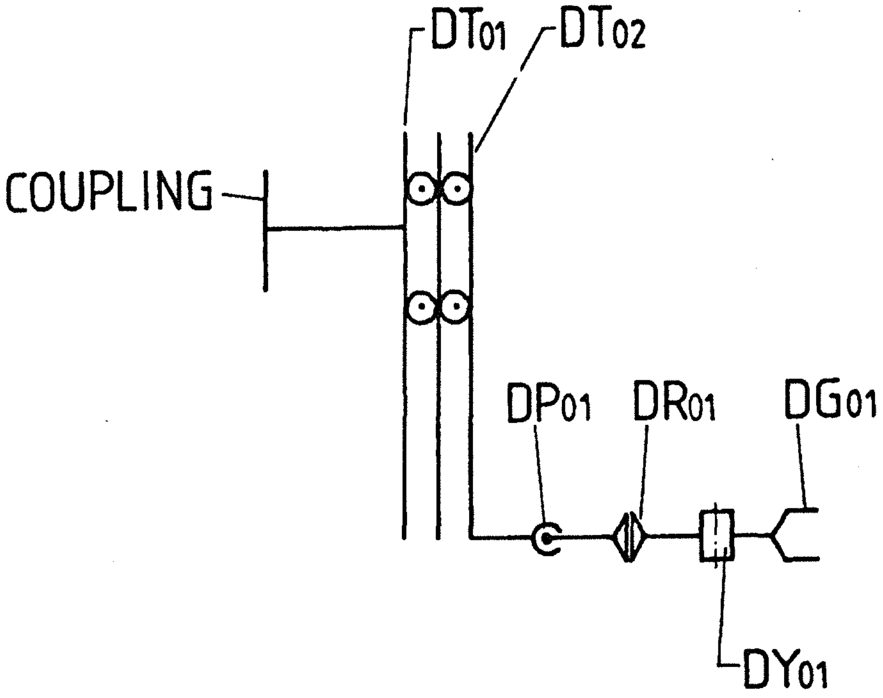


Figure 8. DHD - Kinematics

2.4 Results from Structural Analysis and Materials Selection

2.4.1 Structural analysis

The structural analysis was performed for a steel version of a 90° boom.

Taken into account the requirements of high vertical stiffness and low dead weight, an optimization of the link cross-section for the boom was carried out /12/. The width of the links (0.6 m) is limited by the width of the entry port which the boom must pass on the way into the torus. It is the same for all links. The height of the link boxes is stepwise reduced from 2 m for link C1 to 1.73 m for link B4. The lenght of links B1,B2,B3 is 1.35 m. The lenght of the lugs is 0.55 m. The vertical force is carried only by the second and third lugs from the boom upperside for each link. Therefore, only these lugs have to be very stiff and are designed as box-sections. The wall thicknesses were increased from 5mm for link B3, to 6mm for link B2 and 8 mm for link B1.

The maximum payload at the tip of the boom is 3.9 t. It consists of the weight of a divertor module of 1 t and the weight of the DHD plus gripper of 2.9 t. The dead weight of the boom is about 6.2 t. It consists of the dead weight of the link boxes (1.5t), and of the joints (2.2 t), the dead weight of the coaxial drive units (2.2 t), and the dead weight of the cables (0.3 t).

For the design described above, a deflection of 30 mm was calculated for the most unfavorable working position in the torus. Additional deflections caused by the joint tolerances were not considered.

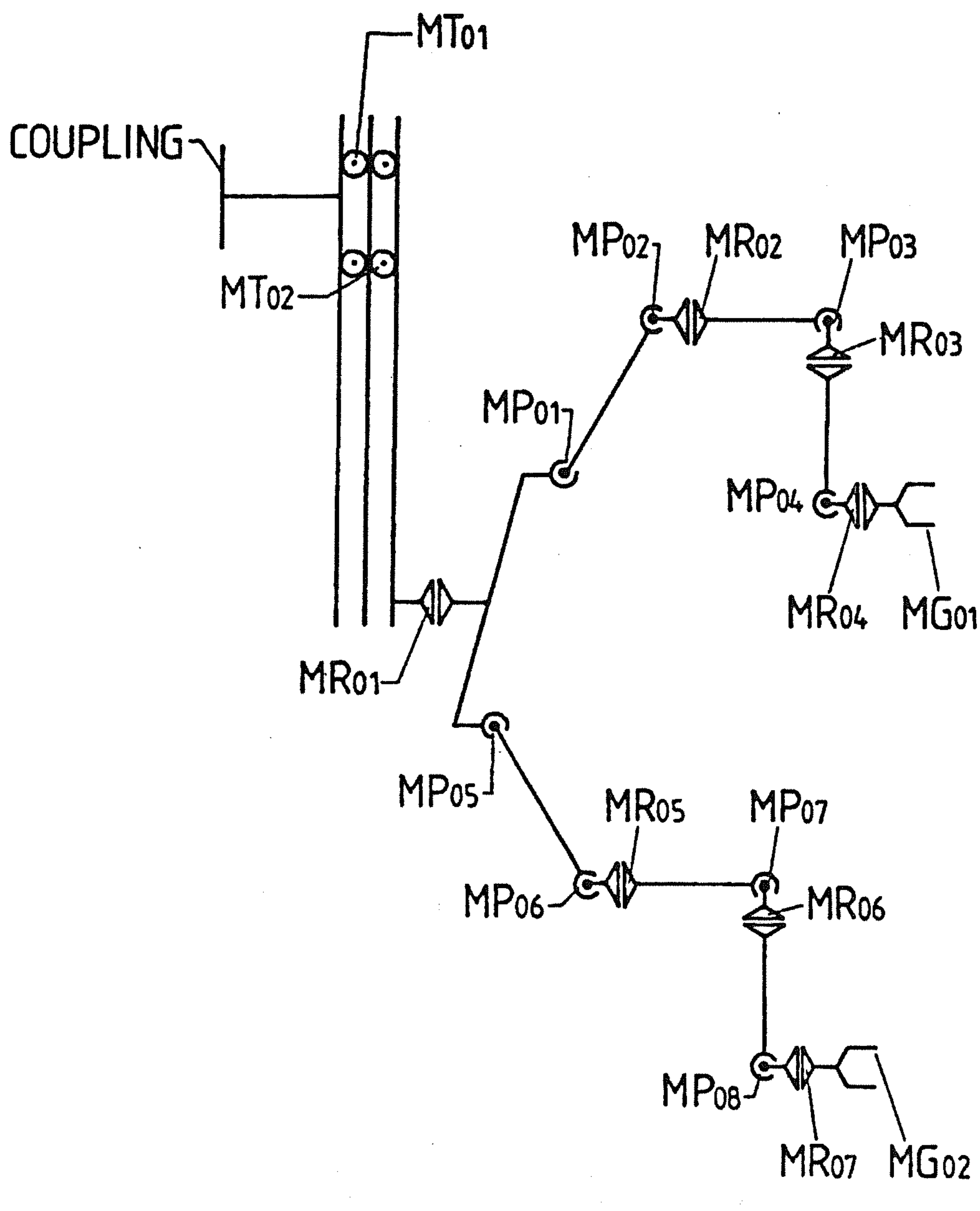


Figure 9. Manipulator Unit - Kinematics

The stress analyses show that the stress peaks occur where the lugs are attached to the link boxes. In order to reduce these peaks, local stiffeners are introduced which allow for a better load transfer from the lugs to the link boxes.

Except of the back plate the membran stresses are dominant for all parts of the links and lugs while the bending stresses of the plates are negligible. At the back plates the weight of the drive units (moment = 0.55m x 4500N = 2475Nm) and the drive forces of these units (moment = 15 kNm per unit) are causing high local bending stresses. Therefore, each back plate is reinforced by two stiffening ribs.

The stress analyses show that the stresses are below the allowed limits. For the link B4 average membrane stresses are only in the region of the 30 N/mm². The peak stresses are about 120 N/mm². With respect to these results a reduction of the wall thicknesses would be advisable. Its influence on the deflection would be small. However, for manufactory reasons such a reduction has not been applied at EDITH.

Buckling analyses show that the links do not need additional reinforcing ribs for buckling reasons.

2.4.2 Material selection

For an appropriate material selection different criteria were considered.

One criterion was the minimization of the vertical deflection caused by a payload. For a given geometry of the link (length,width,height,wall thickness) the deflection is proportional to 1/E, where E is Youngs modulus. The lowest value results for the material with the highest Youngs modulus, which is steel.

Another criterion was the minimization of the vertical deflection caused by the dead weight. Now the deflection is proportional to ρ/E, where ρ is the material density. Again, the lowest ratio is obtained for steel, but the ratio for an aluminium alloy was only slightly higher.

A third criterion was the minimization of the dead weight. It is proportional to ρ/σ_{all}, where σ_{all} is the allowed stress. Here the lowest ratio is obtained for titanium.

Table 7 gives more detailed results from the application of the above criteria.

	1/E (10^{-11} m^2/N)	ρ/E (10^{-8} kg/Nm)	ρ/σ_{all} (10^{-5} kg/Nm)
Steel	0.47619	3.714	4
Titanium	0.95057	4.315	1
Aluminium alloy	1.42857	3.8	1.7

Table 7. Characteristic properties of different materials which are candidates for the articulated boom links

The comparison shows that steel is the most favorable material.

Therefore, in our investigations the boom was considered to be made of steel with a yield strenght of 240 N/mm^2. To obtain a sufficient safety margin, the membrane stresses should not exceed 2/3 of the yield strenght.

An alternative material for the boom could be a high strength aluminium alloy, for instance. It has a slightly reduced allowed stress, but three times lower Youngs modulus and density. Because most of the deflection is due to the weight of parts which cannot be manufactured from aluminium -their weight is 65% of the total weight and includes the payload of 1t, the work unit of 2.9t, the drive units of 2.25t, the bearings of 0.2t, and the cables of 0.32t- the wall thicknesses must be increased about three times in order to obtain the same deflection. Link B3 is an exception. The influence of the deflection of the link B3 on the overall deflection is small and its stresses are on a low level. Therefore, by manufactoring this link of aluminium, the wall thickness must probably not be increased. This results in a reduction of the dead weight of about 200 kg and a reduction of the deflection of about 0.8 mm. These values are only 2 to 3 % of the total amounts. On the other hand, the buckling analyses show that this link needs reinforcing ribs, because of the lower Youngs modulus of aluminium. This results in a lower dead weight reduction, but higher manufactory costs.

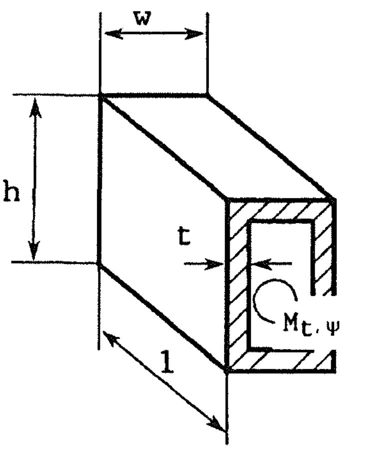
These ribs (of the aluminium version of the link B3) would not be necessary, if the solid wall construction were replaced by a sandwich construction. For all the other cases where ribs are not required, this change would be of no influence. The weight and the stresses of the links would be the same. However, manufactory might be more difficult.

2.4.3 Box type of links or lattice girders ?

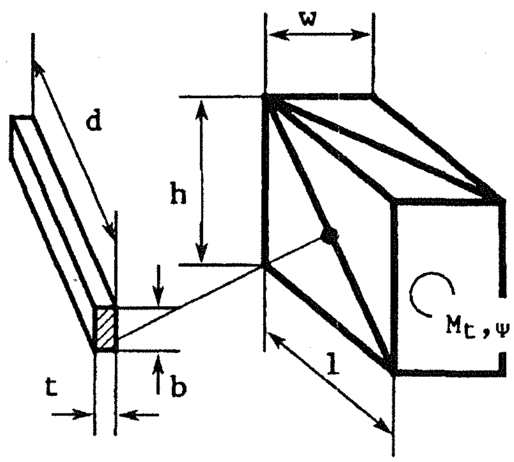
Since under the given conditions the stresses reach rather high values, an investigation was carried out, whether lattice girders would be more favorable for the boom than the box type. As far as beam bending is concerned the maximum stresses occur at the upper and lower fibers of the boom cross-sections. Therefore material accumulation at these fibers which can be provided by a lattice design would be advantageous.

However, depending on the particular boom position, torsion of the boom cross-section may be superimposed causing high shear stresses, too. Since these stresses are inversely proportional to the local thickness of the wall surrounding the boom cross-section, for instance, material accumulations are not advantageous. This can be demonstrated by the formulas for the maximum stress σ and the torsion angle ψ caused by a torque M_t. (E = Young modulus, G = shear modulus).

box type design



lattice girder



$$\sigma = \frac{M_t}{2hwt} \cdot 2$$

$$\psi = \frac{M_t}{2h^2w^2t} \, \frac{(h+w)\ell}{G}$$

$$\sigma = \frac{M_t}{2hwt} \, \frac{d}{b}$$

$$\psi = \frac{M_t}{2h^2w^2t} \, \frac{\ell^3 + d^3}{Eb} \, 2$$

Because

$$d \gg b$$

and

$$\frac{\ell^3 + d^3}{Eb} \cdot 2 \gg \frac{\ell(h+w)}{G}$$

the stress σ and the torsion angle ψ for the lattice girder is considerably higher than for the box type of design. Therefore, with respect to torsion the boxes are more suitable.

Considering both, beam bending and torsion, the drawback of the boxes for the first type of loading is moderate, but the advantage in the case of torsion -as just described- is dominant.

So it is not surprising that for lattice girders deflections have been calculated which were three times higher than for the box type of design.

2.4.4 Natural frequency investigation

To support the selection between several variants with different wall thicknesses the eigenfrequencies of the articulated boom were evaluated in a finite element analysis /13/.

After shape and size of the boom were fixed using kinematical and structural analysis methods it was necessary to choose the wall thickness. To solve the conflict between minimization of weight and deformation, a third criterion is taken into account:
The eigenfrequencies of the complete boom should be as high as possible.

Therefore a simplified analysis has been run with a finite element program. In the simplified model the links are substituted by a beam element. Joints are represented by a torsional spring. Its elasticity describes the gear stiffness. The other parameters of the model are extracted from precise static analysis of the links.

The results turn out that there are only little changes of the eigenfrequencies when the wall thicknesses of the links are varied. The frequencies of the stronger structure are a little bit higher.

More detailed results will become available after commissioning of the dynamic model today under development.

2.5 Results from Drive Units Investigations

The coaxial drive units are used in a computer-controlled servo system to control the yaw joints of the ABT Figure 5, Drwg.Nr. IT-OUT-12-001/3 /10/. Experience at JET has shown that the torque rating, stiffness, efficiency and backlash of the drive units are of primary importance in controlling the speed and accuracy of the system. In addition, the criteria pertinent to equipment which must operate in such a high radioactive environment have been applied. Therefore, γ-radiation sensitive components of drive units, e.g. motors, cables, sensors were identified and are subject of the NET Technology Programme /14/ /15/.

The uppermost design features of the coaxial drive units were:

- High torque achieved by two Cyclo drives and AC-brushless servo-motors per unit
- Zero backlash achieved by mechanical or electrical pre-loading of one gear box against the other
- Redundancy
- Hand drivability
- Joint release feature in the event of a total seizure of the drive
- Remote maintainability as changing the complete coaxial drive units as well as only the motors
- A total gear ratio of less than 600 with respect to inertia
- Direct driven efficiency >70% and back-driven efficiency >40%
- Weight kept to a minimum resulting in Al-alloy as material for the largest drive unit components. To confirm the correct material selection one of the drive units will undergo thorough tests at a temperature of +150°C

In Table 8 the main parameters of the coaxial drive units are listed.

Parameter	Value
Maximum angular joint speed	0.15 rad/sec
Number of motors with fail-safe brakes	2
Maximum continuous torque at rated speed	10 kNm
Maximum pulse torque, repeated at rated speed	14 kNm
Transmission ratio of Cyclo	89:1
Transmission ratio of gear train	5.99:1
Total transmission ratio	532.9:1
Total backlash at 300 Nm	<0.00044 rad
Total stiffness of the system	2.4 x 10^6 Nm/rad
Efficiency direct/back	>70% / >40%

Table 8. Technical data of coaxial drive units for yaw joints Z1 to Z4

The pitch joint Z5 at the DHD end-frame is actuated by a linear drive unit on the basis of a planetary roller spindle which substitutes the spanner (item 8) shown in the Drwg.Nr. IT-OUT-08-411B. The drive unit is shown in Drwg.Nr. IT-OUT-07-082. The planetary roller spindle (type SRC48x5R from SFK is driven by two spur wheel gears with integrated idle wheels. The pinions of the gears are driven via slipping clutches by AC-brushless servo motors of the type D315...L50 (Moog) with fail-safe brakes. Motors and spur wheel gears are redundant. The technical data are listed in Table 9.

Parameter	Value
Maximum angular joint speed	0.01 rad/sec
Number of motors with fail-safe brakes	2
Maximum continuous torque	110 kNm
Transmission ratio of gear train	2.27:1
Total transmission ratio	4184:1
Efficiency	80%

Table 9. Data of drive unit for pitch joint Z5

The rotation joint Z6 located at the end-frame of link B4 (Drwg.Nr. IT-OUT-08-411B) is based on two Cyclo drives (type FR 45), each driven by AC-brushless servo motors type D315...L30 (Moog) with fail-save brakes. The Cyclo drives are followed by spur wheel trains with a common wheel at the end-frame. Each of the drives is able to bring the full required torque, thus providing redundancy. The technical data are given in Table 10.

Parameter	Value
Maximum angular joint speed	0.05 rad/sec
Number of motors with fail-safe brakes	2
Maximum continuous torque at rated speed	16 kNm
Maximum pulse torque, repeated at rated speed	25 kNm
Transmission ratio of Cyclo	179:1
Transmission ratio of gear train	5:1
Total transmission ratio	895:1
Efficiency	80%

Table 10. Technical data of drive unit for rotation joint Z6

2.6 Results from Control System Investigations

The ABT control system is a subsystem of the overall RH control system and therefore the investigation was started by an architectural design of the RH control system to guarantee a homogeneous structure, operation, and maintainability. The top down design results in a structure, separating the RH control system into areas as known from the NET control system /16/ /17/. The area of interest in the context of this paper is the ABS-area integrating all ABS components, that means the ABT, the work units and the supporting devices as for example the camera system (Figure 10). The functional components of the RH-areas are the area control and the various device control systems. The ABT control is one of these device control systems which provide the device dependent functions. Device independent functions of the ABS-area are combined to the ABS-area control. An area is operated via a NRWS. The investigations concerning the RH control system architecture and the NRWS are documented in /18/ /19/.

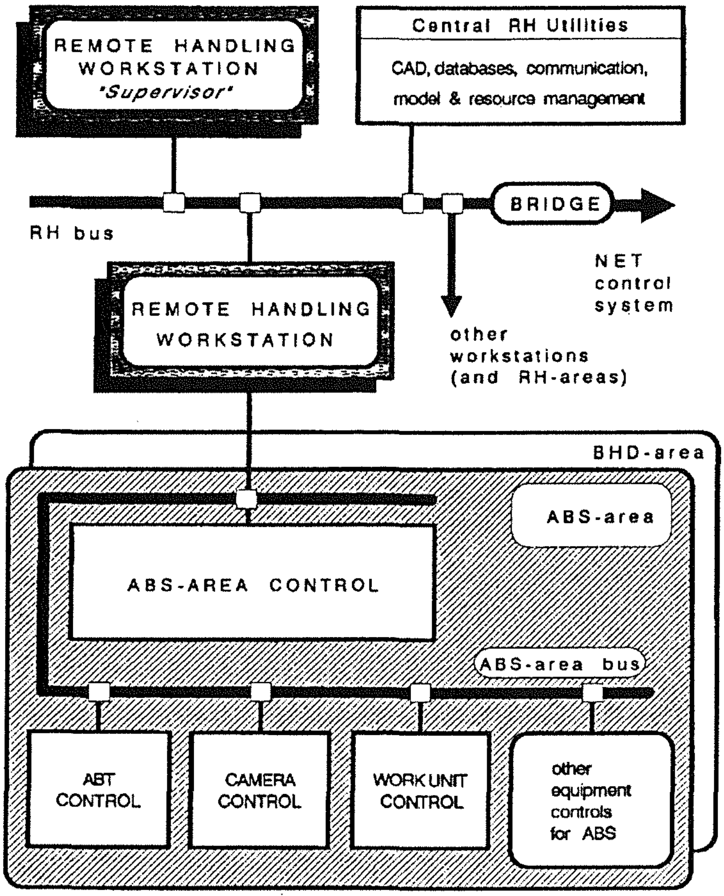


Figure 10. Functional RH control system architecture: The RH control system is functionally partitioned into RH-areas with an area control coordinating the activities of the various device controls of the area and providing device independant functions and a homogeneous interface to the NRWS. In-area communication is done via a separate RH-area bus which may be a LAN or a system bus. To run a RH-area a NET remote handling workstation is attached to the RH-area control. Communication of NRWS with each other or with the central RH utilities is done via the RH bus, which is bridged to the NET control system. The central utilities are services integrated with the NCS-wide data management with distributed data bases.

2.6.1 Requirements for the ABT control system

The ABT control system requirements are documented in /20/. The following main functions are required: basic motion control, backtracking of pathes, operator support for special functions (e.g. jiggs for motion control), general equipment control (non motion), on-line teach/repeat, logging of control actions. The system must be operatable in two modes: single command execution (manual mode), program execution (automatic mode) with interventions. An important feature with respect to the overall system is the controllability via the NRWS, demanding for a full access to all features of the ABS-area control system and in particular to the ABT control. But the central requirement is of course to guarantee a problem suited dynamic behaviour of the ABT.

2.6.2 Design and implementation aspects of ABT control system

The basic design proposal and implementation aspects of the ABT control are documented in /18/. The design is based on standard robot control system techniques enhanced by functions needed for the mixed operations mode and the special kinematics of remote handling systems. The general ABT control system is partitioned into two main parts:

1. A device independent part for program and data management and interfacing to the NRWS. This part represents the basic subset of the ABS area control function and is used for the WUs, cameras and other devices of the area as well.
2. A device dependent part (the ABT control in the narrow sense) providing the basic path planning and the closed loop control.

The objective of separating a device independent part is to make parts of the control system usable for different but comparable devices, which simplifies operatability and maintainability of the whole system. An important design guideline was to get a functionally modular design to guarantee a high flexibility with respect to sytem enhancements, extendability , and adaptability. To set up an open system architecture the implementation is recommended to be based on widely accepted standards for: in-subsystem communication (MULTIBUS II), inter-subsystem communication (Ethernet TCP/IP, ISO/DP-9506 MAP/MMS), real-time operating system (iRMX), programming language (C), motion description language (IRDATA).

3. Justification for EDITH

3.1 General Need to Demonstrate ABT Feasibility and Performances

"The development and construction of a prototype of a NET boom is needed to demonstrate beyond any doubt that the maintenance and removal of plasma facing components, in particular the divertor plates, is an operation that can be conducted with the anticipated reliability and time. In fact, if doubts remain, then one is forced to increase the complexity of the basic machine design to provide a backup option such as divertor cassette." (Quotation Prof.Dr. Toschi)

This demonstration will be performed by means of an "Experimental Device for In-Torus Handling" (EDITH) still without the NET typical radiation field and also not at NET typical temperatures, but otherwise meeting the NET relevant requirements. Accordingly the equipment used for the demonstration will be prototypical and presents the logical step between the "Proof of Principle" (POP) and the operational equipment as it is planned by NET. This prototype EDITH offers also the possibility to utilize some of its components and systems later for the operational equipment.

3.2 Objectives of EDITH Prototype

The purpose of EDITH is to validate handling procedures and to freeze the final design of the relevant components as well as the handling equipment. In particular this includes:

- Testing and validation of remote handling procedures

- Performance of integral tests of ABS components and subassemblies, i.e.

- universal work unit interface with integrated mechanical, electrical and hydraulic connections,
- drive units,
- control system,

with respect to

- integration of components and subassemblies into the main device,
- combined effects of different components and subassemblies, e.g. sensors, drive units and control system,
- identification of possible advancements, e.g. protection against dust, wiring,
- influence of the ABT behaviour on the tool development.

- Testing and validation of ABS work units
- Testing of the ABS-behaviour at the NET reference conditions -excepted are temperature and radiation- but using also the flexibility of the testbed, e.g. with respect to increase the boom length by adding additional links, application of other link material, installation of alternative drive units
  - to assess safety margins, e.g. with respect to stiffness and dynamic behaviour,
  - to test their dynamic behaviour and verify the dynamic model,
  - to investigate dynamic damping if required,
  - to test remote maintenance of equipment.

Boom components testing at NET temperatures and radiation is to be performed separately.

4. Justification for Full Scale Mock-ups

4.1 Technical Issues Requiring Mock-ups

In the following maintenance tasks and technical issues are listed which need to be investigated in mock-ups.

- Demonstration of maintenance tasks and operations as described in "NET In-Vessel Operation Requirements". In particular, emphasis must be given to the replacement of divertor modules and protective armour tiles under NET relevant conditions, as there are
  - NET geometry and available space,
  - typical IVC-installation,
  - remote control,
  - NET typical vision systems.

The aim of the demonstrations are

to show the feasibility of the maintenance operations,

to identify eventually required mudification of IVC-design or its installation,

to assess the reliability of handling equipment and tools,

to assess maintenance time,

to test the suitability of tools,

to identify possible improvement of equipment and tools.

- Testing of components and sub-assemblies in mock-ups and in conjunction with other ones. These are in particular

  WUs, including different types, e.g. EMSMs and DHD, and fabricates,

  sensor systems,

  vision systems.

Some of these tests, like vision and sensor system testing could be performed also in mock-ups in reduced scale, which means mainly with respect to the weight, and using available basic equipment, e.g. the JET boom. Nevertheless, this testing requires a relatively large effort and should therefore already be carried out in a full scale mock-up if such one is available.

4.2 Technical Issues Requiring Full Scale Mock-ups

Even though many aspects of the ABS operational behaviour can be predicted from

- simulation,
- JET experience, or
- small scale tests,

there remains the need for performing full-scale tests. The most critical issues calling for full scale testing are

- to test, improve (if necessary), and demonstrate the interoperability of all mechanical components of the ABS with auxiliary equipment (manipulators, tools) and the handled components (in particular divertor plates),

- to establish experimentally verified duration estimates for all in-vessel handling operations,

- to qualify the effect of deviations from the ideal behaviour of the control system, the drive units, and the mechanical system upon the reliability and performance of the whole ABS system in longterm operations,

- to identify and eliminate problems in recovery and repair of the ABS in case of failure.

The definition of a full scale mock- up is related to full size and full weight of the components to be handled, prototypical maintenance equipment and a realistic NET environment although not all environmental conditions like temperature and radiation can be simulated.

From the listing in section "Technical Issues Requiring Mock-ups", tasks and issues were identified which can only be performed or tested in a full scale mock-up, as there are

- demonstration of divertor module replacement,
- testing of work units,
- assessment of safety margins,
- dynamic behaviour and active damping,
- controllability and manouvrebility,
- verification of the calculated deflection and checking buckling deformations.

5. Integration of EDITH in the Full Scale Mock-up

Both the testbed EDITH and the mock-up will have to be performed in full scale. Therefore it is necessary and usefull to combine them in a common test facility. This combination has also the following advantages:

- Saving costs and manpower by having only one test device
- The mock-up and EDITH are only used for the previously described tasks. Thus EDITH is independent from other working interests than maintenance demonstration and tests
- Using eventually improved and advanced features in the mock-up
- Some components and systems may be used later for the operational NET equipment
- Improvements of EDITH are possible without respect to other functions of the testbed

6. Description of the Proposed EDITH and Full Scale Mock-up

6.1 Testbed EDITH

EDITH is the prototypical basic handling equipment for in-vessel components. The design is based on NET requirements as described in "NET In-Vessel Operation Requirements" with some exceptions described in "Differences between EDITH and operational equipment".

The testbed EDITH (Figure 11) is composed of the following main subassemblies:

- Support structure
- Articulated boom with four links and the end-frame

- Work unit interface flange (WUIF)
- Work units
- Control system consisting of the supervisory, motion and drive unit control

6.1.1 Support structure

The support structure Drwg.Nr. IT-OUT-08-423B is supposed to substitute the transport carrier of the later operational equipment in EDITH. It consists of a girder construction which is attached to the floor. Structure and fixation of the structure are calculated for maximum bending moments and maximum torques of 1200 kNm. The material of the support structure is RSt.37-2.

6.1.2 Articulated boom

The EDITH articulated boom as shown in Figure 11 is composed of the four links B1 to B4. The end-frame acts as interface for the attachment device of work units or directly as the work unit interface. The boom links B1 to B4 as well as the cantilevered arm C1 are connected by the link joints Z1 to Z4. One of these yaw joints is shown as an example in the drawing IT-OUT-08-423B. The link B4 (Drwg.Nr. IT-OUT-08-411B) has an additional pitch joint Z5 and a rotation joint Z6.

6.1.3 Work units and work unit interface

The WUs for EDITH will be prototypes of those for the NET operational equipment which are described in "Summary of ABT Requirements Resulting from Work Unit Investigations". They are remotely attachable and detachable via the work unit interface flange (WUIF) (Figure 12). As there are at least two types pf WUs (DHD and manipulator unit) a common WUIF will be used.

For the WUIF there are two options possible:

- Locating the interface at the end-frame of the ABT
- Locating the interface at the slide of the WU, thus having a common trolley plus slide for all WUs

The advantage of the first solution is that trolley and slide can be different for DHD and manipulator unit, resulting in a reduced weight for the latter one. On the other hand the second solution has the advantages to reduce the numbers of trolley and slide, as the same WUs may be used at the ABS and the IVVS, and to handle smaller WUs and consequently reducing the costs. Although the second solution is preferable it must be guaranteed that inside the torus a disconnection of trolley and end-frame will be possible for emergency case, e.g. seizure of the trolley and required removal from the top of the NET device. Both options are to be investigated further on.

For taking over loads, e.g. for the withdrawal of divertor modules by means of the DHD, sensors are needed. The required investigations and tests will be performed by means of a work unit dummy (Drwng.Nr. IT-OUT-08-164), which consists of a telescopic arm with a load capacity of 1000kg and which is attachable to the end-frame of EDITH.

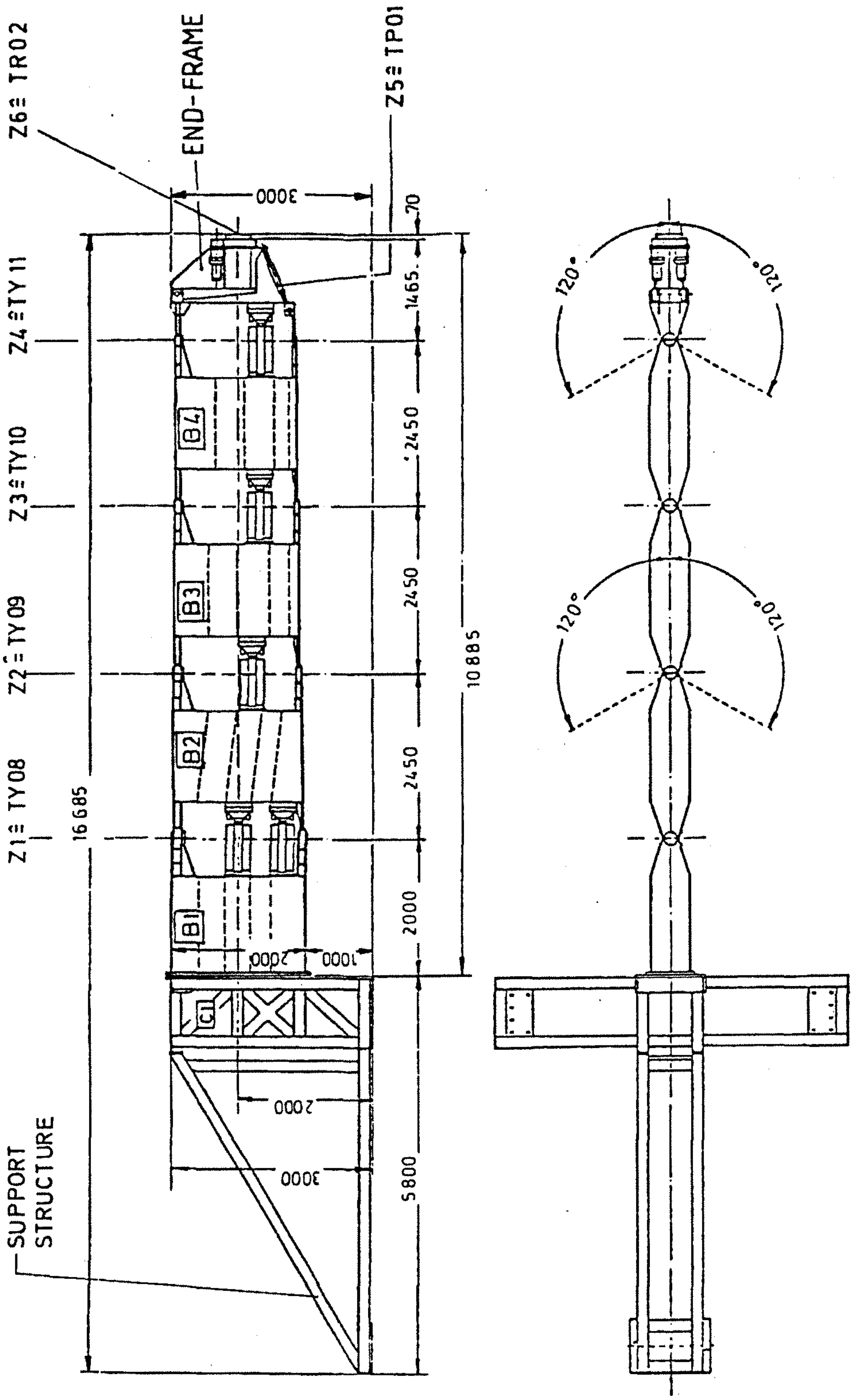


Figure 11. Testbed EDITH

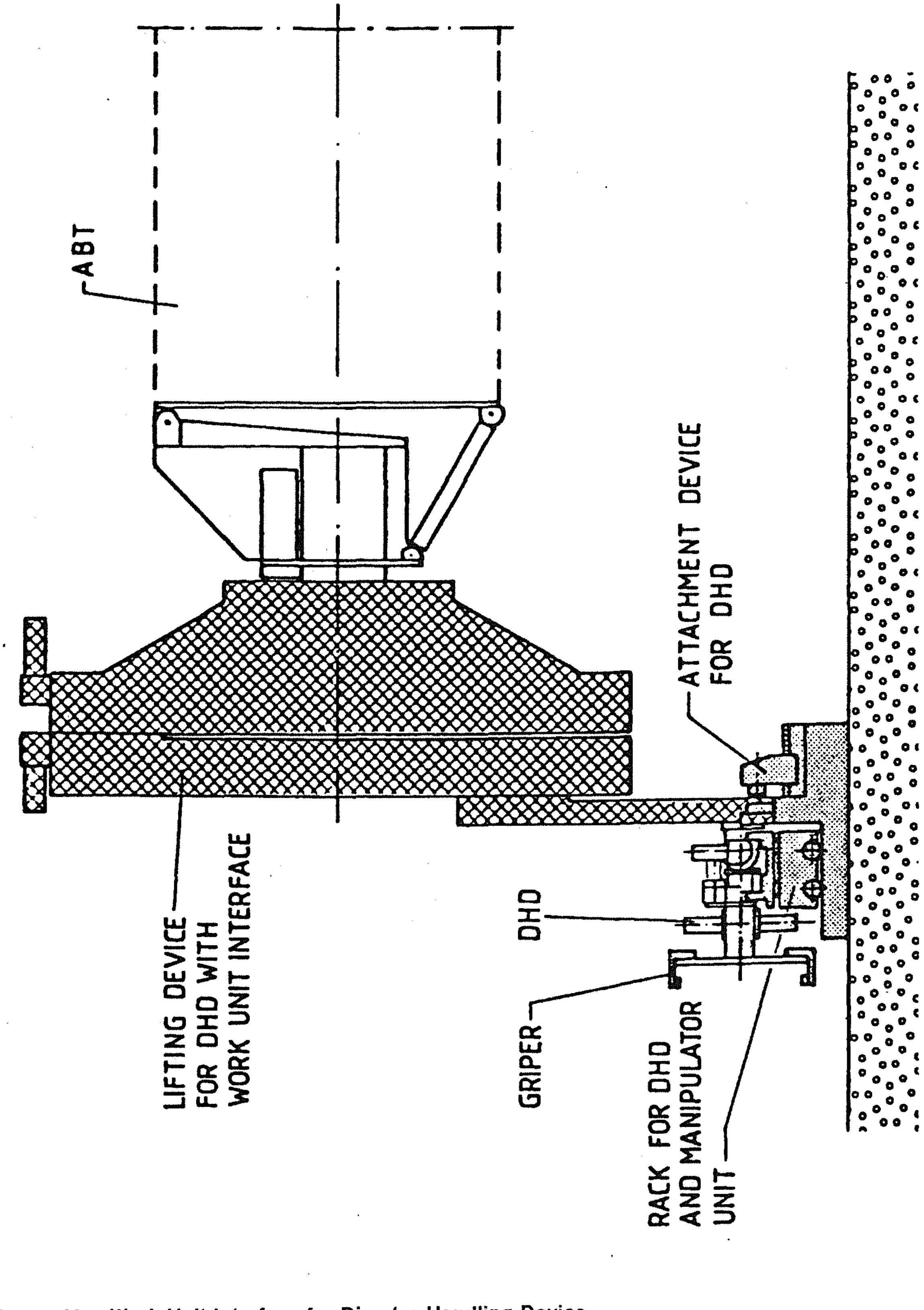


Figure 12. Work Unit Interface for Divertor Handling Device

6.1.4 Differences between EDITH and operational equipment

In the following differences between EDITH and the NET operational equipment are listed. They are mainly caused by having good accessibility for maintenance and improvement of EDITH and to reduce the costs of EDITH and the mock-up.

- The EDITH cantilever arm is shorter than the ABS one and the movable carrier of the ABS is substituted by a fixed support structure.
- EDITH will operate at temperatures $\leq$40°C and in a radiation free field.
- EDITH is made of ferritic steel which has the same admissible stresses at a temperature <40°C as the austenitic steel used for the operational equipment at a temperature of +150°C.
- For the operational equipment link B3 may be manufactured in Al-alloy.
- The remote maintainability of EDITH will be demonstrated only at one subassembly if there are more than one subassemblies of the same type in order to allow pretesting.
- In a first step of EDITH, standard cables and transmission lines are used. Based on the experience of the separate irradiation tests they will be substituted later. The same is also valid for other radiation sensitive components.

6.2 *Full Scale Mock-up*

Figure 13 shows the plan view of the full scale mock-up. It is based on the NET torus geometry and simulates two areas of the torus.

One area represents a torus sector of 22.5°. Its center is located almost perpendicular to the maintenance entry port, thus gaining the maximum loads for the boom. The area is devoted to simulate maintenance operations, e.g. divertor module replacement and tile replacement. In a first step the equatorial plane of the mock-up is at a height of 2m to have relative good access to the boom. In this case the upper half of the torus is simulated (Figure 14). To simulate also the lower part, in a second step EDITH will be lifted and fixed on an auxiliary support structure (Figure 15).

The second area of interest is the maintenance port itself to simulate the insertion and withdrawal of the boom. Both areas are connected at a height of 2m around the equatorial plane to simulate the torus boundary.

The mock-up will be completed by the racks for the storage of WUs.

Later additions such as carrier and cantilever arm can be made as well as simulations of the influences of these components on the operational behaviour by simpler means added to the EDITH suspension.

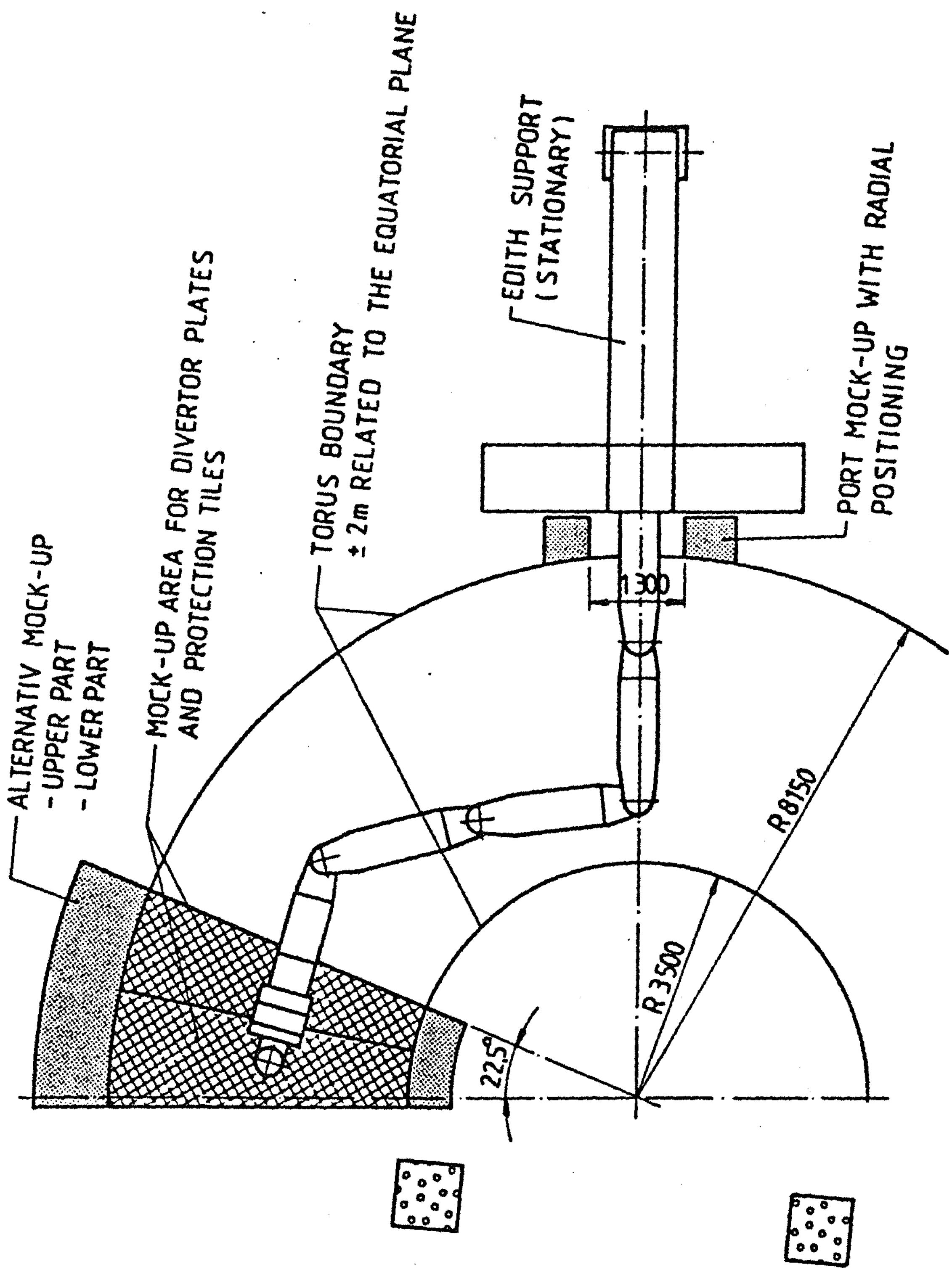


Figure 13. Scheme of Full Scale Mock-up - Plan view

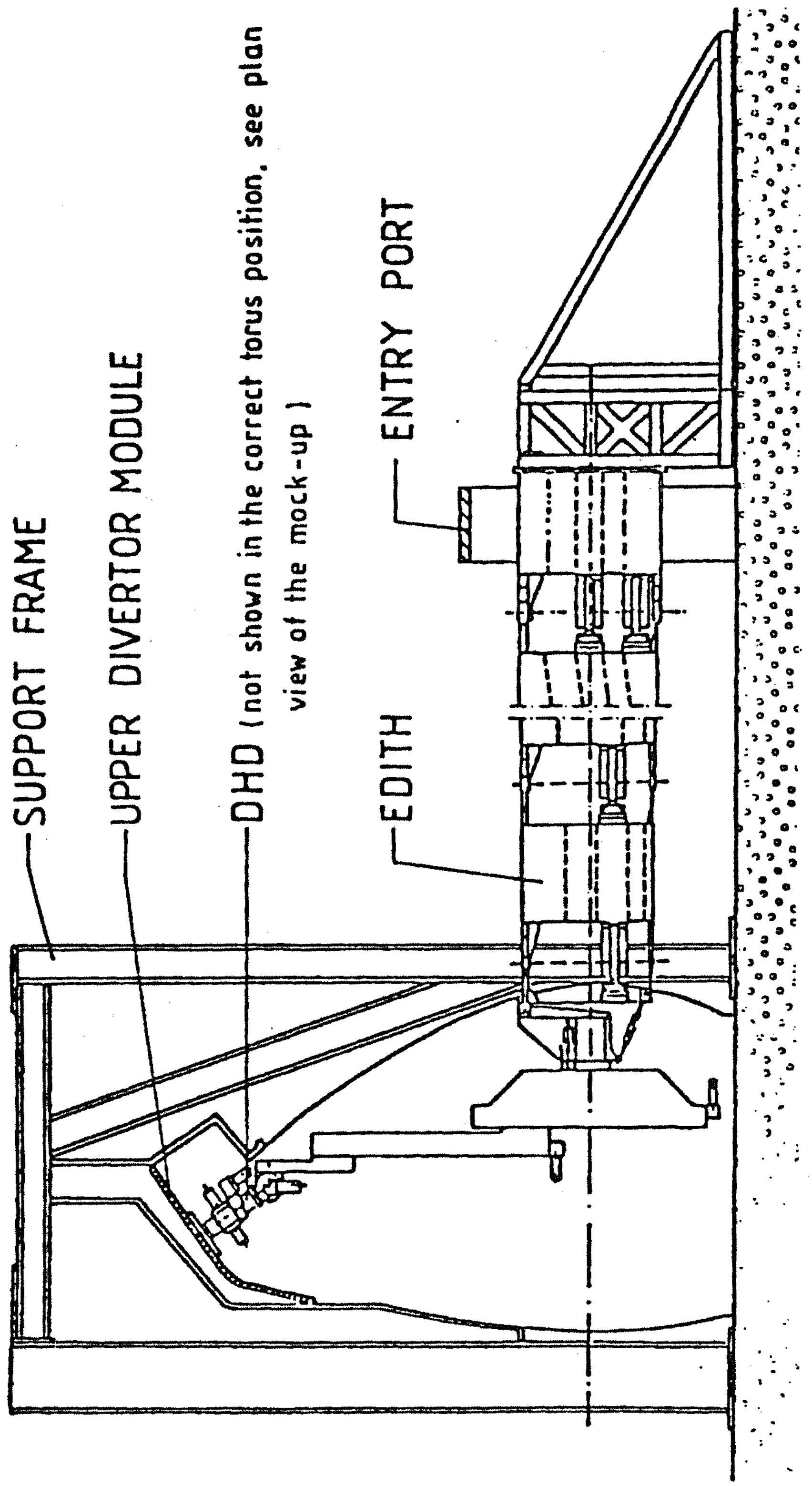


Figure 14. Scheme of Full Scale Mock-up - Upper Part

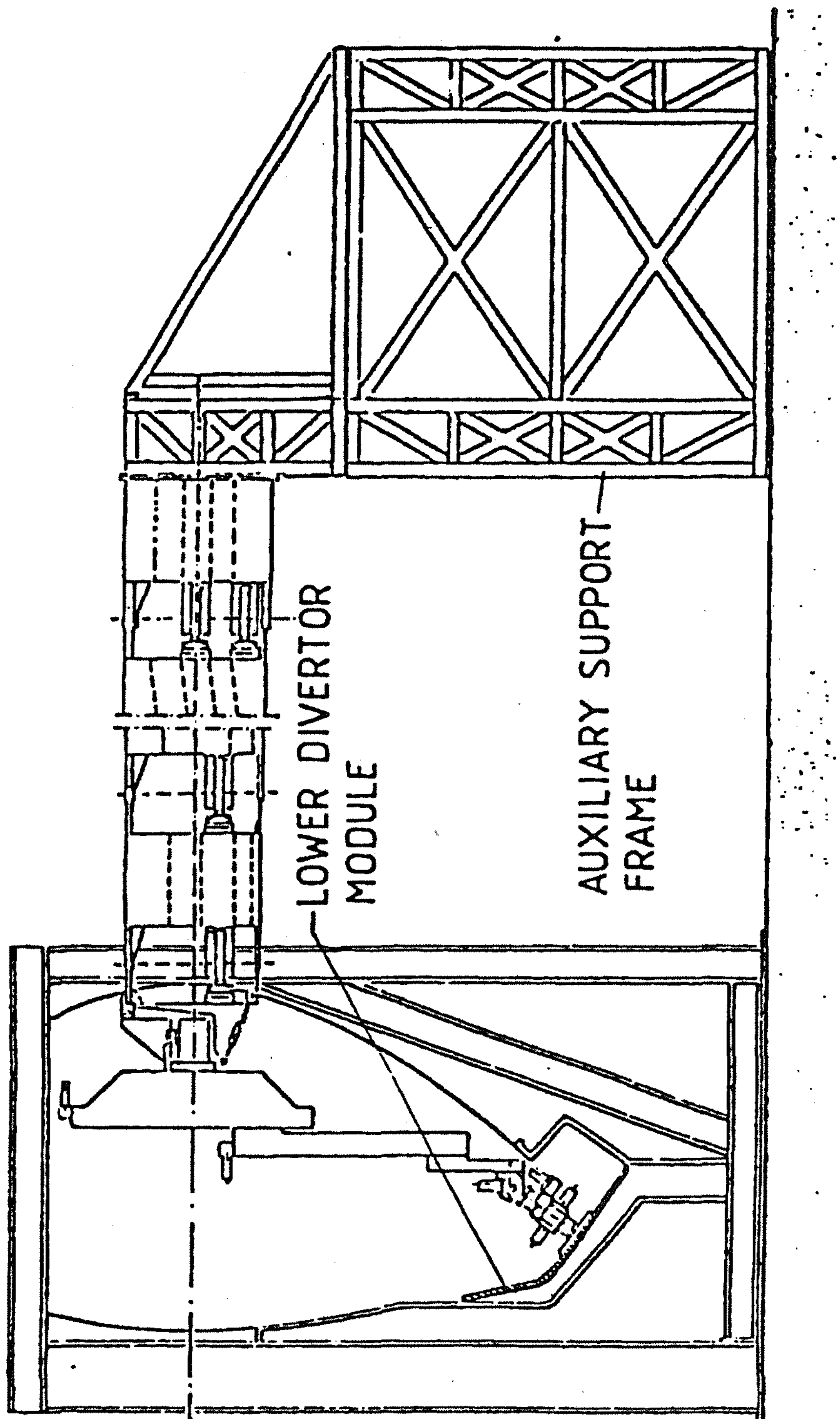


Figure 15. Scheme of Full Scale Mock-up - Lower Part

6.3 *EDITH Motion Control System*

The motion control system has to control EDITH as the central transport unit in the remote handling area. The control system was designed for easy extendability and adaptability allowing to include further enhancements of hard- and software.

The specification of the EDITH motion control system is documented in /21/.

6.3.1 Motion control system architecture

In the process of realizing the EDITH control system the JET-TARM control system was investigated as an implementation base. It turns out that the JET-TARM control system functions and components form a subset of the requested ABS functions and components /20/.

The TARM HLCS (High Level Control System) represents the device independent functions (basis of the ABS-area control), the TARM LLCS (Low Level Control System) the device dependant part of the ABT control.

Figure Figure 16 shows how the EDITH control system architecture based on the TARM control system concept is mapped on real hardware. The main difference to the TARM control system is, that the low level control system is now implemented on a MULTI-BUS-II system, running on powerfull CPU-boards (INTEL 80386) with an application software being adapted to the iRMX-II-operating software.

The reasons for these modifications are the following:

- To allow a step by step development of the final ABS control system, the EDITH control system must be easily expandible with respect to hardware and software. It must be an "Open System", i.e. a system beeing open to modifications by third parties and a high degree of integrability
- Upgrade to higher performance should easily be possible, as the complexity of the final ABS control system is likely to increase. A demand for higher performance could be coped with either by distribution of functionality or by means of increasing computer power

The most important argument for basing the EDITH control system on the TARM control system was to facilitate the close cooperation between KfK and JET especially in the area of MMI (workstation development and enhancements) and advanced control algorithms.

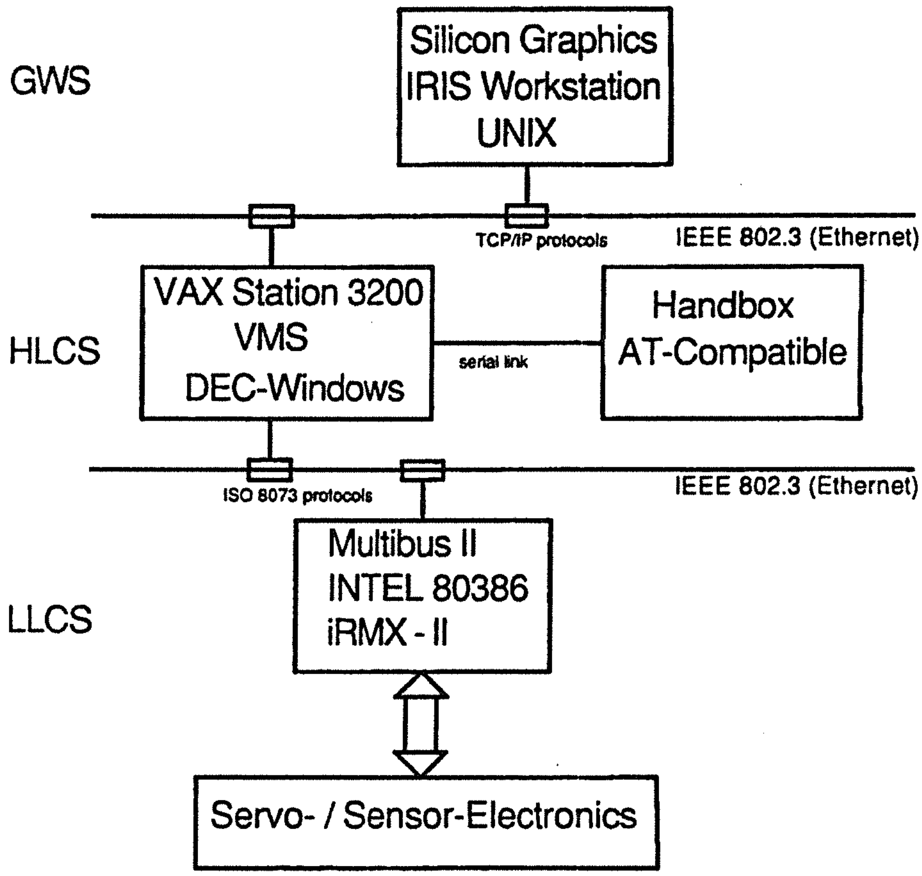


Figure 16. EDITH Motion Control System Hardware Architecture

6.3.2 Position control

Position control is a vital part of the motion control system. The position control has the task to convert as exactly as possible and without delay the desired values given for example from the path planning modul into a real motion. The effect of disturbances, e.g. force impacts, have to be compensated.

In a first stage it is intended to use and test a single joint control. Performance tests have to be done e.g. concerning

- repeatability
- absolut positioning accuracy
- time response, maximal overshoot
- minimal commanded change (motion step)

If the dynamic performance using the above control scheme is not satisfying, it may be necessary to implement advanced control algorithms like Inverse Model or adaptive control techniques:

Adaptive control schemes: As the parameters of EDITH vary during operation (e.g. taking over divertors with a weight of about 1000 kg) one possible approach is to use an adaptive control technique especially a so called reference model concept. In this concept the differences between the states of a reference model (which is an explicit realization of an optimal system) and those of the real plant are measured and used to modify the controller to achieve a certain index of performance.

Inverse model techniques: If there are higher demands concerning path accuracy and velocity it might be necessary to apply Inverse Model techniques, which consider nonlinearities and couplings between motion axis directly in the control algorithm.

Other points of interest are:

- To remove backlash and to stiffen the boom additionally it is intended to implement electric backlash removal. As the drives of EDITH are split into units due to the high driving torques required, these units may also be used to preload the gears electrically

- To eliminate oscillations of the motors resulting from elasticity inherent to the drive units additionally internal damping will be needed. This may be done e.g. by measuring the motor and axis speed, deriving suitable signals and adding these signals to the set point current.

- Taking over heavy loads results in exciting oscillations of the boom. These oscillations may be measured and compensated either by corresponding movements of the boom itself or by additional active spring-damper-mass-systems

7. Integration of EDITH in the European Technology Programme

EDITH and the Full Scale Mock-up are essentials of the European Technology Programme /14/ and discussed in several expert group meetings. They are based on the experience gained from JET.

Exploitation of EDITH and the Full Scale Mock-up by other associations which are also involved in in-vessel maintenance and which are developing or modifying equipment for this purpose is foreseen. For example this is valid for work units, i.e. master slave servo manipulators, tools but also maintenance operations.

8. Timeschedule

The timeschedule for the manufacture is given in the following. In addition, the schedule is extented to a certain degree for the test planning although due to the exploitation of EDITH and the mock-up by other associations the detailed planning will have to be worked out in cooperation with NET and the associations. To assess exactly the reliability of the ABS, a functional analysis will be performed until October '90.

Timeschedule for EDITH, Full Scale Mock-up and Testing																									
Activity	1990												1991												1992
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	
Manufacture EDITH mech. part	x	x	x	x	x	x	x	x	x	x	x	x													
Assembly and commissioning of EDITH (assembly of drive units and resolvers, wiring etc.)													x	x	x	x	x	x	x	x	x	x	x		
Implementation of EDITH control system													x	x	x	x	x	x							
Testing of EDITH components and subassemblies															x	x	x	x	x	x	x	x	x	x	x
Design WUIF				x	x	x	x	x	x																
Manufacture WUIF										x	x	x	x	x	x	x	x	x	x	x	x	x	x		
Testing availaible WUs, e.g. manipulator units																								x	xxx
Design full scale mock-up				x	x	x	x	x	x																
Manufacture full scale mock-up									x	x	x	x	x	x	x	x	x	x	x	x	x				

Timeschedule for EDITH, Full Scale Mock-up and Testing (continued)

Activity	1990												1991												1992
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	
Conceptual design of the DHD	x	x	x	x	x	x	x	x																	
Preliminary design and specification of DHD									x	x	x	x													
Manufacture and commissioning DHD, performing preliminary tests													x	x	x	x	x	x	x	x	x	x	x	x	
Divertor handling maintenance tests																							x	x	x->Jun 92
Investigation tile handling tools				x	x	x	x	x	x																
Preliminary design and specification of tile handling tools										x	x	x	x	x	x										
Manufacture and commissioning tile handling tools, performing preliminary tests																x	x	x	x	x	x	x	x	x	
Tile handling maintenance tests																									xxx

9. List of Drawings

IT-OUT-08-423B	Support Structure for EDITH (Teststandgerüst)
IT-OUT-08-422B	Link Joint Z1 (Gelenk 3L)
IT-OUT-08-411B	Link B4 (Gliederarm K1)
IT-OUT-08-414B	Link B1 (Gliederarm L3)
IT-OUT-08-164	Work Unit Dummy
IT-OUT-12-001/3	Coaxial Drive Unit
IT-OUT-07-082	Linear Actuator for Pitch Joint Z5

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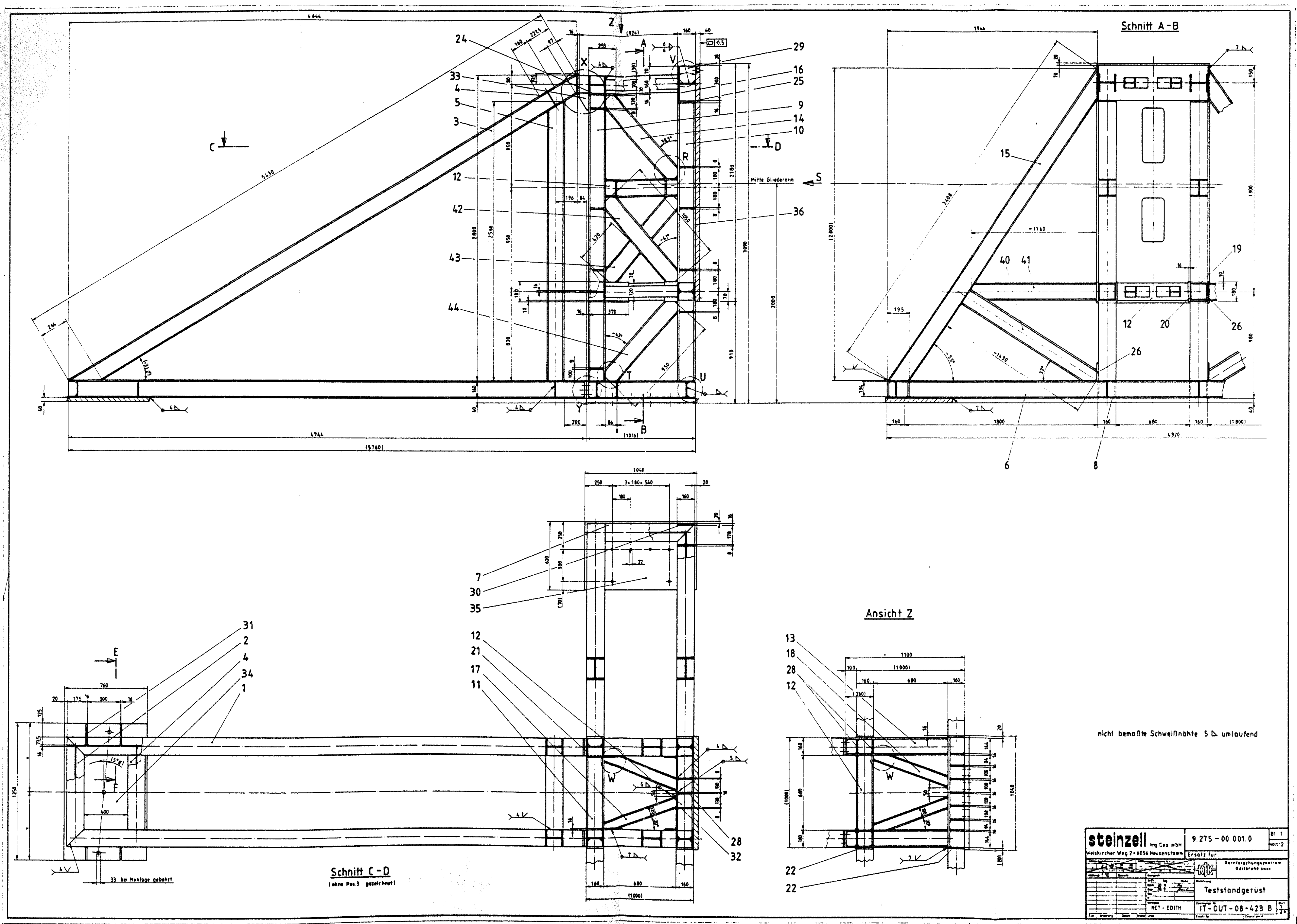
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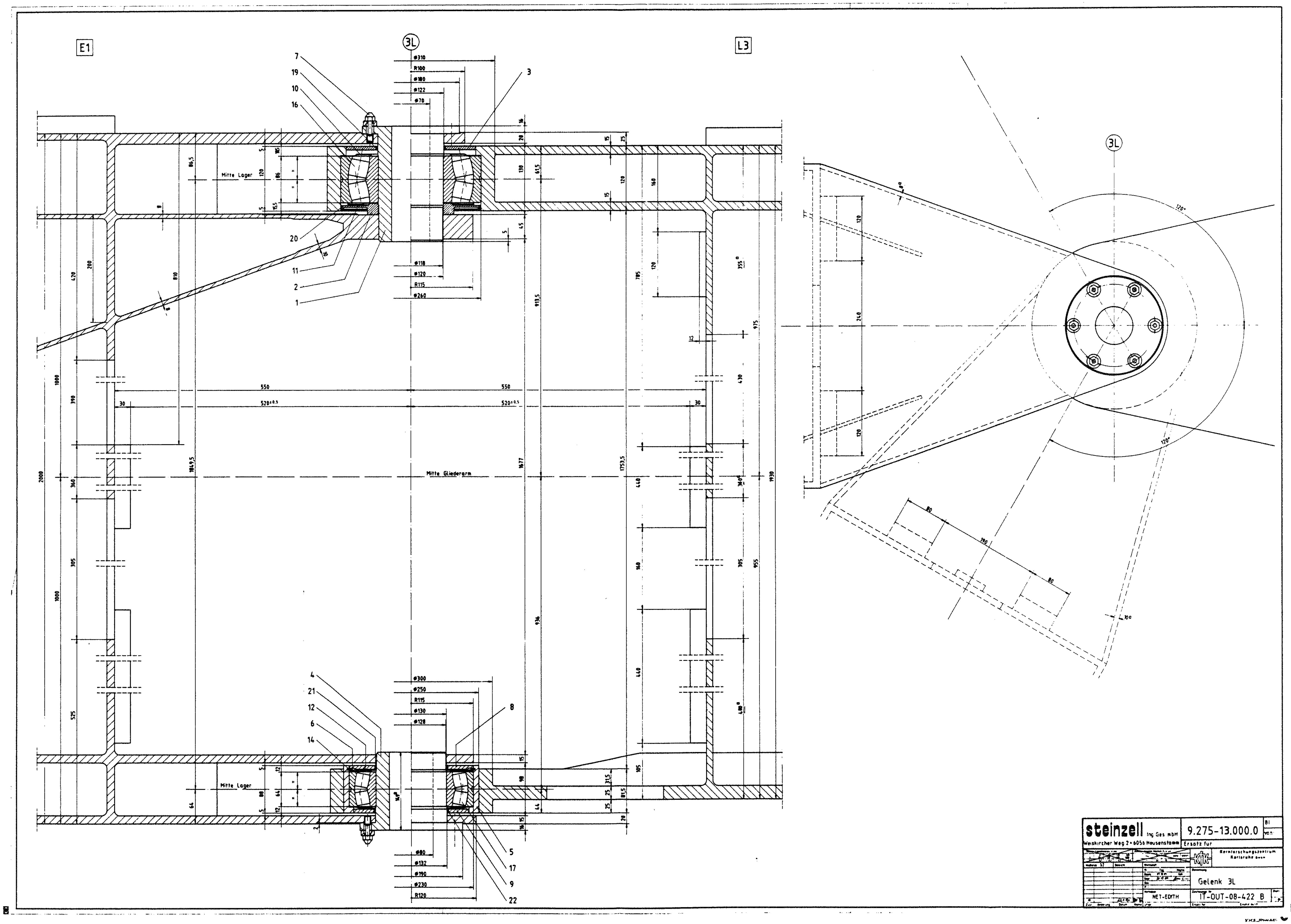
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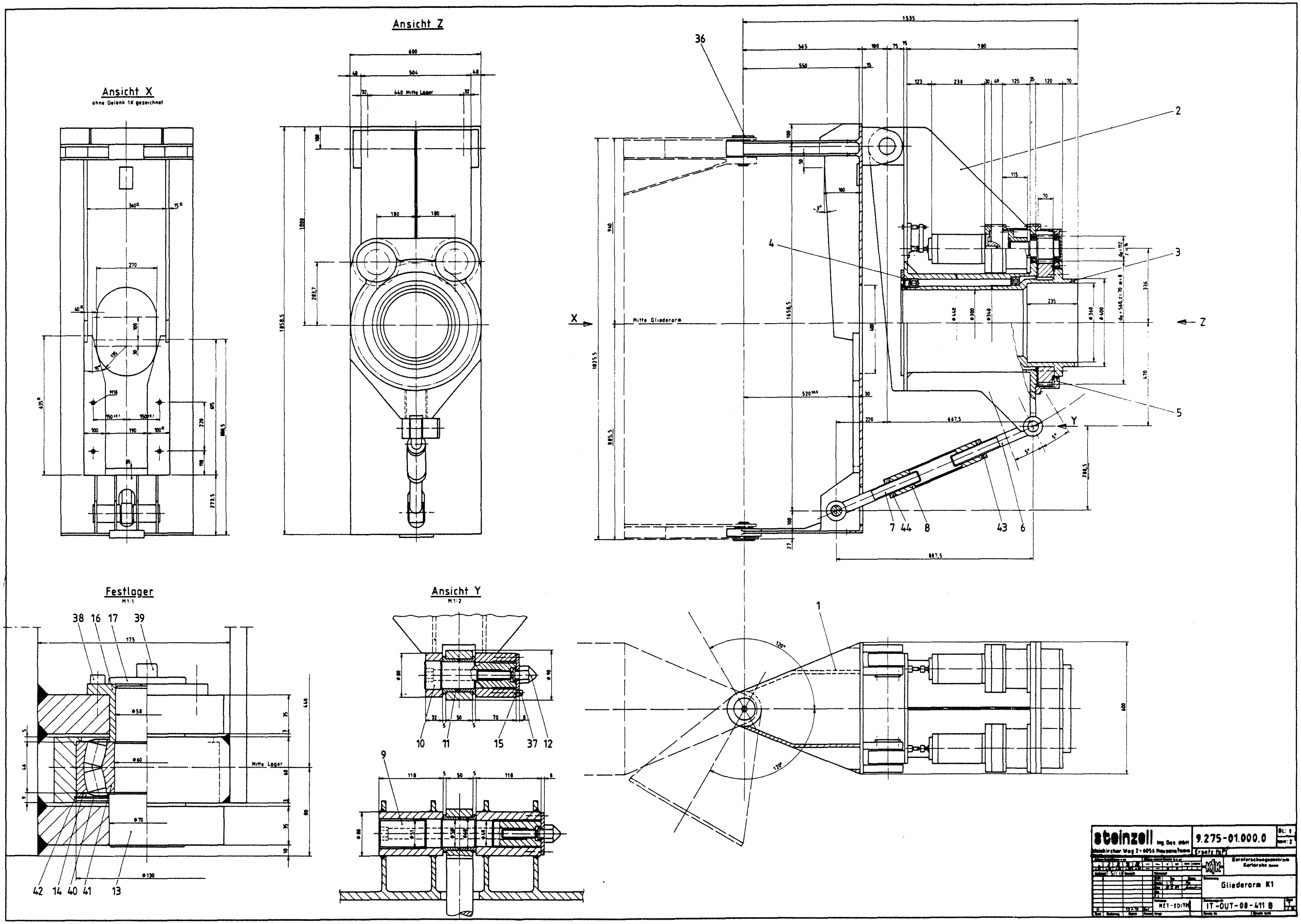
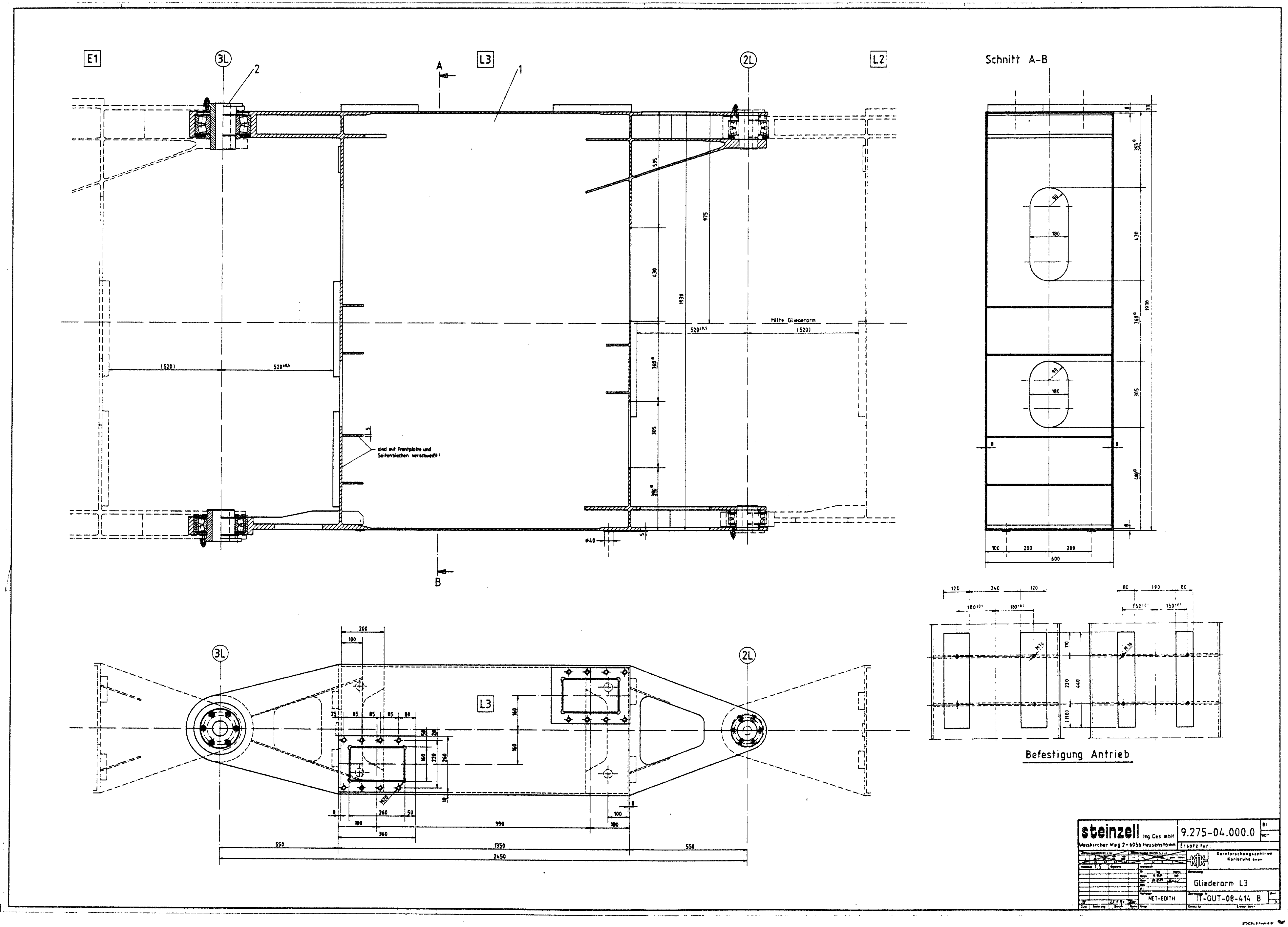
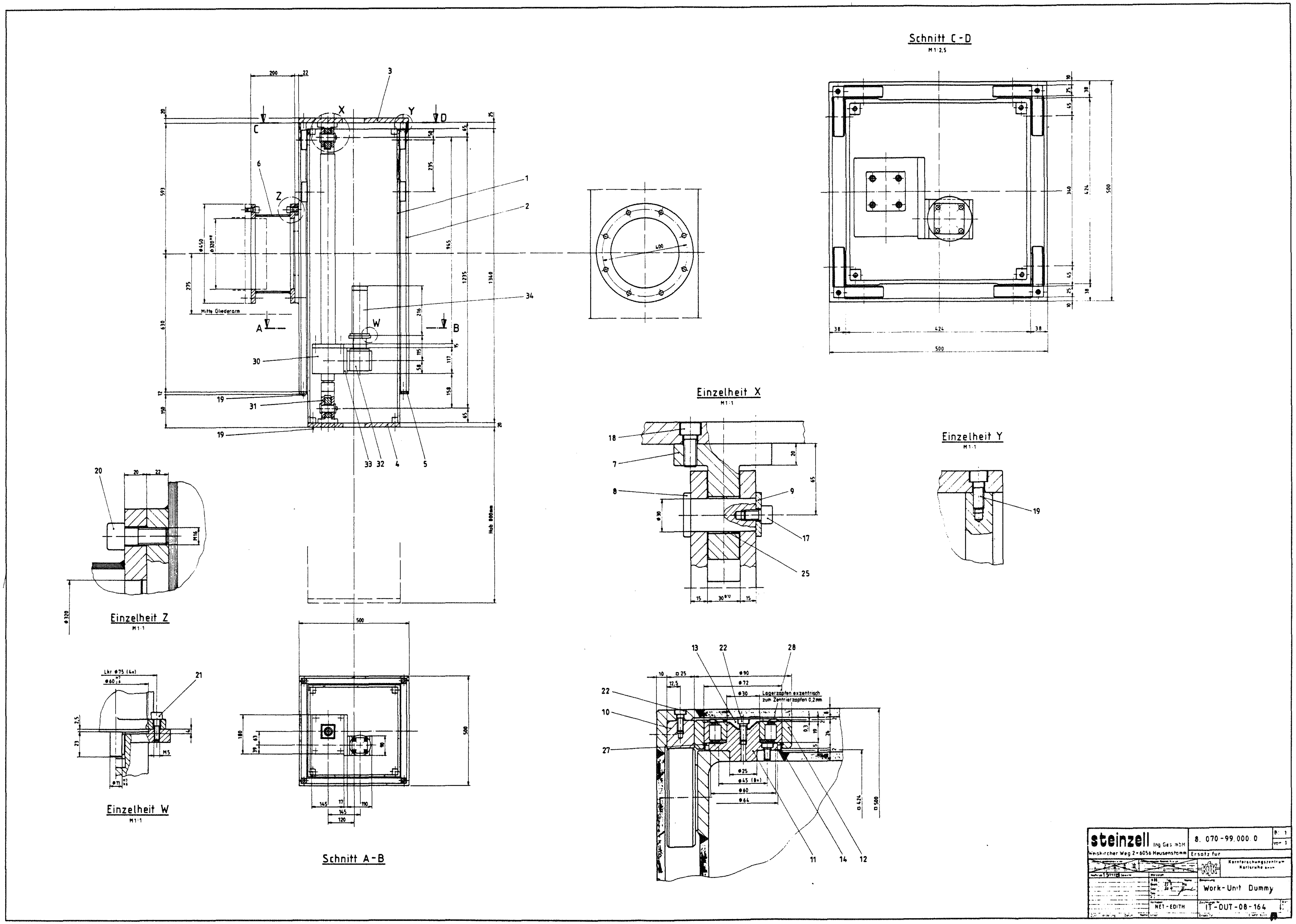
von
Ersatz für
Kernforschungszentrum
Karlsruhe GmbH
Gelenk 3L
NET-EDITH
IT-OUT-08-422 B



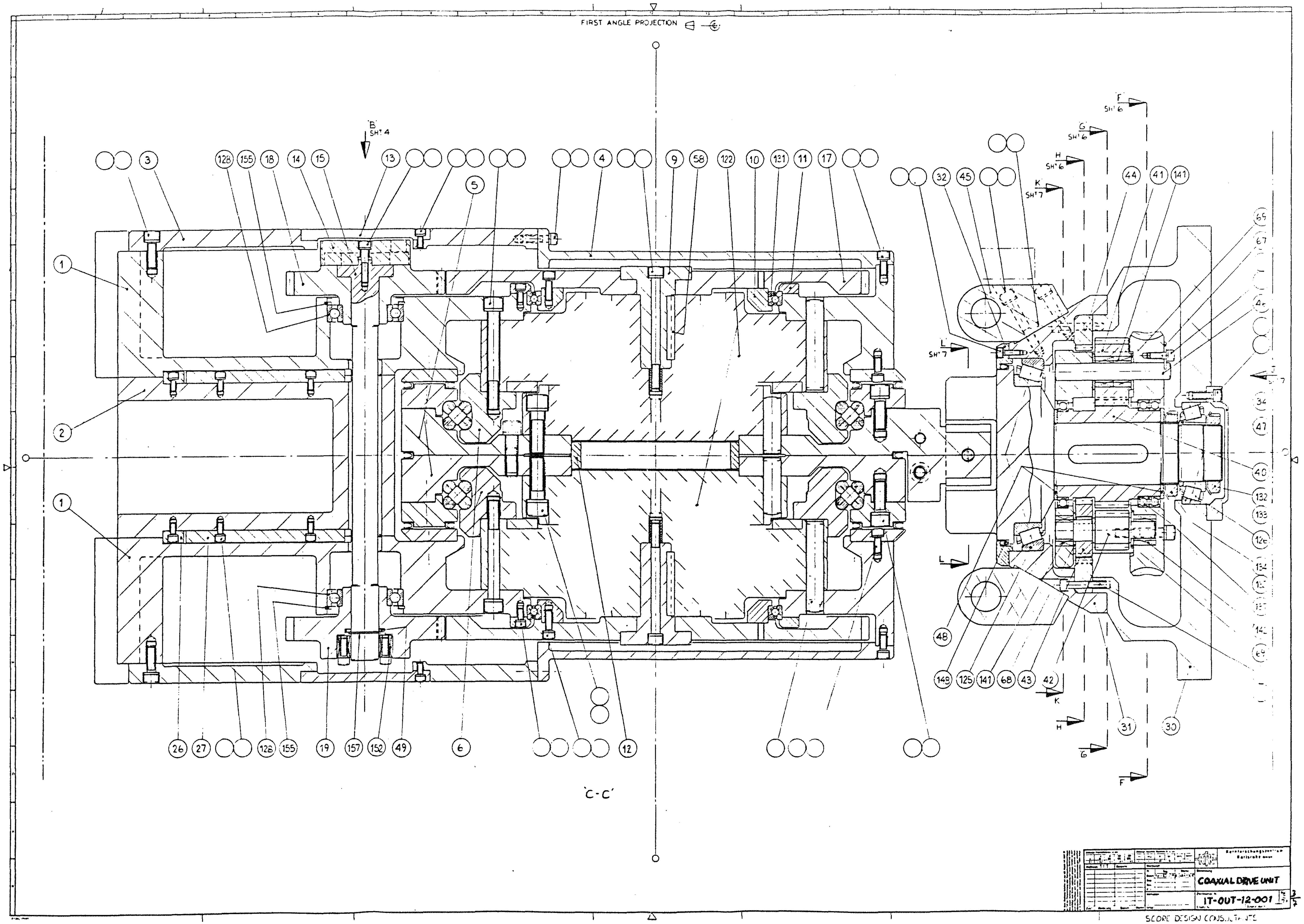
Ansicht X
ohne Gelenk 1K gezeichnet
Ansicht Z
Mitte Gliederarm
X
Z
Y
Festlager
M 1:1
Mitte Lager
Ansicht Y
M 1:2
steinzell Ing. Ges. mbH
9.275-01.000.0
BL: 1
von: 2
Ersatz für:
Kernforschungszentrum Karlsruhe
Gliederarm K1
NET-EDITH
IT-OUT-08-411 B



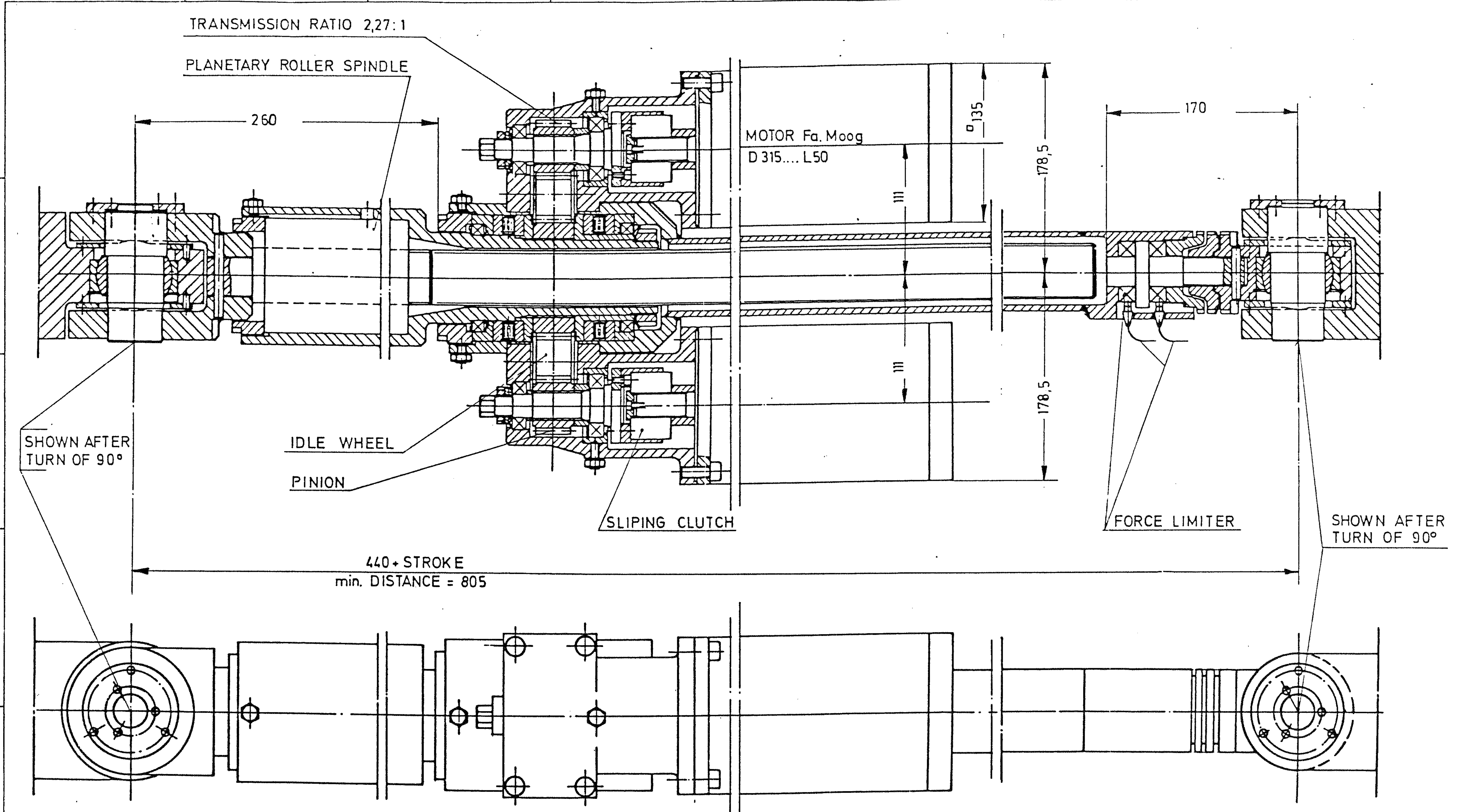
E1
3L
2
A
L3
1
2L
L2
Schnitt A-B
Mitte Gliederarm
sind mit Frontplatte und Seitenblechen verschweißt!
B
Befestigung Antrieb
steinzell Ing Ges mbH
Weiskircher Weg 2 • 6056 Heusenstamm
9.275-04.000.0
Ersatz für:
KfK
Kernforschungszentrum Karlsruhe GmbH
Gliederarm L3
NET-EDITH
IT-OUT-08-414 B



Schnitt C-D
M 1:2,5
Einzelheit X
M 1:1
Einzelheit Y
M 1:1
Einzelheit Z
M 1:1
Einzelheit W
M 1:1
Schnitt A-B
Mitte Gliederarm
Hub 800mm
Lagerzapfen exzentrisch zum Zentrierzapfen 0,2mm
steinzell Ing Ges mbH
Weiskircher Weg 2 • 6056 Heusenstamm
8. 070-99.000.0
Ersatz für
KfK
Kernforschungszentrum Karlsruhe GmbH
Work-Unit Dummy
NET-EDITH
IT-OUT-08-164



SCORE DESIGN CONSULTANTS



Zulässige Freimaßtoleranz in mm					Zulässige maximale Rauhtiefe R_t in µm					
- 6	6-30	30-120	120-400	400-1000	—	~	▽	▽▽	▽▽▽	▽▽▽▽
± 0,1	± 0,2	± 0,3	± 0,5	± 0,8	—	—	63	16	4	1

Kernforschungszentrum Karlsruhe GmbH

Maßstab 1:3,3 | Gewicht | Werkstoff

1990	Tag	Name
Bearb.	12. 04.	Lück
Gepr.		
Ges.		
P. I.		

Benennung: **LINEAR ACTUATOR FOR PITCH JOINT Z5**

Vorhaben: IVHU

Zeichnungs-Nr.: **IT-OUT-07-082**

Blatt | Bl.

Zust.	Änderung	Datum	Name

Urspr. | Ersatz für: | Ersetzt durch: