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Entwicklung und Erprobung eines benthischen Landersystemes zur *in situ*-Bestimmung von Sulfatreduktionsraten mariner Sedimente

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The answers to questions are gained

in joy and in pain.

F. Bornemann

Vorwort und Danksagung

Diese Arbeit wurde inspiriert und gefördert von Prof. Dr. Bo Barker Jørgensen und finanziell unterstützt durch die Max-Planck-Gesellschaft. Dr. Ronnie Glud und Dr. Jens Gundersen fungierten während der Entwicklungs- und Erprobungsphase des Gerätes sowie während der verschiedenen Projekte als Ansprechpartner und Betreuer. In der vorliegenden Arbeit sind drei eigenständige Manuskripte zusammengefaßt, die bei international anerkannten, englischsprachigen Fachzeitschriften zur Veröffentlichung eingereicht sind. Außerdem finden sich am Ende der Arbeit die technischen Zeichnungen aller Bauteile und Bauteilgruppen des von mir entwickelten und gebauten Landers.

Als Doktorand am Max-Planck-Insititut für marine Mikrobiologie arbeitete ich als Mitglied der sogenannten Landergruppe, die aus den Doktoren Ronnie Glud und Jens Gundersen bestand. Beide befaßten sich bereits seit einigen Jahren mit der Landertechnologie und besitzen auf diesem Gebiet umfangreiche Kenntnisse. Die existierenden Lander waren zum einen ein Gerät zur *in situ*-Erfassung von Sauerstoffmikroprofilen (und später auch anderer Parameter wie z. B. Sulfid, pH) über die Sediment-Wasser-Grenze (PROFILUR), zum anderen ein benthischer Kammerlander, mit Hilfe dessen die Austauschraten gelöster Substanzen *in situ* erfasst werden können (ELINOR). Die vielfache erfolgreiche Anwendung dieser beiden Lander in den vorausgegangenen Jahren war Anlaß, die Entwicklung eines weiteren Gerätes in Betracht zu ziehen, das die *in situ*-Bestimmung der Sulfatreduktion ermöglichen sollte, einem bedeutenden Prozeß im globalen Abbaugeschehen organischen Kohlenstoffes. Die Anregung zu diesem Projekt kam ursprünglich von Herrn Prof. Bo Barker Jørgensen, der sich seit vielen Jahren mit dem marinen Schwefelkreislauf befaßt und insbesondere die herausragende Rolle der Sulfatatmung bei dem Abbau organischer Substanz herausgestellt hatte.

Die Ideen, wie ein Lander zur Messung der *in situ* Sulfatreduktionsraten technisch und wissenschaftlich zu realisieren sei, wurden von mir entworfen und in konstruktiven Gesprächen innerhalb der Landergruppe verbessert. Dabei orientierte ich mich, soweit dies sinnvoll und möglich war, an den bereits im Institut bestehenden Ansätzen bzw. technischen Lösungen und

konzipierte das Gerät (LUISE) so einfach wie möglich, um eine optimale Anwendbarkeit zu erzielen. Zur Erprobung verschiedener technischer und wissenschaftlicher Ansätze, die bei dem Bau des Gerätes Verwendung fanden, führte ich eine Reihe von Experimenten durch, auf die im Rahmen dieser Arbeit nur kurz eingegangen wird (siehe Einleitung). Das Instrument selbst wurde von der dänischen Firma KC Denmark Research Equipment als Auftragsbau nach von mir erstellten detaillierten technischen Zeichnungen angefertigt. Diese Zeichnungen sind als Anhang der vorliegenden Arbeit beigefügt und entsprechen dem gegenwärtigen Stand des Landers. Die Zeichnungen habe ich erstellt, mit Ausnahme von wenigen, die im Anhang mit dem Namen des Zeichners gekennzeichnet sind.

Im Folgenden gebe ich eine Übersicht über die von mir und meinen Kollegen geleisteten Arbeiten, die in Form der Veröffentlichungen in den einzelnen Kapiteln dieser Arbeit zusammengefaßt worden sind. Im ersten Manuskript (Kapitel 2.1) wird das von mir entwickelte Landegerät zum ersten Mal vorgestellt, zusammen mit einem Datensatz, der auf einer Ausfahrt ins Gotlandbecken gewonnen wurde und der die neuartigen *in situ*-Daten den auf herkömmlichem Wege im Labor ermittelten gegenüberstellt. Ich organisierte und koordinierte diese Fahrt und war verantwortlich für die Einsätze meines Landers; außerdem stammen alle in den gezeigten Daten verwandten Berechnungen von mir. Andreas Weber half mir bei der zeitaufwendigen Bearbeitung der Sulfatreduktionsproben. Ich verfaßte das Manuskript mit inspirierender Unterstützung von Prof. Jørgensen und Dr. Glud. Das zweite Manuskript (Kapitel 2.2) beinhaltet den kompletten Datensatz der bereits erwähnten Ausfahrt ins Gotlandbecken. Die auf dieser Reise gewonnenen *in situ*- und Labordaten verwandte ich, um die am benthischen Abbaugeschehen beteiligten Prozesse zu quantifizieren und in Relation zur örtlichen Primärproduktion und dem dauerhaften Entzug organischen Materials durch Vergrabung zu stellen. An dieser Fahrt nahmen außer mir noch Wolfgang Rieß, Andreas Weber und Frank Wenzhöfer teil, die als Doktoranden am MPI beschäftigt sind. Dr. Ola Holby begleitete uns als Fahrtleiter. Diese Ausfahrt war die erste, auf der alle drei Lander des MPIs erfolgreich zusammen eingesetzt wurden. Frank Wenzhöfer betreute den Lander PROFILUR und stellte für das Manuskript die Messungen des diffusiven Sauerstoffflusses ins Sediment zur Verfügung. Wolfgang Rieß arbeitete mit dem Kammerlander ELINOR; von ihm stammen die *in situ*-Daten der benthischen Nährstoffflüsse, an deren Analyse

auch ich beteiligt war, sowie die Daten zur beobachteten Makrofauna. Andreas Weber fuhr die CTD Einsätze und unterstützte mich bei der Vor- und Nachbereitung der Einsätze von LUISE sowie bei der Verarbeitung der zahlreichen Proben, anhand derer ich die Sulfatreduktionsraten errechnete. Die Berechnung aller Daten, die im Kapitel 2.2 Verwendung fanden, habe ich durchgeführt; desweiteren schrieb ich auch das Manuskript, wiederum mit konstruktivem Einfluß seitens Dr. Glud und Dr. Holby. Noch bevor der Lander LUISE fertiggestellt war, nahm ich an einer Ausfahrt in das Europäische Nordmeer bei Spitzbergen teil. Auf dieser Fahrt untersuchte ich die Aktivität der Sulfatatmung in Abhängigkeit von der Inkubationszeit an vier Stationen. Ein Großteil dieser von mir erhobenen Daten fand Eingang in eine Veröffentlichung (Kapitiel 2.3), die sich mit der Adaptation von sulfatreduzierenden Bakterienpopulationen an permanent kalte Bedingungen befaßt. Jens Sagemann bestimmte in Laborversuchen die Temperaturabhängigkeit und -anpassung der Bakterien. Weiterhin verfaßte er das Manuskript, während Prof. Jørgensen und ich an der Gestaltung der Daten und des Textes teilhatten. Alle beschriebenen Manuskripte sind zum Zeitpunkt der Einreichung dieser Arbeit dem Review-Prozeß unterworfen; daher sind nachträgliche Änderungen inhaltlicher Art möglich. Das Kapitel 'Acknowledgements' wurde jeweils entfernt und in die allgemeine Danksagung integriert.

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Gliederung

1 Einleitung 6

2 Zur Veröffentlichung eingereichte Artikel 21

2.1 A benthic lander for tracer studies in the sea bed: *in situ* measurements of sulfate reduction 21
Abstract 21
Introduction 22
Description of the lander 23
Structure and dimensions 23
The central unit and the operating sequence 23
Electronics and power supply 25
Release systems and relocation 28
Principle of measurement 28
Materials and methods 29
Study area 29
Results 30
Discussion 33
References 36

2.2 Pathways of carbon oxidation in Gotland Basin, Baltic Sea, measured *in situ* by use of benthic landers 41
Abstract 41
Introduction 42
Materials and methods 44
Results 50
Discussion 62
References 76

2.3 Temperature dependence and rates of sulfate reduction in cold sediments of Svalbard, Arctic Ocean. 86
Abstract 86
Introduction 87
Materials and methods 88
Sulfate reduction measurements 90
Arrhenius plots 92
Results 92
Results of whole core incubations 92
Results of temperature gradient incubations 95
Arrhenius plots 96
Discussion 96
References 102

3 Zusammenfassung und Ausblick 108

Übersicht der Zeichnungen im Anhang 111

1 Einleitung

Der globale Kohlenstoffkreislauf

Die Bedeutung des globalen Kohlenstoffkreislaufes für die Steuerung des Klimageschehens der Erde ist in den letzten Jahrzehnten zunehmend erkannt worden (Überblick z. B. in Wollast und Chou, 1993). Pflanzen und photosynthetisch aktives Plankton (Algen und Bakterien) fixieren Kohlendioxyd in organischen Verbindungen, deren größter Teil durch mikrobiellen Abbau letztendlich wieder zu anorganischen Nährstoffen und CO_2 abgebaut wird und so wieder am Kreislauf teilnehmen kann. Der verbleibende Teil wird in marinen Sedimenten vergraben und so (vorübergehend) dem direkten Kreislauf entzogen.

Die jährliche Gesamtproduktion organischer Materie wird mit ca. 105 (±50%) Gt C angegeben, von denen ca. 50% auf die Meere entfallen (Longhurst *et al.*, 1995). Von der durch marine Primärproduktion synthetisierten organischen Substanz verlassen nur ca. 20% die photische Zone (Hedges und Keil, 1995), und aufgrund von Abbauprozessen während des Absinkens erreicht mit zunehmender Wassertiefe ein immer geringerer Anteil den Meeresboden. Diese sogenannte Exportproduktion ermöglicht die Existenz komplexer benthischer Lebensgemeinschaften, die die organischen Verbindungen abbauen; nur ca. 0.4% der ursprünglichen Gesamtmenge werden schließlich vergraben. Da terrestrische Sedimente hingegen nicht zur Vergrabung beitragen (Romankevich, 1984), kommt dem Weltmeer als einziger Senke für CO_2 eine entscheidende Rolle bei der Steuerung des Kohlendioxydhaushalts und damit des Klimas zu. Neben der natürlichen Produktion dieses Gases ist nach neueren Erkenntnissen durch verstärkten Nutzung fossiler Energieträger auch anthropogenen Einflüssen eine nicht unwesentliche Beteiligung an der globalen CO_2-Bilanz zuzuschreiben (de Baar und Suess, 1993). Da Sauerstoff der terminale Elektronenakzeptor bei der Oxidation organischer Materie ist, ist es letztlich die Vergrabung organischer Materie und reduzierter Schwefelverbindungen in marinen Sedimenten, die über geologische Zeiträume die Anreicherung von Sauerstoff in der Atmosphäre ermöglicht (Hedges und Keil, 1995).

Das in den Ozeanen sedimentierte organische Material verteilt sich unterschiedlich auf die verschiedenen Tiefenstufen der Weltmeere: Während der offene Ozean mit ca. 79% den größten Anteil der Weltmeerfläche innehat, liegt der Anteil dieses Sedimentationsraums an der globalen jährlichen Mineralisation doch nur bei ca. 2%. Dies und der Umstand, daß die Bodenwässer in der Tiefsee im Allgemeinen eine hohe Sauerstoffsättigung aufweisen, führt dort zu einem fast vollständigen aeroben Abbau, und nur ca. 4% des weltweit jährlich durch Vergrabung dem Kreislauf entzogenen Kohlenstoffes verbleiben in pelagischen Sedimenten. Die Kontinentalhänge und die Schelfe hingegen, die zusammen nur ca. 21% der Fläche der Weltmeere einnehmen (Kennett, 1982), erhalten durch die Zufuhr der Flüsse vom Festland erhebliche Mengen sowohl terrigenen Materials als auch organische Substanz in gelöster und partikulärer Form (0.4 Gt C a^{-1}, Hedges, 1992; Mackenzie *et al.*, 1993) sowie gelöster Nährsalze. Letztere bedingen zusammen mit den von unterhalb der photischen Schicht eingemischten Nährstoffen eine hohe Primärproduktion, die wiederum, in Kombination mit dem Eintrag klastischer Partikel, zu hohen Sedimentationsraten führt. Zudem gibt es zwischen ca. 40°N und 40°S meist an längengradparallelen Abschnitten der Westküsten der Kontinente Auftriebsgebiete, in denen die Zufuhr nährstoffreichen Wassers aus größeren Tiefen weiter verstärkte Primärproduktion und infolgedessen höhere Sedimentationsraten nach sich zieht. In der jährlichen Mineralisationsbilanz stehen die Schelfe und Kontinentalhänge daher mit ca. 98% des weltweit im marinen Milieu sedimentierten organischen Materials an erster Stelle. Alleine die küstennahen Sedimente tragen mit 83% dazu bei; weiterhin enthalten sie 87% des jährlich vergrabenen organischen Materials (Berner, 1982; Jørgensen, 1983).

Abbauwege organischer Substanz in marinen Sedimenten

In den sogenannten "anoxischen Oberflächensedimenten" (Henrichs und Reeburgh, 1987), die in wenigen Millimetern bis Zentimetern Tiefe keinen Sauerstoff mehr enthalten, ist das Abbaugeschehen, im Gegensatz zur Tiefsee, bereits in den oberen Dezimetern des Sedimentes in eine Vielzahl verschiedener Stoffwechselwege aufgeteilt. Diese lassen sich vertikal in der Sedimentsäule nach abnehmendem Redoxpotential und abnehmendem Energiegewinn ($-\Delta G$) bei der Reaktion mit den verschiedenen Elektronenakzeptoren zonieren. Der hohe Gehalt an organischen Verbindungen in den Sedimenten der Schelfe und oberen Kontinentalhänge bedingt hohe

Raten aerober und anaerober Respiration. Dies hat zur Folge, daß Sauerstoff bereits innerhalb der obersten Sedimentschichten verbraucht wird, und zwar zum einen durch direkte Reduktion während aerober Atmungsprozesse, zum anderen bei der chemischen (Re-) Oxidation reduzierter Stoffwechselprodukte anaerober Atmungswege, die in Richtung Sedimentoberfläche diffundieren. Unterhalb der Zone aerober Atmung schließt sich typischerweise ein Bereich an, in dem das durch (oxischen und anaeroben) Abbau organischer Substanz produzierte Nitrat (NO_3^-) als Elektronenakzeptor dient und zu molekularem Stickstoff (N_2, Denitrifikation) oder, zu geringeren Anteilen, Ammonium (NH_4^+, Nitratammonifikation) reduziert wird. Mangan(hydr)oxide, in denen Mangan in der Oxidationsstufe +IV vorliegt, kommen typischerweise in marinen Sedimenten vor und werden vermutlich von Bakterienpopulationen als Elektronenakzeptor genutzt, die auch Eisen(hydr)oxide umsetzen können. Die Existenz von Bakterien, die ausschließlich Mangan(hydr)oxide als Elektronenakzeptor nutzen, ist bislang ungesichert. Bei der dissimilatorischen Manganreduktion wird Mangan zu seiner zweiwertigen Form reduziert, die bei den im Sediment vorherrschenden pH-Werten zwischen 6 und 8 löslich ist. Ein weiterer Stoffwechselweg beruht auf der Reduktion von Eisenverbindungen, die, meist in Form von Oxiden oder Hydroxiden, in allen marinen Sedimenten in großen Mengen enthalten sind. Sie werden von den bereits erwähnten eisenreduzierenden Bakterien genutzt, um organische Substanz zu oxidieren, ein Prozeß, bei dem Eisen in der Oxidationsstufe +II freigesetzt wird. Dieses reagiert chemisch mit durch Sulfatreduktion produziertem Sulfid (S^{2-}), das im Sediment nach oben diffundiert, zu unlöslichen Eisensulfiden, welche die oft zu beobachtende dunkle Färbung der tieferen Horizonte (mariner) Sedimente bedingen. Die beschriebenen sogenannten Metallatmungen und die Denitrifikation tragen im Allgemeinen nur in geringem Maße zur Umsetzung organischer Materie bei, verglichen mit der aeroben Atmung und der Sulfatreduktion. Nur in speziellen Sedimentationsräumen, wie zum Beispiel im Amazonasdelta oder in der Norwegischen Rinne vor Südnorwegen, herrschen Bedingungen, die die Prozesse der Mangan- und Eisenreduktion anscheinend fördern, so daß dort der Abbau organischer Materie fast ausschließlich über diese Stoffwechselwege erfolgt (Aller, 1990; Canfield *et al.*, 1993). Bei der sich der Eisenreduktion im vertikalen Sedimentprofil anschließenden Sulfatatmung wird das im Meerwasser in hohen Konzentrationen vorhandene gelöste Sulfat (SO_4^{2-}) bakteriell zu Sulfid (S^{2-}) reduziert. Obwohl der Energiegewinn ($-\Delta G$) dieser Reaktion recht niedrig ist (siehe nachfolgend aufgeführte Über-

sicht), bestimmen die hohe Verfügbarkeit von Sulfat zusammen mit der Effizienz bei der Oxidation organischen Kohlenstoffes (ein Mol Sulfat kann zwei Mol Kohlenstoff der Oxidationsstufe 0 oxidieren) die große Bedeutung dieses Stoffwechselprozesses im Abbaugeschehen. Als letzter, am wenigsten energiereicher Prozeß folgt in der Tiefe die Methanogenese, bei der organische Materie zu Kohlendioxyd und Methan (CH_4) umgesetzt wird. Das freiwerdende Methan wird von sulfatreduzierenden Bakterien direkt wieder aufgenommen und zu Kohlendioxyd und Wasser abgebaut.

Nachfolgend findet sich nun eine Übersicht über die beschriebenen Stoffwechselwege mit den zugehörigen Reaktionsenthalpien in der Reihenfolge, wie sie in einem Modellsediment vorzufinden wären (nach Froelich *et al.*, 1979). Angegeben sind jeweils die stöchiometrisch korrekten Reaktionen, die bei der Oxidation eines Mols einer nach dem Redfield-Verhältnis (Redfield *et al.*, 1963) aufgebauten Modellsubstanz bei den verschiedenen Prozessen ablaufen:

Aerobe Atmung ($\Delta G° = -3190$ kJ/ Mol Glucose)

$$(CH_20)_{106}\,(NH_3)_{16}\,(H_3PO_4) + 138\,O_2 \;==>\; 106\,CO_2 + 16\,HNO_3 + H_3PO_4 + 122\,H_2O$$

Dentrifikation ($\Delta G° = -3030$ kJ/ Mol Glucose)

$$(CH_20)_{106}\,(NH_3)_{16}\,(H_3PO_4) + 94.4\,HNO_3 \;==>\; 106\,CO_2 + 55.2\,N_2 + H_3PO_4 + 177.2\,H_2O$$

Manganreduktion ($\Delta G° = -3020$ kJ/ Mol Glucose)

$$(CH_20)_{106}\,(NH_3)_{16}\,(H_3PO_4) + 236\,MnO_2 + 472\,H^+ \;==>\; 106\,CO_2 + 236\,Mn^{2+} + 8\,N_2 + H_3PO_4 + 366\,H_2O$$

Eisenreduktion ($\Delta G° = -1330$ kJ/ Mol Glucose)

$$(CH_20)_{106}\,(NH_3)_{16}\,(H_3PO_4) + 424\,FeOOH + 848\,H^+ \;==>\; 106\,CO_2 + 424\,Fe^{2+} + 16\,NH_3 + H_3PO_4 + 742\,H_2O$$

Sulfatreduktion ($\Delta G° = -380$ kJ/ Mol Glucose)

$$(CH_20)_{106}\ (NH_3)_{16}\ (H_3PO_4) + 53\ SO_4^{2-} \Longrightarrow 106\ CO_2 + 53\ S^{2-} + 16\ NH_3 + H_3PO_4 + 106\ H_2O$$

Methanogenese ($\Delta G° = -350$ kJ/ Mol Glucose)

$$(CH_20)_{106}\ (NH_3)_{16}\ (H_3PO_4) \Longrightarrow 53\ CO_2 + 53\ CH_4 + 16\ NH_3 + H_3PO_4$$

Quantitativ sind aerobe Atmung und Sulfatreduktion die bedeutendsten Prozesse bei der Mineralisierung organischen Kohlenstoffs in allen normalen Sedimenten (Bender und Heggie, 1984; Henrichs und Reeburgh, 1987).

Die Rolle der Sulfatreduktion

Obwohl biologische Sulfatreduktion schon seit Ende des letzten Jahrhunderts bekannt ist (Beijerinck, 1895), führten erst Entdeckung und Isolierung verschiedener sulfatreduzierender Bakterien in den siebziger und achtziger Jahren wieder zu einem verstärkten Interesse an der Rolle dieses Prozesses im globalen Kohlenstoffkreislauf. Der Grund dafür ist darin zu finden, daß die neu entdeckten Bakterien im Gegensatz zu den wenigen bisher bekannten Isolaten aus dem marinen Milieu in der Lage waren, eine Vielzahl verschiedener Substrate vollständig, d.h. zu Kohlendioxyd, abzubauen (z.B. Widdel, 1988; Widdel und Pfennig, 1981). Unter anderem durch diesen Generalismus bei der Wahl der Kohlenstoffquelle läßt sich die große Bedeutung der Sulfatatmung - trotz ihrer relativ zur aeroben Atmung geringen Energieausbeute - verstehen. Während früher die Sauerstoffzehrung eines Sedimentes als ein gutes Maß für die im Sediment abgebaute Menge organischer Substanz angesehen wurde (z.B. Teal und Kanwisher, 1961), erkannte Jørgensen (1982) bei Untersuchungen an flachmarinen Sedimenten mit Hilfe neuartiger Tracertechniken zur Bestimmung von Sulfatreduktionsraten (Zhabina und Volkov, 1978), daß die Sulfatatmung eine dem Sauerstoff vergleichbare Rolle spielt. Den Anteil beider Prozesse am benthischen Gesamtabbau in küstennahen Sedimenten quantifizierte er auf jeweils ca. 50%. Eine weitere Verschiebung dieser Bewertung zugunsten der Sulfatreduktion ist in den vergangenen

Jahren erkennbar, und neueste Forschungen deuten auf eine Dominanz dieses Stoffwechselweges nicht nur in anoxischen Becken (Canfield, 1989; Kapitel 2.2), sondern zunehmend auch in vielen küstennahen und Schelfsedimenten, die von sauerstoffhaltigem Bodenwasser überlagert sind (Thamdrup und Canfield, 1996; Kapitel 2.2). Ausgehend von diesen Erkenntnissen entstand die vorliegende Arbeit, deren Zielsetzung es war, einen benthischen Lander zu entwickeln und zu erproben, der die Bestimmung der Sulfatreduktionsaktivität unter *in situ*-Bedingungen ermöglichen sollte. Im Folgenden gehe ich kurz auf die Geschichte und den gegenwärtigen Stand der Landertechnologie ein und diskutiere die Probleme für biogeochemische Untersuchungen, die aus gängigen Probennahmetechniken entstehen.

Problemstellung und Lösungsmöglichkeiten mittels der Landertechnologie

Biogeochemische Untersuchungen an marinen Sedimenten beruhen auf Beprobung vor Ort und anschließender Ausführung der vorgesehenen Experimente an Bord des Forschungsschiffes; nur beim Einsatz von bemannten Unterseebooten oder in Gebieten, die für Taucher zugänglich sind, können Daten unter den *in situ*-Bedingungen gewonnen werden. Die Frage nach einer eventuellen Beeinflussung der Sedimente durch Temperaturänderung und - im Falle von Tiefseeproben - Druckentlastung bei der Probengewinnung wird schon lange diskutiert und ist gerade bei dem Untersuchungsfeld der Biogeochemie von besonderer Bedeutung. Da die untersuchten Reaktionen meist bakteriell katalysiert werden, unterliegen sie der Temperaturabhängigkeit der Stoffwechselvorgänge der Bakterien; diese wird oft als Q_{10}-Wert angegeben und gibt Auskunft über den Faktor, mit dem die Stoffwechseltätigkeit der Bakterien pro 10°C Temperaturerhöhung steigt. Für die meisten marinen Bakterien ist dieser Wert als zwischen ca. 2 und 4 liegend bestimmt worden (z. B. Isaksen und Jørgensen, 1996; Pomeroy *et al.*, 1991). Das bedeutet, daß bei herkömmlicher Probennahme mit einer Erhöhung der bakteriellen Aktivität gerechnet werden muß, wenn die *in situ*-Temperatur des Sedimentes merklich unter der oberflächennaher Wasserschichten liegt. Zudem beansprucht die Präparation der Proben auch Zeit, in der sie höheren Temperaturen ausgesetzt sein können, und selbst Equilibration und Inkubation unter *in situ*-Temperaturbedingungen resultiert nicht in einer Wiederherstellung der originalen *in situ*-Verhältnisse (Glud *et al.*, 1994b). Dekompression infolge der Probennahme kann weiterhin für manche barophile Organismen den Tod bedeuten (Smith und Hinga, 1983; Turley *et al.*, 1988;

Yayanos, 1986), und da Wasser bei einem Druck von 400 bar ein um 2% geringeres Volumen einnimmt (Kell, 1975), kann Druckentlastung außerdem zu einer Expansion des Porenwassers und damit zu einer Verschiebung der Konzentrationsprofile führen.

Als Konsequenz dieser Überlegungen und Beobachtungen wurden seit den frühen siebziger Jahren freisinkende, autonome Landegeräte entwickelt, die verschiedene Messungen *in situ* ausführen können sollten (Übersicht in Tengberg *et al.*, 1995). Die Entwicklung dieser sogenannten Lander begann mit Instrumenten, die in einer abgeschlossenen Kammer während einer gewissen Inkubationszeit die Konzentrationsänderungen von Sauerstoff und anderen Nährstoffen erfassen sollten (z. B. Smith *et al.*, 1976). Später folgten Geräte, die mittels neuentwickelter Mikroelektroden Mikroprofile von Sauerstoff, pH, etc. über die Sediment-Wasser-Grenze aufzeichneten (Gundersen und Jørgensen, 1990; Reimers, 1987) und dadurch eine genauere Beschreibung der in den obersten Sedimenthorizonten ablaufenden Prozesse ermöglichten. Neueste Entwicklungen beinhalten den Einsatz von Opt(r)odentechnik bei der Messung tiefer (ca. 1 m) Sauerstoffprofile (Glud *et al.*, in prep.) sowie die Erfassung zweidimensionaler Sauerstoffprofile, ebenfalls mit Hilfe der Opt(r)odentechnik (Glud *et al.*, 1996). Überdies gibt es Bestrebungen, mobile Instrumente zu entwickeln, die während mehrwöchiger Meßkampagnen vielfach ihre Position auf dem Meeresboden wechseln können, um so einerseits kostengünstig bei einem Einsatz ein große Datenmenge zu produzieren, und andererseits Daten zur Heterogenität des Sedimentes zu liefern.

Die bislang durch die Lander gewonnenen Daten deuten darauf hin, daß bei Tiefseesedimenten die *in situ*-Messungen z. B. der Sauerstoffeindringtiefe oder der Nährstoffflüsse niedriger ausfallen als die parallel ausgeführten Bestimmungen im Labor (Glud *et al.*, 1994a). Berichte über Daten aus flacheren Bereichen des Meeres hingegen scheinen nahezulegen, daß der beschriebene Sachverhalt dort umgekehrt vorzufinden ist, d.h., die *in situ*-Flüsse höher sind als die entsprechenden im Labor ermittelten (Devol und Christensen, 1993). Die Diskussion bezüglich des Vergleichs der Lander-Ergebnisse mit den herkömmlichen dauert noch an (Deming und Colwell, 1985; Jahnke *et al.*, 1989; Jannasch und Wirsen, 1982).

Der weltweit erfolgreiche Einsatz verschiedenster Landertypen (Tengberg *et al.*, 1995), vor allem aber die diesbezüglich positiven Erfahrungen im MPI, waren Ausgangspunkt für Überlegungen, ein Gerät zu konzipieren, das die Messung von *in situ*-Sulfatreduktionsratenermöglichen sollte. Auf diese Weise sollten auch bei diesem wichtigen Parameter der Mineralisation organischer Substanz eventuelle Unterschiede zu den bisher im Labor gewonnenen Daten erfaßt werden, um schließlich - zusammen mit *in situ*-Daten anderer Abbauwege - eine realistischere Abschätzung der tatsächlichen Stoffwechseltätigkeit erreichen zu können.

Entwicklung und Bau des Landers

Grundlegend für die eigentliche technische Verwirklichung des geplanten Instrumentes waren verschiedene Experimente und Berechnungen, die in der Vorphase des Baus durchgeführt wurden. Dabei handelt es sich einerseits um technisch-materialkundliche Versuche, zum Beispiel im Zusammenhang mit den verwendeten Elektromotoren und Injektionskanülen, auf der anderen Seite um wissenschaftliche Ansätze, absehbare Komplikationen - etwa durch Beeinflussung des Diffusionsgeschehens durch die vertikale Injektion und durch Erwärmung der Proben - zu vermeiden.

Zur Kategorie der Betrachtung technischer Einzelfragen gehörten zum Beispiel Untersuchungen zur benötigten Kraft, Kerne mit Rohren gegebenen Durchmessers und gegebener Wandstärke in verschiedenen Sedimenten zu nehmen, wobei die Kompaktion des Sedimentes so gering wie möglich gehalten werden sollte. Die Resultate der dazu ausgeführten Versuche gingen in die Berechnungen zur Dimensionierung der Elektromotoren ein, die die sechs Kernrohre von LUISE gleichzeitig langsam ins Sediment drücken. Um bei der Injektion des Tracers eine Balance zwischen minimaler mechanischer Beeinflussung des Sedimentes und maximaler vertikaler Stabilität der verwendeten Kanülen zu erlangen, wurden Nadeln unterschiedlichen Durchmessers untersucht. Zum Einsatz kommen nun speziell angefertigte Hohlkanülen aus Stahl, die mittels vier seitlich angebrachter Auslaßöffnungen eine optimale Verteilung des Tracers im Sediment gewährleisten. Diese Kanülen sind mit einer Glaskeramikbeschichtung überzogen, damit ein Stromfluß zwischen oxischen und reduzierten Horizonten im Sediment verhindert wird, der sonst unter Umständen biogeochemische Prozesse beeinflussen könnte. Sie verbleiben

nach erfolgter Injektion im Sediment, um nicht durch das Zurückziehen einen Kanal zu schaffen, entlang dessen sich vertikale Porenwasserbewegungen vollziehen könnten (siehe Abbildungen in Kapitel 2.1).

Auf der Seite der wissenschaftlichen Voruntersuchungen stehen zum einen Diffusionsversuche mit Bromid als inertem Modelltracer, anhand dessen das Diffusionsverhalten vertikal eingespritzter Substanzen analysiert und mit der Verteilung verglichen wurde, die bei (herkömmlicher) seitlicher Injektion erreicht wird. Es konnte gezeigt werden, daß sich der Tracer wie angenommen horizontal im Sediment ausbreitet und keine Komplikationen auftreten, solange die Diffusionsfront nicht die Wandung des Kernrohres erreicht. Für die Ausbreitung von Sulfat ist dies jedoch bei Inkubationszeiten unter ca. 30 Stunden nicht anzunehmen. Desweiteren wurden vergleichende Versuche zur eventuellen Beeinflussung von Sulfatreduktionsraten durch verschiedene Injektionstechniken ausgeführt. Üblicherweise wird die Tracerlösung seitlich durch silikongefüllte Öffnungen in den Sedimentkern gespritzt, während beim Lander die vertikale Injektion über die gesamte Länge des Kerns zur Anwendung kam. Es konnte gezeigt werden, daß die Ergebnisse bei vertikal eingespritztem radioaktiven Tracer keinen signifikanten Unterschied zeigen zu solchen, die mit horizontal injiziertem erzielt wurden. Entscheidend jedoch für die wissenschaftliche Anwendbarkeit des Landers waren Überlegungen, wie eine Beeinflussung der bakteriellen Umsatzraten in den injizierten Sedimentkernen während der Aufstiegsphase durch wärmere Wasserschichten sowie durch Druckentlastung verhindert bzw. kompensiert werden könne. Hierzu wurden Versuche mit spezifischen oder unspezifischen Inhibitoren (Molybdat bzw. ca. 10 N NaOH) durchgeführt. Es zeigte sich, daß exakte Sulfatreduktionsraten nur dann zu erhalten wären, wenn das genaue Diffusionsverhalten des Inhibitors wie des Sulfats bekannt wäre und damit die zwei quasi einander folgenden Diffusionsfronten modelliert werden könnten. Dieses Unterfangen stellte sich, ähnlich Überlegungen zum *in situ*-Einfrieren der Kerne, als zu kompliziert heraus, zumal auch eine einfachere Lösung gefunden wurde. Diese besteht, wie in Kapitel 2.1 näher beschrieben wird, in der Injektion zweier "Sets" von je drei Kernen zu unterschiedlichen Zeitpunkten, wobei eines der "Sets" direkt nach dem Landen, das andere hingegen erst kurz vor dem Auftauchen injiziert wird. Die gemessene Sulfatreduktionsaktivität des letzteren umfaßt folglich nur die Zeitspanne, in der das

Sediment nicht *in situ*-Bedingungen ausgesetzt war. Durch Subtraktion der Ergebnisse von denen des anderen "Sets" kann die Sulfatreduktionsaktivität des Zeitraumes, in dem der Lander auf dem Meeresboden stand, berechnet werden.

Bei der Konzeption des Landers orientierte ich mich im Rahmen des Möglichen an den Erfahrungen, die durch erfolgreiche Einsätze der anderen Lander des MPIs gewonnen worden waren, und übernahm zum Beispiel die Struktur des Rahmens, die Auftriebstechnik (evakuierte Glaskugeln) und in Grundzügen das Ballastsystem für LUISE. Alle mechanischen Vorgänge und angewandten Prinzipien sind möglichst einfach gehalten, um zu gewährleisten, daß der Lander ohne langwierige Vorbereitung oft und erfolgreich eingesetzt werden kann.

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2 Zur Veröffentlichung eingereichte Artikel

2.1

A benthic lander for tracer studies in the sea bed: *in situ* measurements of sulfate reduction

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Abstract

A new benthic lander for *in situ* tracer studies to a water depth of 6000 m is presented. This instrument allows *in situ* injections of radiolabeled sulfate into six enclosed sediment cores to determine sulfate reduction rates to 60 cm sediment depth. In order to correct for possible artifacts caused by decompression and rise in ambient water temperature during ascent and recovery of the instrument, one set of three cores was incubated *in situ* for 20 h, whereas another set was injected shortly before the ascent. The turnover of sulfate in the latter was subtracted from the first set to calculate the true *in situ* rates. This approach was tested in the laboratory on sediment cores from a coastal marine sediment. The results of a deployment at 155 m in the Gotland Basin, Baltic Sea, are presented. Sulfate reduction rates were measured to a sediment depth of 40 cm both *in situ* by the lander and in parallel onboard the ship. Results of *in situ* and laboratory incubations match well, showing slightly higher rates in the laboratory cores, especially in the deeper sediment strata.

Introduction

The development of landers since the mid-seventies has enabled accurate sudies of the chemical gradients and fluxes across the sea floor (for an overview see Tengberg *et al.*, 1995). While diver supported chamber studies focusing on benthic exchange processes were carried out already 1972 (Hallberg *et al.*), the first generation of autonomous chamber landers followed shortly after (e.g., Smith *et al.*, 1976; Jahnke and Christiansen, 1989a; Sayles and Dickinson, 1991; Glud *et al.*, 1994). These instruments were constructed to incubate a certain sediment area, and by monitoring concentration changes of oxygen, nutrients and other solutes in the enclosed water, benthic flux rates were determined. Profiling landers capable of measuring pore water gradients of various solutes using microelectrodes were developed later (Reimers, 1987; Gundersen and Jørgensen, 1990; Epping and Helder, in press). Instruments retaining the pressure of deep-sea samples or capable of *in situ* water column studies (Albert *et al.*, 1995) were built to measure microbial turnover and some of the results obtained pointed to an effect on the microbial metabolism due to decompression and transient warming, yet the extent and direction of this effect is still discussed (Jannasch and Wirsen, 1982; Deming and Colwell, 1985; Jahnke *et al.*, 1989b; Devol and Christensen, 1993).

Glud *et al.* (1994) ascribed the observed differences between *in situ* and laboratory measurements of oxygen microprofiles in deep-sea sediments to the effect of decompression and transient heating on microbial metabolism, combined with an expulsion of pore water. These changes are known to affect and possibly be lethal to some psychrophilic and barophilic bacteria and meiofauna (Smith and Hinga, 1983; Yayanos, 1986; Turley *et al.*, 1988). The results of Glud *et al.* (1994) indicated that *in situ*-determination of anaerobic processes involved in the degradation of organic matter could also yield different results as compared to laboratory studies. In the anaerobic degradation of organic matter sulfate is quantitatively the most important electron acceptor, especially in deeper shelf and continental slope sediments (Canfield, 1989). In these environments with their low bottom water temperatures and often warm upper mixed layers sulfate reduction measurements can be assumed to be affected by recovery proce-

dures. We here present a benthic lander system capable of measuring sulfate reduction, LUISE (Lander for Underwater *In Situ* Experiments). First results are presented and discussed.

Description of the lander

Structure and dimensions

The main frame is a tripod of about 1.9 m height and 1.7 m width that narrows at the top to 1.1 m (Fig. 1). It has adjustable legs to suit different types of sediment; iron disks that serve both as landing feet and as releasable ballast are fixed to the legs, each with a weight of 81 kg in air. The main frame carries the central unit described below, the batteries, the electronic cylinder and the ballast-release system. The flotation frame is 1.4 m in height and carries 12 glass spheres of 50 cm diameter that provide the buoyancy for ascending after deployment. The height of the assembled lander is 3.3 m without relocation devices, and the overall weight in air is 900 kg and 150 kg in sea water. After the release of the ballast the lander has a negative buoyancy of about 60 kg. Descending speed is about 1 m s^{-1}, ascending speed around 0.7 m s^{-1}. LUISE is constructed for deployments down to 6000 m. For the time the lander is on deck, a safety tub attached to the frame catches possible spills of sediment or water from the core liners. The lander was built by KC Denmark Research Equipment.

The central unit and the operating sequence

The injection unit (Fig. 2) consists of four POM (polyoxymethylene) plates that are connected by three steel tubes (3 cm O.D.). The upper and the lower plates (nos. 1 & 4) are fixed to the frame, while the two plates in the middle (nos. 2 & 3) can be moved mechanically along the supporting steel bars. Six coreliners (3.6 cm I.D, 70 cm length, polycarbonate) are fixed to the lower moving plate (no. 3) and can be lowered into the sediment (max. 60 cm) by a central spindlebar driven by two 80 W electrical motors (Co. Maxon, type 22.60.885, geared to a 100:1 gearbox). Motors and gears are positioned at the top of the central unit in a pressure compensated housing. Reed-type switches interrupt the power supply for the motor when the plates have reached their end positions. A piston is used in order to avoid compaction of the

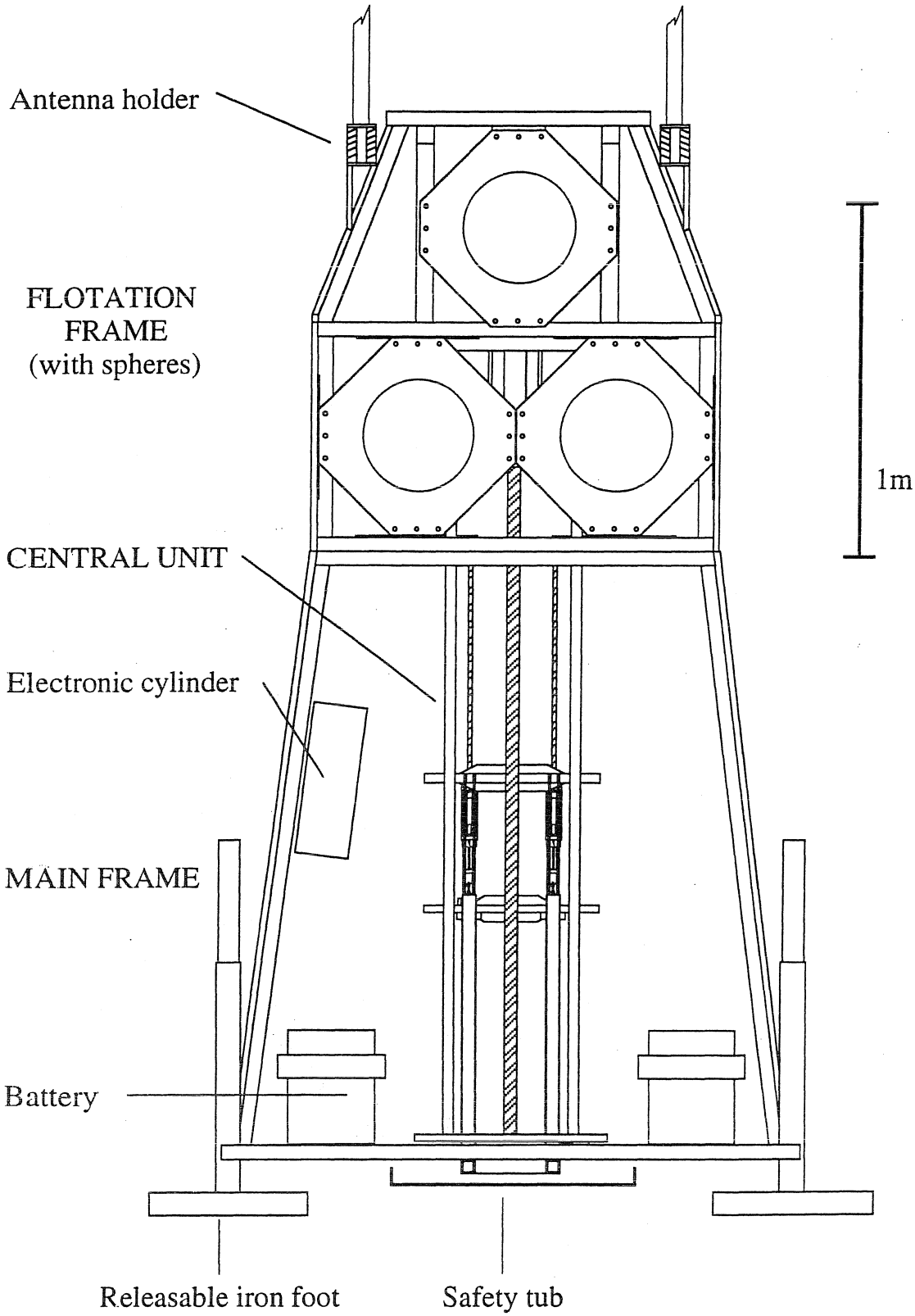

Fig.1: Overview of the benthic lander LUISE.

sediment during coring. The canulas (2.7 mm O.D., 1.1 mm I.D., 70 cm length) are driven each by a small motor (Co. Faulhaber, type 1331.012S, geared to a 159:1 gearbox), placed in a pressure compensated housing. The motor housing itself glides along steel tubes holding the piston for each core (Fig.2). The motors move the whole injection unit downwards by a spindlebar. The motion of the motors is also transferred onto a piston moving the plunger of the syringe containing the tracer, thus injecting the tracer continuously while the canula is being inserted into the sediment. This principle allows an even distribution of tracer, even if the implantation of the canula is hampered by obstacles. The cores and the injection units are retrieved into the main frame at the end of the incubation by the central motor. The cores are sealed *in situ* by corecatchers on the underside of the bottom plate. The spring loaded corecatchers are released upon contact with the downward moving plate (plate no. 3; Fig. 2) and move small plates horizontally under the end of each coreliner when they are at their top position.

An overwiew of the actions performed by the central unit during a deployment is given in Fig. 3. After landing on the sea floor (1) a wait cycle is executed to allow for the stabilization and settling of resuspended sediment particles. Subsequently the core-liners are pushed into the sediment (2) and the injection of the tracer (3+4) can be executed individually for each core. The cores with the canulas still in the sediment (retrieval of the canulas would result in a channel that would allow pore water to migrate) are retrieved into the main frame after the preset incubation time (5) and the ballast is released via a burnwire or acoustically from shipboard (see below).

Electronics and power supply

The lander is controlled by a computer housed in a pressure stable aluminum case. This computer features a 16 bit micro-controller, 2 MB RAM memory, a 16 bit A/D converter with 16 channels and 40 digital I/O-channels for controlling purposes. The power consumption of the computer is ca. 200 mA. On-deck communication is via a serial port to a PC. The software enables the user to store predefined programs for the lander to carry out movements or measurements at given times and to extract stored data from the memory. The power for the electro-

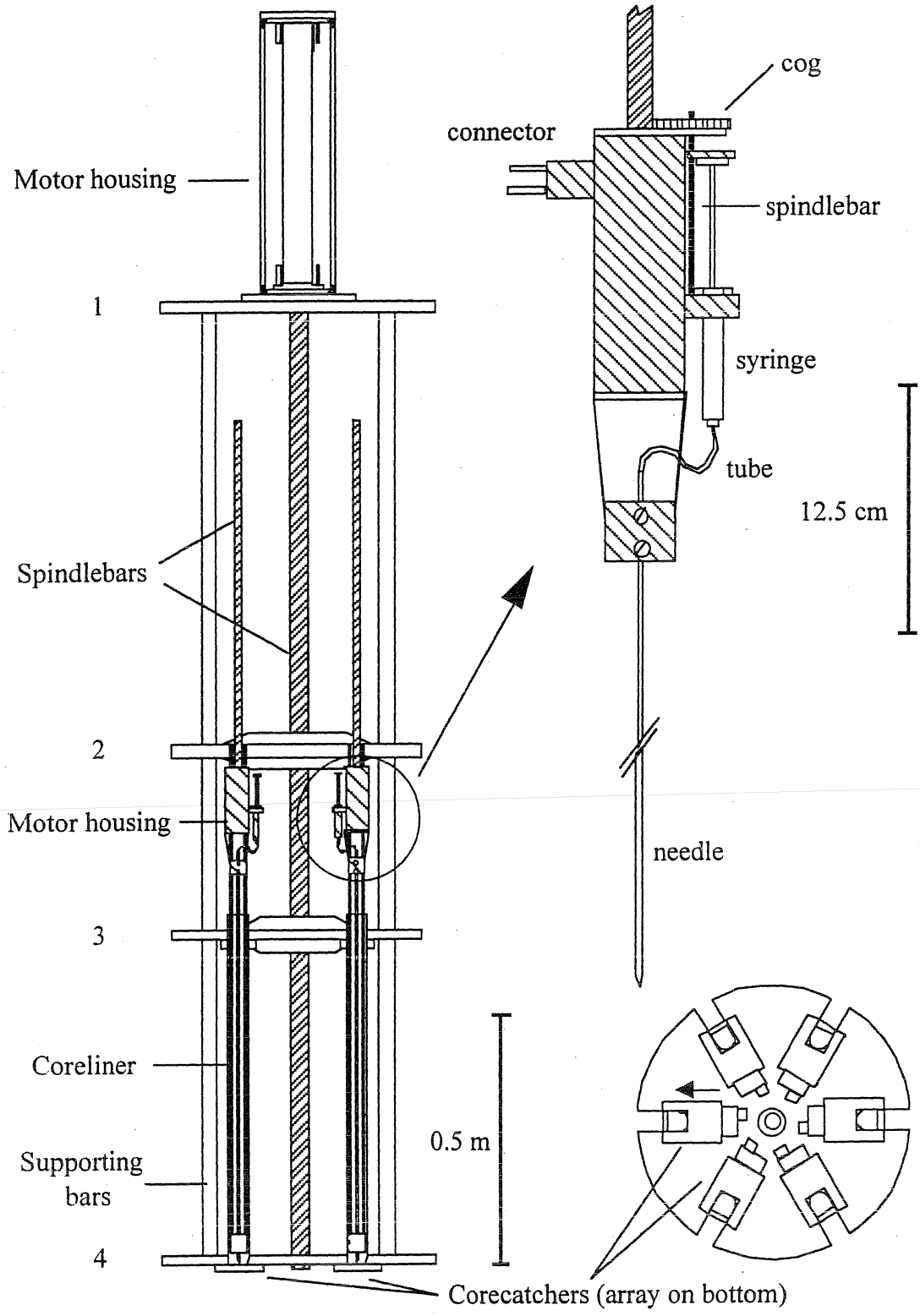

Fig.2: Schematic overview of the central unit of LUISE. Plate numbers refer to numbers given in the text. Enlarged section shows a detailed view of an injection unit. Only two of the six injection systems are shown.

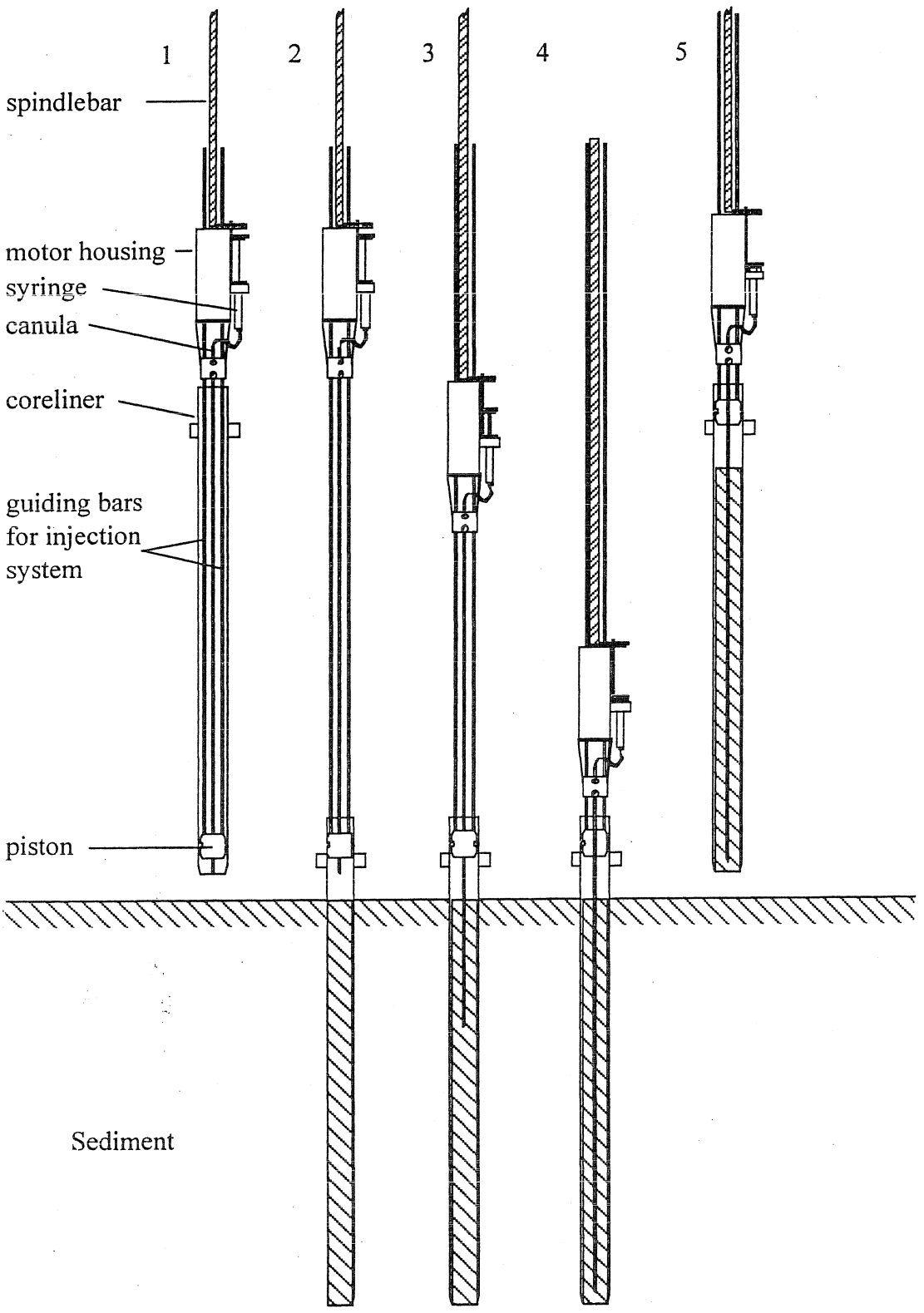

Fig.3: Deployment sequence of the lander LUISE. Position of the injection systems: 1) upon landing; 2) during coring; 3) during injection; 4) after injection and 5) before retrieval of the lander.

nics, the sensors (pressure and temperature) and the ballast release system (see below) is provided by a 24 V/38 Ah lead acid rechargeable battery (Deep-Sea Power and Light), sitting on the base of the main frame next to the central unit. Another battery (12 V/76 Ah) provides the power for the motors that drive the cores in and out of the sediment and for the small injection motors.

Release systems and relocation

Each ballast iron disk is held to the leg by a clamp on a steel wire. The three steel wires from the legs are connected to a ring held by a lever hook that is kept in position by three serially connected ballast release systems: a) a simple burnwire controlled by the computer; b) a release hook that can be activated acoustically from shipboard, and, if both systems fail, c) a magnesium bolt that galvanically corrodes when submerged. For surface location a flash and a radiobeacon (Co. Novatech, 7-10 NM and 15-20 NM range, resp.) are fixed on top of the flotation frame by two polycarbon rods of 2 m length. In case the lander surfaces when the ship is not on location, it can be tracked by an ARGOS satellite system.

Principle of measurement

Profiles of sedimentary sulfate reduction rates are determined by whole-core injections of ^{35}S-labelled sulfate that, together with the unlabelled pool of sulfate in the pore water, is bacterially reduced to H_2S. The reduced ^{35}S (H_2S, FeS, FeS_2, S^0) is separated by acid distillation in a Cr(II) solution (Fossing and Jørgensen, 1989). In our case of *in situ* injected and incubated cores, additional sulfate reduction takes place under non-*in situ* conditions during ascent and recovery of the lander. This artifact needs to be corrected for, and as it turned out to be too difficult to stop the metabolic activity at the end of the incubation by injection of an inhibitor into the sediment, we applied a dual period incubation scheme: All six cores of LUISE are implanted after landing; after an initial wait cycle, three cores are injected with tracer, whereas the remaining cores are injected shortly before ascending. This second set of cores experiences the temperature and pressure changes on the background of a very short *in situ* incubation and

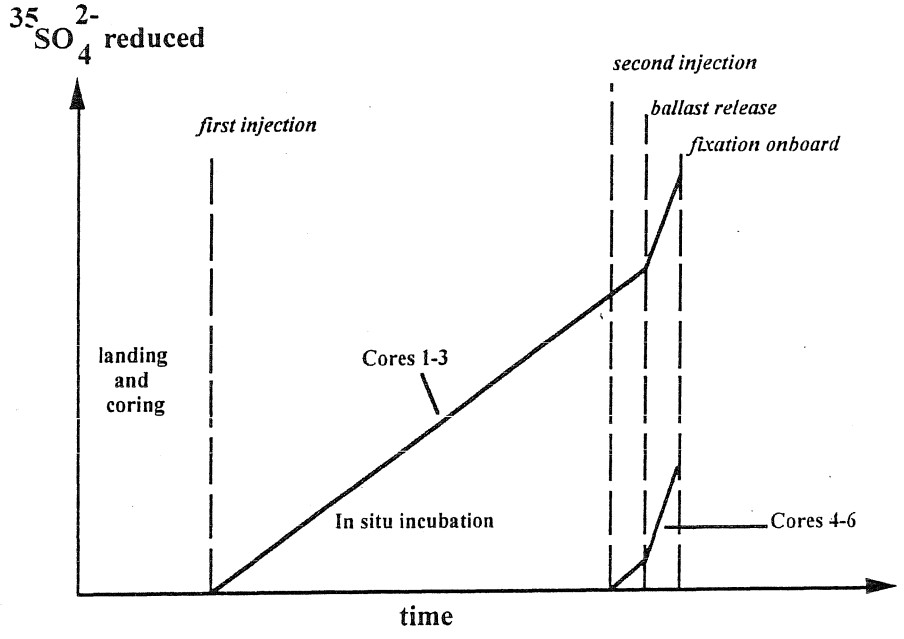

Fig.4: Principle of the sulfate reduction scheme in injected cores during a lander deployment. Note the different incubation times for the two sets of cores.

thus gives a good estimate of the artifact caused by the ascent and recovery. By subtracting the results of this second set from the first one that has also experienced a long *in situ* incubation, the mentioned artifacts can be corrected for (Fig.4).

Materials and methods

Study area

LUISE was first deployed successfully on a cruise to Gotland Basin, Baltic Sea, between August 15th and 20th, 1996. The results from one station at 155 m depth, positioned at 57°15.6 N, 20°21.8 E are presented here as an example. The results from other stations will be published elsewhere. The temperature of the surface water was 18°C, while the bottom water was 4.5°C. The bottom water oxygen concentration was 40 µM (11% air saturation) and the salinity at the bottom was 11.2‰. The sediment consisted of mud showing fine laminations in the first ca. 2 cm, below which followed silty gray strata to a depth of ca. 10 cm. Below that and to the bottom of the core a pure clay of light gray colour persisted; the transition to the overlying sediments was sharp and uneven. This sediment was deposited during the Ancylus stage of the

Baltic Sea, some 7000 years ago (Kögler & Larsen, 1979). As normally the holocene muds on top of this freshwater deposit are much thicker (up to 7 m in the central Gotland Basin; Winterhalter*et al.*, 1981), erosion must have occurred. Six cores of 35-40 cm length were taken by LUISE. Each core was injected *in situ* with 0.5 ml of a carrier-free $^{35}SO_4^{2-}$ solution (Amersham) diluted in bottom water of the station to a specific activity of 12 MBq ml^{-1}. Three cores were incubated *in situ* for 19.8 h, the three remaining ones for 1.8 h. Immediately after recovery on deck the cores were sliced into 1 cm segments and fixed in 20 ml 20% zinc acetate solution. As the total sulfate reduction in the short-time incubated cores was only ca. 10% of that of the long incubated cores, the error caused by the preparation of the cores at ambient temperature was small.

A set of parallel cores of the same diameter were subsampled from multicorer cores and kept in an incubator at *in situ* temperature before injection. After an 8 h equilibration time 10 µl of the tracer solution were injected at 1 cm depth intervals with a microliter syringe horizontally through silicone filled ports. Three cores were incubated for 19.8 h in the incubator kept at *in situ* temperature (4.5°C), while three more cores were incubated only for 1.8 h. At the end of the incubation periods the cores were treated as the recovered lander cores. Sulfate concentration was measured by unsuppressed ion chromatography (Waters) from the supernatants of samples from one core. Porosity (vol/vol) was determined from the water content of a core subsampled from a multicorer core (24h drying to constant weight at 70°C).

The samples were processed in the laboratory by the single-step chromium reduction method, where the reduced sulfur species in the sediment are volatilized by means of distillation in an acid chromium-II solution (Fossing & Jørgensen, 1989). The produced hydrogen sulfide was trapped in a 5% zinc acetate solution and 5 ml of the trap solution containing the reduced ^{35}S were mixed 1:2 with scintillation cocktail (Ultima Gold XR, Canberra Packard). Subsamples of 100 µl of the $^{35}SO_4^{2-}$-containing supernatant were diluted with 5 ml water and 10 ml scintillation cocktail. All samples were counted in a Tricarb scintillation counter. Sulfate reduction rates were calculated as described by Jørgensen (1978).

Results

For a successful application of the described approach to compensate for artifacts it is thus necessary to keep the ratio between the incubation times of the long vs. the short incubated cores as large as possible. The method has been tested on laboratory incubated cores from Århus Bight (homogeneous silty sediment) and Kysing Fjord (heterogeneous sandy sediment with macroalgal debris), Denmark. Six parallels of sulfate reduction profiles were determined in sets of: a) control cores incubated for 12 h at 4°C, b) cores that were exposed first to 4°C for 12 h, and after that to 22°C for 30 min (simulating the first set of injected cores of LUISE), and c) cores incubated for 30 min at 22°C (simulating LUISE's second set of cores). The expectation that the calculated turnovers of set b) minus the turnover of set c) cores should equal the turnover of the control cores that only had been incubated in the cold, was confirmed for both sampling sites (Table 1 shows as an example the results from Kysing Fjord).

The depth profiles from the station in Gotland Basin, showing the amount of sulfate reduced during the respective incubation times are presented in Fig. 5 (top and middle panel). The three parallel cores of each setup were averaged. Profiles of all cores show maximum sulfate reduction activity at the sediment surface and a rapid decline with depth. From ca. 5 cm depth, the amount of sulfate reduced after 1.8 h or even 19.8 h decreased to < 5 nmol cm^{-3} in all cores. The profiles of the short-time incubated cores - both *in situ* and in the laboratory - show much more scatter (a higher core-to-core variability) than those of the long incubation times. The depth integrated (0-15 cm) rates were 3.68 (± 1.78) mmol m^{-2} d^{-1} and 3.36 (± 0.40) mmol m^{-2} d^{-1} for the short incubations *in situ* and laboratory, respectively. The long incubations resulted in 0.96 (± 0.22) mmol m^{-2} d^{-1} and 1.18 (± 0.08) mmol m^{-2} d^{-1} *in situ* and laboratory, respectively (Table 2). Thus, the rates determined from the short incubations were higher by a factor of about 3 than those from the long incubations due to warming during ascent and recovery.

Applying the approach to correct for recovery artifacts leads to the activity profiles shown in Fig. 5 (lower panel). The calculated values represent the sulfate reduction activity of 18 h incubation time. The two profiles show a general agreement in shape; both have a maximal

Table 1: Results of the laboratory experiments to test the working principle of LUISE. Results shown are mean values of six parallels from Kysing Fjord. The indicated standard error of the mean value is given through: standard deviation/SQR (n)

Depth interval (cm)	Setup	Incubation temperature and time (h)	Sulfate turnover (± std. error of the mean value)
3-4	a	4°C, 12	7.85 (± 0.49)
	c	22°C, 0.5	1.00 (± 0.07)
	a+c		8.85 (± 0.89)
	b	4°C, 12 + 22°C, 0.5	9.26 (± 0.46)
5-6	a	4°C, 12	2.58 (± 0.25)
	c	22°C, 0.5	0.57 (± 0.11)
	a+c		3.15 (± 0.31)
	b	4°C, 12 + 22°C, 0.5	3.22 (± 0.30)

Table 2: Overview of the calculated areal rates of sulfate reduction to a depth of 15 cm for the different incubation times and approaches. Rates are given in mmol SO_4^{2-} m^{-2} d^{-1} and represent mean values of three cores. Standard errors of the mean values are indicated in parentheses.

	19.8 h *in situ*	19.8 h lab.	1.8 h *in situ*	1.8 h lab.	calc. 18 h *in situ*	calc. 18 h lab.
Areal rates in mmol m^{-2} d^{-1} (std.error of mean value)	0.96 (0.22)	1.18 (0.08)	3.68 (1.78)	3.36 (0.40)	0.80 (0.31)	1.01 (0.40)

activity at the sediment surface and exhibit a sharp decline below. The profile gained from the *in situ* cores does not show any significant activity below 5 cm depth, while the laboratory profile indicates sulfate reduction activity at a low level (around 2 nmol cm^{-3} d^{-1}) to depths of ca. 27 cm. The areal rates of the two assays partially reflect this difference in that the depth integrated rate of the laboratory setup is ca. 25% higher than the *in situ* data. The difference, however, is statistically not significant (Table 2).

Discussion

A transient warming of the sampled cores during recovery of the instrument will result in increased microbial activity. Sulfate reducing bacteria respond without lag to rising temperatures and the factor by which the respiration increases per 10°C, expressed as the Q_{10}-value, lies around 3 (1.5-4) for sulfate reducing bacteria (Jørgensen, 1977; Westrich and Berner, 1988; Skyring *et al.*, 1983; Isaksen and Jørgensen, 1996). At our station in the Gotland Basin the cores were incubated *in situ* for 19.8 h at 155 m depth, the sulfate reduction rate of the investigated sediment was 30 nmol cm^{-3} d^{-1}, the water temperature was 4°C below 20 m and the

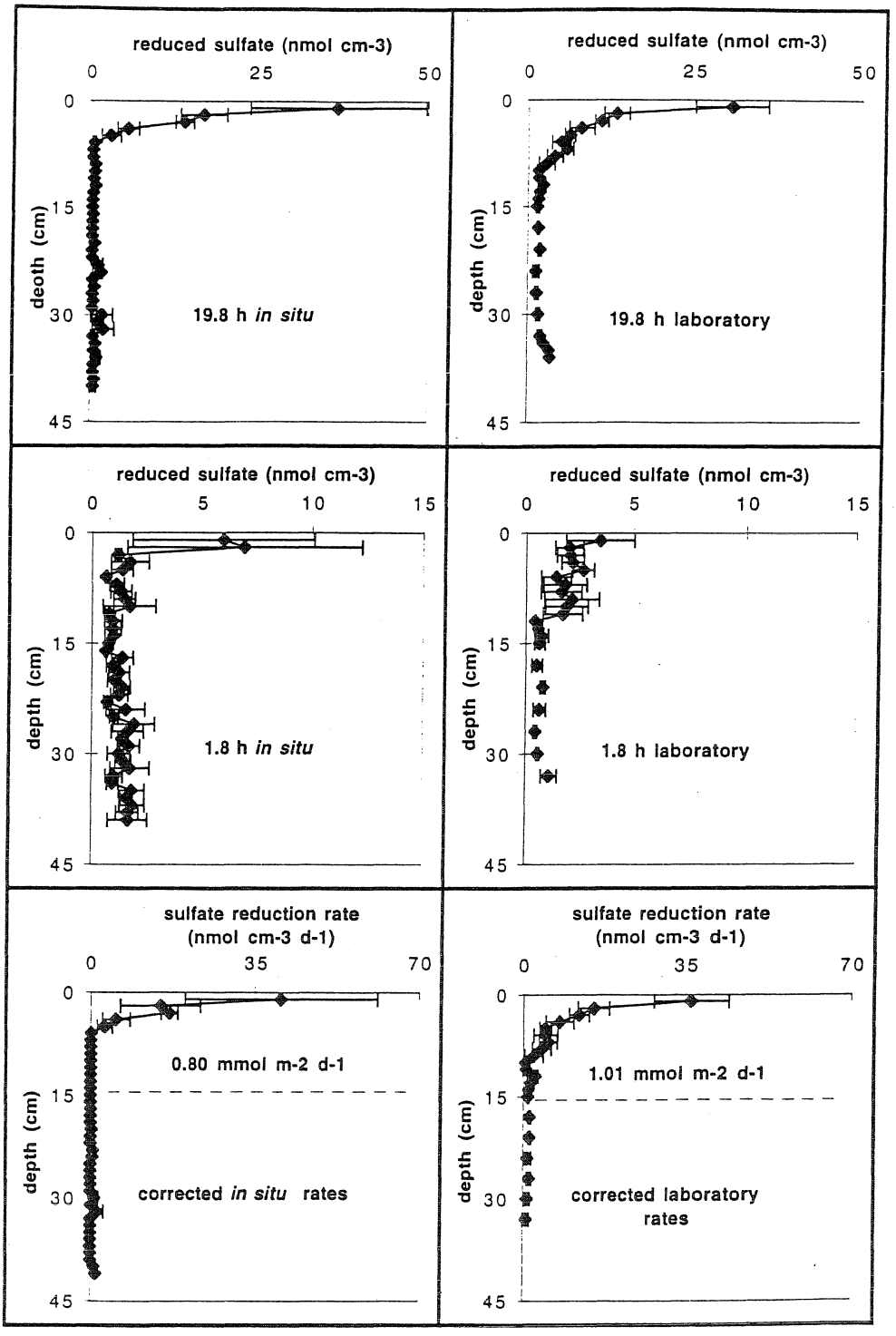

Fig.5: Sulfate reduction in Baltic Sea sediments: Depth profiles of 19.8 h (top), 1.8 h (middle), and corrected 18 h (bottom) incubations. Note that the top and middle panel show the *amount of reduced sulfate* during the respective incubation time, while the bottom panel indicates the *corrected rate of sulfate reduction.* Depth integrated rates (0-15 cm) are given above the dashed line. Error bars indicate standard error of mean value.

upper mixed layer was 18°C. Assuming immediate heating of the sediment and that the Q_{10} of the population of sulfate reducers equals 3, the heating during ascent and 30 min drifting prior to recovery would then cause an error of ca. 12% of the *in situ* turnover (25 nmol cm^{-3}). Assuming furthermore it takes another 30 min to cut the cores, the effect would increase to 24% of the *in situ* turnover. This scenario would yield values of up to 41% if deep-sea conditions are assumed,where the upper mixed layer is thicker and hence takes longer to travel through.

Whole core incubations are normally carried out by horizontal injections of radiotracer into the sediment-filled core. The new benthic lander system presented here injects the tracer vertically through the center of the core. To prevent vertical migration of the tracer solution, it must have the same density as the pore water into which it is injected. A comparison of vertical and horizontal injections of radiolabelled sulfate to a depth of 6 cm in sediment cores from Århus Bight proved that the two methods yield comparable results (areal rates were 0.20 mmol m^{-2} d^{-1} and 0.21 mmol m^{-2} d^{-1}, data not shown).

The specific sulfate reduction rates of the investigated sediment are slightly lower compared to rates determined for other coastal sediments at comparable depths (Jørgensen, 1989, review in Skyring, 1987). A comparison of the depth integrated rates to other data reported in literature shows the results from Gotland Basin to be at the lower range. We attribute this observation on the one hand to the decrease of sulfate reduction activity below ca. 10 cm, a depth from which the sediment changes to freshwater deposits from the Ancylus stage (ca. 7000 a BP) of the Baltic Sea (Kögler & Larsen, 1979). On the other hand erosion probably reduced the original thickness of the sediments overlying the Ancylus clay, exposing older, refractory organic matter to be decomposed instead of the fresh material lying at the sediment surface. This, of course, leads to lower sulfate reduction rates in the topmost sediment layers.

The depth integrated data presented here show a relatively good agreement between *in situ* and laboratory measurements. The difference between the two depth integrated results is statistically not significant, given the low overall values (Table 2). However, it was conspicuous that the laboratory incubated cores showed higher turnover in deeper sediment strata. The

investigated sediment was recovered from only 155 m depth, where pressure effects should be negligible. The data, however, indicate that the temperature artifact can be corrected for by the applied approach.

The duration of the recovery of the instrument and the handling of the cores took approx. one hour altogether. The high rates observed in the short-time incubated cores from Gotland Basin reflect this relatively long exposure to elevated temperatures (Table 2). In general, it is recommended to incubate tracer injected cores for relatively short periods because of potential reoxidation of reduced ^{35}S formed. This reoxidation is of increasing importance with increasing incubation time and leads to a non-linearity between incubation time and calculated sulfate reduction rates (Fossing, 1995). The technique proposed here is therefore a trade-off between temperature induced artifacts and reoxidation of reduced tracer.

The first application of LUISE has shown that rates of sedimentary sulfate reduction can now be determined *in situ* . The described method to overcome recovery induced artifacts was proven to yield good results for a station comparable in water depth to shelf or slope environments. The measured *in situ* rates were slightly lower than laboratory rates. In deep-sea environments suitable for deployments of LUISE (e.g., anoxic basins, upwelling areas), where artifacts like e.g., decompression can be expected to be of more importance than in the Baltic, the lander should be an ideal tool for measuring sulfate reduction. Furthermore, the injection of a variety of other substances for benthic studies (^{15}N-labeled nitrate, substrates for different groups of bacteria etc.) is possible with this instrument.

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2.2

Pathways of carbon oxidation in Gotland Basin, Baltic Sea, measured *in situ* by use of benthic landers

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Abstract

Benthic landers measuring diffusive (DOU) and total oxygen uptake (TOU), release rates of nutrients, and sulfate reduction rates *in situ* were deployed along a transect of four stations from the slope into the basin of Gotland Deep in August 1996. Additionally pore water fluxes of Fe^{2+}, Mn^{2+}, NH_4^+ and S^{2-} were measured in the laboratory. Degradation rates of the various pathways were calculated and related to a mean annual primary production. Calculation of chemical reoxidation rates for sulfide derived from sulfur burial data showed that most of the DOU was consumed in the reoxidation of reduced metabolic species, predominantly sulfide. Sulfate reduction was the overall dominant degradation process at all stations (30-96% of the total degradation), with *in situ* rates showing a tendency towards slightly lower activity as compared to onboard laboratory experiments. Although reduction of manganese (hydr)oxides apparently was coupled to biogenic degradation of organic matter, this process as well as denitrification and iron-reduction did not contribute significantly to overall mineralization. In the almost permanently anoxic sediments of the deep Gotland Basin a considerable part of the

sedimentary sulfur inventory seems to be fixed in organosulfur compounds. Sedimentary C:S ratios of all stations, however, were found to be in the range of normal marine sediments (Berner and Raiswell, 1983); hence, evidence for lower C:S ratios in anoxic settings as suggested by Berner and Raiswell (1983) could not be confirmed. Activity profiles of ^{137}Cs revealed bioturbation and pointed to a considerable diffusional mobility of Cs in the holocene sediments of Gotland Deep.

Introduction

About 90% of the world's annual organic carbon input to marine sediments is believed to accumulate in anoxic surficial sediments (oxygen penetration ≤ 2 cm) (Berner, 1982; Hedges and Keil, 1995). These sediments underlie highly productive coastal and shelf areas, covering only ca. 21% of the world's sea floor (Henrichs and Reeburgh, 1987; Kennett, 1982). Microbial mineralization under oxic or anoxic conditions recycles the carbon and the nutrients fixed in sedimenting organic matter, and eventually all of the organic matter is reoxidized, except for a certain percentage that is permanently buried in the sediment. This fraction is positively correlated to the sediment accumulation rate and consequently higher in coastal and shelf sediments (e.g., Canfield, 1989; Henrichs, 1992). Mineralization in the sediment follows an intricate pattern of interwoven paths of degradation; oxygen and sulfate are generally considered quantitatively the most important electron acceptors in this chain of decomposition (Bender and Heggie, 1984; Henrichs and Reeburgh, 1987). The contribution via these pathways to overall degradation in normal marine sediments (with oxygenated bottom water) has been quantified to be around 50% each (Jørgensen, 1982), leaving only small percentages to be contributed by denitrification and metal reduction. The benthic oxygen consumption can be separated into two fractions: one sustains the continued reoxidation of reduced metabolic products from anaerobic degradation pathways, while the second goes into direct heterotrophic respiration. Jørgensen (1982) quantified the oxygen demand of these processes to be equally high in a study of coastal sediments. The situation in euxinic and semi-euxinic environments, however, is different; in these settings sulfate reduction rates alone are considered a good measure of the total carbon degradation (Westrich, 1983; Canfield, 1989). Inferred from ancient deposits rich in organic

carbon (e.g., black shales), euxinic milieus have often been seen as places where more carbon escapes degradation and is permanently buried compared to normal marine settings (Canfield, 1993). Yet investigations in anoxic and oxic (normal) marine sediments revealed the carbon mineralization rates to be in the same order of magnitude (Henrichs and Reeburgh, 1987; Canfield, 1989; Henrichs, 1992), leaving an incomplete understanding of the mechanisms of enhanced carbon preservation. Since most sedimenting organic matter accumulates in sediments which are anoxic close to the surface (Henrichs and Reeburgh, 1987), the efficiency of anaerobic decomposition processes seems to be a key parameter in determining carbon burial. Furthermore, sedimentation rates have been found to control burial efficiency (review in Henrichs and Reeburgh, 1987). Thus, anoxic environments with high fluxes of organic matter to the sediment (e.g., Black Sea, deep basins of the Baltic Sea) are promising settings to investigate and compare rates of mineralization and burial efficiencies.

The Baltic Sea is the largest brackish water body in the world, covering ca. 372000 km^2. A permanent halocline at ca. 60-80 m depth prevents vertical mixing between the almost homohaline surface waters and deeper water masses of higher salinity; additionally, a seasonal thermocline develops during the summer months in the surface water body, producing an intense stratification (Kullenberg, 1981). The estuarine-like circulation pattern of the Baltic Sea is driven by river discharges and precipitation that generate the brackish (6-9 psu) surface layer and a difference in sea level between the Baltic and the North Sea (Grasshoff and Voipio, 1981). Rare and discontinuous events supply oxygenated higher salinity (12-25 psu) bottom waters from the North Sea to the Baltic Sea via the Kattegat and the Danish Straits. As the Baltic Sea consists of a series of basins separated by shallow sills that impede the migration of this inflowing denser water, salinity and oxygen saturation levels in the deep water decrease to the east and north (Kullenberg, 1981). During stagnation periods the deep water can be subdivided into two bodies: a subhalocline layer with a permanent oxygen deficiency but no deoxygenation, and the bottom water below ca. 170 m that is frequently anoxic (Grasshoff and Voipio, 1981; Stigebrandt and Wulff, 1987). Gotland Basin is part of the Baltic Proper, the largest part of the Baltic Sea. It is a flat basin with gentle slopes and a maximum depth of 249 m that displays almost permanently anoxic conditions in its deepest parts. Annual sediment accumulation rates

of 1.0-1.3 mm a^{-1} have been estimated in the central Gotland Basin, but on the slopes these values are lower and occasionally erosion can occur (Winterhalter *et al.*, 1981). The holocene muds in the Central Baltic have very high contents of organic matter (10-15% dw, Winterhalter *et al.*, 1981), favouring high remineralization rates both by oxygen (when present) and anaerobic degradation pathways. In this investigation it was our aim to study benthic remineralization along a transect from the oxic slopes of Gotland Basin into its anoxic center. Three autonomous benthic landers capable of measuring different key parameters in carbon mineralization (diffusive and total oxygen uptake, benthic exchange rates, and sulfate reduction) were deployed together at 4 stations. Further, pore water nutrient profiles were obtained in the lab along with sulfate reduction rates. Additionally we determined sediment accumulation rates (profiles of ^{137}Cs), profiles of sedimentary CNS contents and the sulfur inventories of the sediment column.

Materials and methods

Study area and sampling methods

Four stations along a transect from the oxic into the anoxic part of Eastern Gotland Basin, Baltic Sea, were visited with RV "Professor A. Penck" between 13th and 22th of August 1996 (Fig. 1). CTD profiling reflected the oxic and hydrographic conditions (stratified water column with thermocline and pycno-/oxycline) at each station (Fig. 2). Basic station information is summarized in Table 1. Sediment was sampled by a multiple corer modified for use in the very soft sediments of Gotland Basin. At all stations our three benthic landers were deployed together to measure oxygen-microprofiles (PROFILUR, Gundersen and Jørgensen, 1990), total oxygen uptake, flux rates (NH_4^+, NO_3^-, Mn^{2+}, Fe^{2+}) of an enclosed sediment area (ELINOR, Glud *et al.*, 1995) and sulfate reduction rates (LUISE, Greeff *et al.*, subm.) *in situ*.

Profiling oxygen analyses by the benthic lander PROFILUR

PROFILUR is a preprogrammed free falling benthic lander system (Glud *et al.*, 1993; Gundersen and Jørgensen, 1990; Reimers, 1987) designed to measure *in situ* microprofiles of oxygen

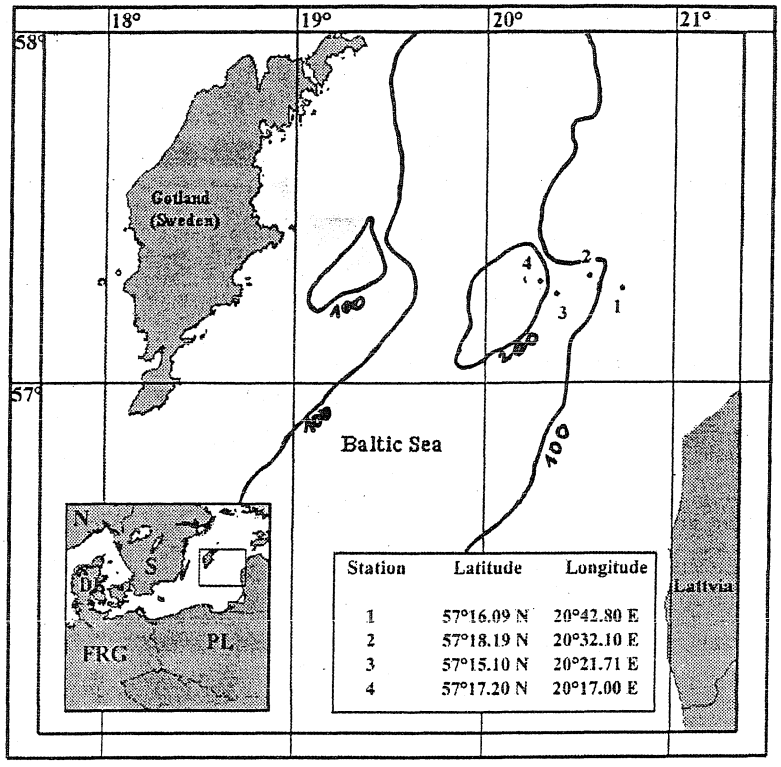

Fig. 1: Map of the study area and position of the stations along the transect into Gotland Basin. The map in the lower left corner shows the Baltic proper and, in the enlarged section, the position of the study area.

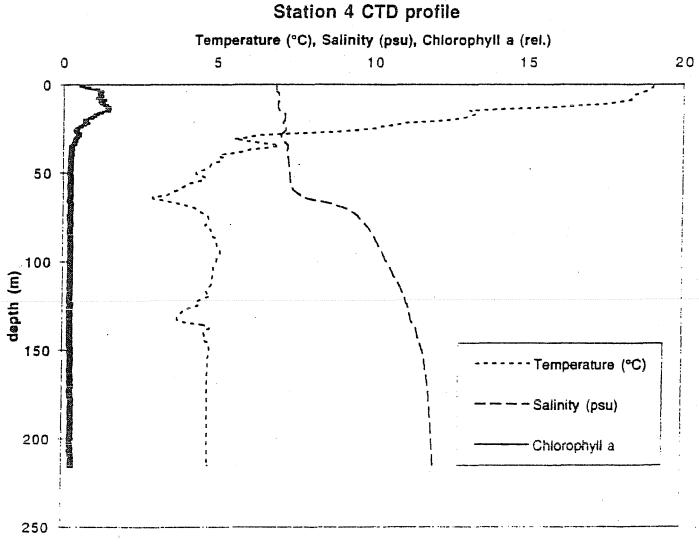

Fig. 2: CTD water column profiles of temperature, salinity and Chl a from Station 4. Note that Chl. a values are dimensionless and only a relative measure of concentration estimated from fluorescence.

Table 1: Basic station information of the visited stations. Oxygen data are from water samples taken by landers, other hydrographical data are from CTD casts and refer to bottom water.

Station	Depth	Temperature	bottom water O_2		Salinity	pH
	m	°C	µM	% air sat.	‰	
1	75	4.5	112	29.4	8.5	6.98
2	110	4.5	68.1	18.1	11	7.06
3	155	4.3	40	10.6	11	7.04
4	210	4.0	0	0	12	6.96

with a depth resolution of 25-200 µm through the sediment-water interface. During this cruise PROFILUR was equipped with six oxygen electrodes and the depth resolution was set to 100 µm. The oxygen microelectrodes were of Clark type with a guard cathode and internal refernce and a tip diameter of 10-30 µm (Revsbech, 1989b). The sensors were allowed to equilibrate at each sediment depth for 15 s before the signal was recorded. The lander was also equipped with a Niskin bottle to collect a bottom water sample, which was used for electrode calibration by Winkler titration (Gundersen and Jørgensen, 1990). All electrodes were checked for drift by comparing *in situ* readings in bottom water before and after the profiling. The oxygen penetration depth and the thickness of the diffusive boundary layer (DBL) were determined directly from the profiles as described by Jørgensen and Revsbech (1985). The sediment surface was detected by a change of the slope of the oxygen concentration gradient due to impeded diffusive conditions in the sediment as compared to the bottom water (Revsbech, 1989a; Sweerts *et al.*, 1989). The diffusive oxygen uptake (DOU) was calculated using Fick's first law of diffusion (eq. (1), see below).

Measurements of TOU and nutrient fluxes by the benthic lander ELINOR

The benthic lander ELINOR is a free falling lander system equipped with a chamber that incubates 30 x 30 cm of sediment. The chamber penetrates 20 to 30 cm into the sediment and is closed by a lid after landing on the sea floor (Glud *et al.*, 1994). Two Clark type oxygen mini-electrodes are mounted in the lid to monitor the decrease of oxygen in the enclosed bottom water. During incubation the water is gently mixed by a central stirrer, which gives rise to a diffusive boundary layer thickness of ca. 500 µm (Glud *et al.*, 1995). A water sampling system equipped with five syringes takes samples from the chamber at preprogrammed times. Manganese, ferrous iron, nitrate and ammonium were determined from these water samples that were fixed after recovery and kept deep frozen until analysis. Benthic exchange rates were calculated from the concentration changes of the various nutrients in the chamber over time (Glud *et al.*, 1993; Glud *et al.*, 1994). After recovery the sediment was sieved and analysed for macroinfauna.

Measurements of sulfate reduction by the benthic lander LUISE

The autonomous benthic lander LUISE is constructed to vertically inject and incubate six sediment cores with radiolabeled sulfate to determine sulfate reduction rates *in situ* (Greeff *et al.*, subm., chapter 2.1 of this thesis). To overcome the artifacts of transient warming and decompression during ascent and recovery of the lander, the turnover of three cores injected shortly before the return of the lander was subtracted from the turnover of the remaining cores which have been incubated *in situ* for a given incubation time (see Greeff *et al.*, subm. for details). In order to evaluate potential differences between *in situ* and laboratory studies, the injection and incubation pattern of the lander was mimicked in the laboratory (incubation time and temperature). However, these cores were recovered by a multiple corer and were injected sideways through silicone-stoppered ports. Upon recovery, the cores were immediately sliced in steps of 1 cm and fixed in 20 ml 20% zinc acetate to stop metabolic activity (slicing procedure was app. 20 min per core at room temperature). In the laboratory the samples were distilled in an acid Cr(II) solution to volatilize and trap the reduced sulfur species (Fossing and

Jørgensen, 1989). Sulfate reduction rates were calculated according to Jørgensen (1978). Core lengths at the different stations varied between 38 cm (Station 2) and 54 cm (Station 4). As we expected sulfate reduction rates to decrease with increasing water depth, the incubation times were chosen between 13 h (Station 1) and 18 h (Station 4).

Pore water analysis

At each station, a sediment core recovered with a multicorer was segmented in a glove box under oxygen free conditions in 5 mm slices to a depth of 3 cm, in 1 cm slices from 3 to 20 cm depth and in 2 cm slices to the end of the core. Pore water was obtained with a low pressure pore water press (Reeburgh, 1967). The obtained pore water was acidified and kept frozen until analysis. Mn(II) was determined by flame atomic absorption spectrometry and Fe(II) was measured photometrically after Stookey (1970). Ammonium was measured by the flow injection method after Hall and Aller (1992), and nitrate concentrations were determined by chemoluminescence detection after reduction to NO (Braman and Hendrix, 1989). Sulfate was measured unsuppressed by ion chromatography (Waters) from samples fixed in zinc acetate, and porosity (vol/vol) was determined from the water content of a core subsampled from a multicorer core (24h drying to constant weight at 70°C).

Flux calculations

Fluxes of pore water nutrients and diffusive oxygen uptake were calculated using Fick's first law of diffusion (Berner, 1980):

$$J = - \Phi D_S \frac{dC}{dz} \qquad (1)$$

Φ = porosity

D_0 = sea water diffusion coefficient

C = concentration of the solute of interest

z = sediment depth

$D_S = D_0 \Phi^2$

The sea water diffusion coefficients (D_0) of the various solutes given in Li and Gregory, (1974) were corrected for the *in situ* temperature by the Stokes-Einstein equation. For the calculation of sediment diffusion coefficients (D_S) the coefficient for sea-water was multiplied by the squared porosity of the actual sediment-layer according to Ullmann and Aller (1982). The DOU was calculated without using D_S. The fluxes of oxygen, nitrate, Mn(II) and Fe(II) into or out of the sediment were converted to units of mmol C m^{-2} d^{-1} by use of the oxidation capacity of each electron acceptor. Organic carbon was assumed to have an oxidation state of zero, manganese oxides of 4, and N_2 was assumed to be the product of nitrate reduction. An estimate of the aerobic mineralization was calculated by subtracting the oxygen necessary to reoxidize the reduced species diffusing upward (ammonium, Mn^{2+}, Fe^{2+} and sulfide) from the *in situ* diffusive oxygen uptake. Here we assumed the complete oxidation of ammonium, Mn^{2+} and Fe^{2+}, before the reoxidation of sulfide commenced. Reoxidation of sulfide was calculated with a simple model that used the sedimentary sulfur inventory (corrected for the contribution of sea water sulfate) at the deepest (marine) strata of the respective station and annual sediment accumulation rates of 0.5 mm (Station 1 and 2) and 1 mm (Station 3 and 4), respectively (Winterhalter *et al.*, 1981). Together with the measured rates of sulfate reduction (= sulfide production), the rate of reoxidation (sulfide was assumed to be reoxidized to sulfate, Cline and Richards, 1969) necessary to maintain the sedimentary sulfur inventory was determined. Similarly we calculated the annual carbon burial related to a mean annual primary production of 15 Mol C m^{-2} a^{-1} (Schulz *et al.*, 1992). The calculated fluxes of ammonium were converted to carbon equivalents by multiplication with the mean C:N ratio of the sediment layers used for the calculation of the ammonium gradient.

Solid phase analysis

Measurements of total reducible inorganic sulfur (TRIS) were carried out with the methylene blue technique after Cline, (1969) with subsamples of trap solutions (5% zinc acetate) of chromium distillations. The contents of total nitrogen, sulfur and carbon as well as organic carbon were determined by CNS analysis (Fisons NA 1500). Dried and ground subsamples of a core from each station segmented in 1 cm slices were analysed in triplicate. Samples for deter-

mination of organic cabon were treated with ca. 6 molar HCl and dried prior to analysis to drive out carbonate. Activities of ^{210}Pb ($t_{1/2}$ = 22.3 a) and ^{137}Cs ($t_{1/2}$ = 30.2 a) were measured by gamma spectroscopy on subsamples of dried and ground sediment from each station. The determination was carried out in gastight stoppered plastic vials, in which the samples (ca. 1-8 g) were left for about 12 d prior to counting to enable the establishment of the secular $^{226}Ra/^{214}Bi$ equilibrium in the container. Counting times were between 3 and 48 h, and the error was at ca. 5% and higher for decreasing activities. Excess activities of ^{210}Pb, given in Bq g^{-1} dw, were calculated by subtraction of the supported activity from the total activity. All samples of all stations were measured to a depth of 5 cm, below that every second cm-sample was used to a depth of 9 cm, and every third to the depth from which the activities remained constant. ^{137}Cs profiles were used to check for mixing and diffusion processes, while the one obtained profile of ^{210}Pb could not be used to derive sediment accumulation rates.

Results

Sediment description

The surface sediment of all stations was a very soft black, organic rich mud with porosities around 0.9. A simplified stratigraphy is shown in Figs. 6 and 7. Station 1 had a gray to black muddy sediment with occasional darker patches in the upper strata. An orange bacterial mat (possibly a microaerophilic Fe^{2+}-oxidizing bacterium, J. Küver, MPI, pers.comm.) covered a part of the surface at Station 1. Stations 2 and 3 showed laminated fluffy layers to ca. 8-10 cm. Below that, freshwater deposits of creamy colour from the Ancylus stage of the Baltic Sea (Kögler and Larsen, 1979) followed with a sharp transition. At Station 2 sandy layers between 11 and 30 cm occurred, below which the freshwater deposits followed. A whitish mat, probably sulfur bacteria, covered the sediment surface at Station 2. Station 4 sediment was completely black, extremely soft (the landers sunk in app. 50 cm) and had a sulfidic smell. Only Station 1 had macroinfauna; the dominating species were a hesionid polychaete (ca. 20 ind. m^{-2}), *Macoma balthica* (ca. 30-40 ind. m^{-2}) and the gamarid amphipod *Monoporeia affinis* (ca. 200-250 ind. m^{-2}).

Oxygen dynamics

The diffusive oxygen uptake (DOU) of all stations is listed in Table 2a and examplary profiles obtained by use of microelectrodes are shown in Fig. 3. The DOU varied from 8.7 mmol m^{-2} d^{-1} (Station 2) to 7.6 mmol m^{-2} d^{-1} at Station 3. The mean oxygen penetration depths decreased with water depth and bottom water oxygen concentration from 1.3 mm at Station 1 to 1.2 mm at Station 2 and 0.7 mm at Station 3 (Fig. 3). At Station 4 (210 m) no oxygen was present in the bottom water (Table 1). Total oxygen uptake (TOU) as measured by *in situ* uptake rates in the benthic chamber was higher than DOU at Station 1 (20%, Table 2a/b), the only station with benthic macrofauna. At Station 2 DOU and TOU agreed closely (8.7 and 8.9 mmol m^{-2} d^{-1}). At Station 3, however, TOU was lower by 56% compared to DOU.

Benthic *in situ* flux rates

Fig. 4 shows the concentration changes of various nutrients in the benthic chamber from Station 1 and 2. Station 1 and Station 2 showed **nitrate** uptake rates of ca. 900 µmol m^{-2} d^{-1} (Table 2b). No rates could be calculated for Station 3 as no meaningful regression was evident in the concen-

Table 2a: Overview of the calculated fluxes of pore water nutrients at all stations. Dissolved oxygen uptake (DOU) was calculated from *in situ* microprofiles (n=5). All fluxes calculated using eqn. (1); numbers in µmol m^{-2} d^{-1}. nm = not measured. -/+ indicates fluxes out of and into the sediment, respectively.

Station	DOU	NH_4^+	NO_3^-	Mn^{2+}	Fe^{2+}
1	8300	-425	134	-14	-88
2	8700	-392	-502	-7	nm
3	7600	-273	-528	-208	-489
4	0	-117	0	-659	4185

Table 2b: Overview of the calculated nutrient fluxes from benthic chamber lander incubations. Numbers in μmol m^{-2} d^{-1}. TOU= total oxygen uptake measured *in situ*. Values in parantheses indicate r^2 of the linear regression-fit of concentrations monitored in the benthic chamber. nm = not measured. -/+ indicates fluxes out of and into the sediment, respectively.

Station	TOU	NH_4^+	NO_3^-	Mn^{2+}	Fe^{2+}
1	10000	-407 (0.99)	897 (0.99)	-130 (0.60)	0
2	8900	-823 (0.98)	917 (0.93)	-131 (0.78)	-415 (0.91)
3	4300	nm	nm	nm	nm
4	0	nm	0	nm	0

tration changes over time, and no nitrate was present in the enclosed water in the chamber at Station 4. An efflux of **ammonium** into the bottom water was measured at Stations 1 and 2, and the fluxes increased with water depth (Table 2b). No fluxes of ammonia could be calculated for the deeper stations as the data did not show a clear trend. Station 1 did not show an efflux of ferrous iron, but dissolved Mn(II) was found to be released at around 130 μmol m^{-2} d^{-1}. Station 2 was found to release Mn^{2+} and Fe^{2+} from the sediment (Table 2b). No measurements of *in situ* iron fluxes were obtained at Station 3, and at Station 4 no detectable iron was found in the chamber water. Manganese was not measured at Stations 3 and 4.

Pore water nutrient profiles and fluxes

The pore water depth profiles of ammonium, nitrate, reduced manganese and ferrous iron of all stations are shown in Fig. 3; the fluxes calculated from the concentration profiles are listed in Table 2a. Ammonium fluxes decreased linearly (r^2 = 0.96) with increasing water depth. At Station 1, nitrate was taken up by the sediment at ca. 130 μmol m^{-2} d^{-1}, and at Stations 2 and 3

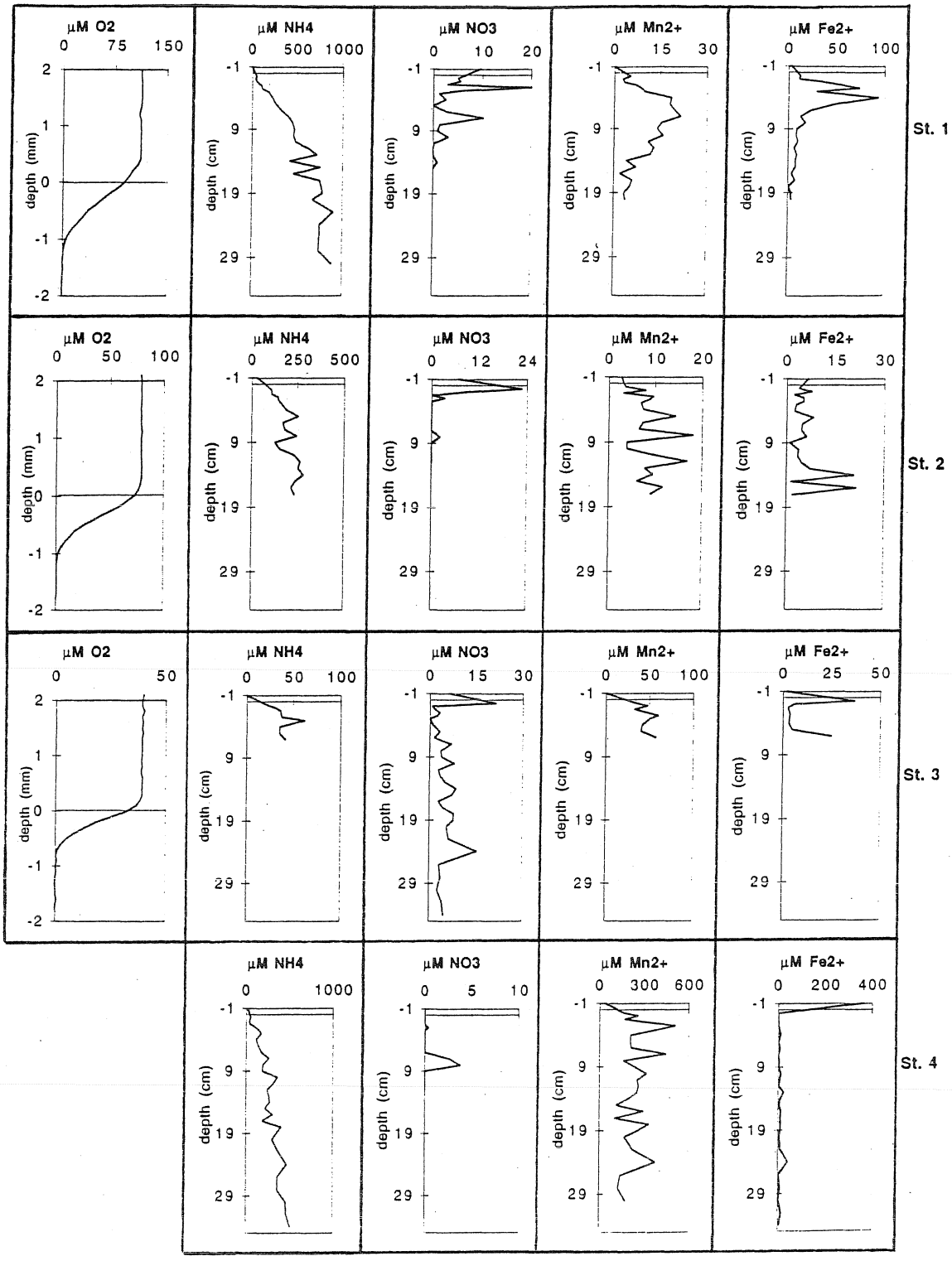

Fig. 3: Overview of the pore water nutrient profiles of oxygen, ammonium, nitrate, manganese and iron of Station 1 (top) to Station 4 (bottom). Oxygen data are from the profiling lander PROFILUR. Note different depth scale for oxygen profiles.

fluxes into the bottom water of around 500 µmol m^{-2} d^{-1} could be calculated. No nitrate was found in the bottom water or the pore water of Station 4, except for a probably artificial subsurface peak at ca. 7 cm that we neglect in the further course of discussion. The release of Mn^{2+} from the sediment into the water column increased with increasing water depth, and the minimum amount of degraded carbon that could be estimated from the fluxes of Mn^{2+} increased

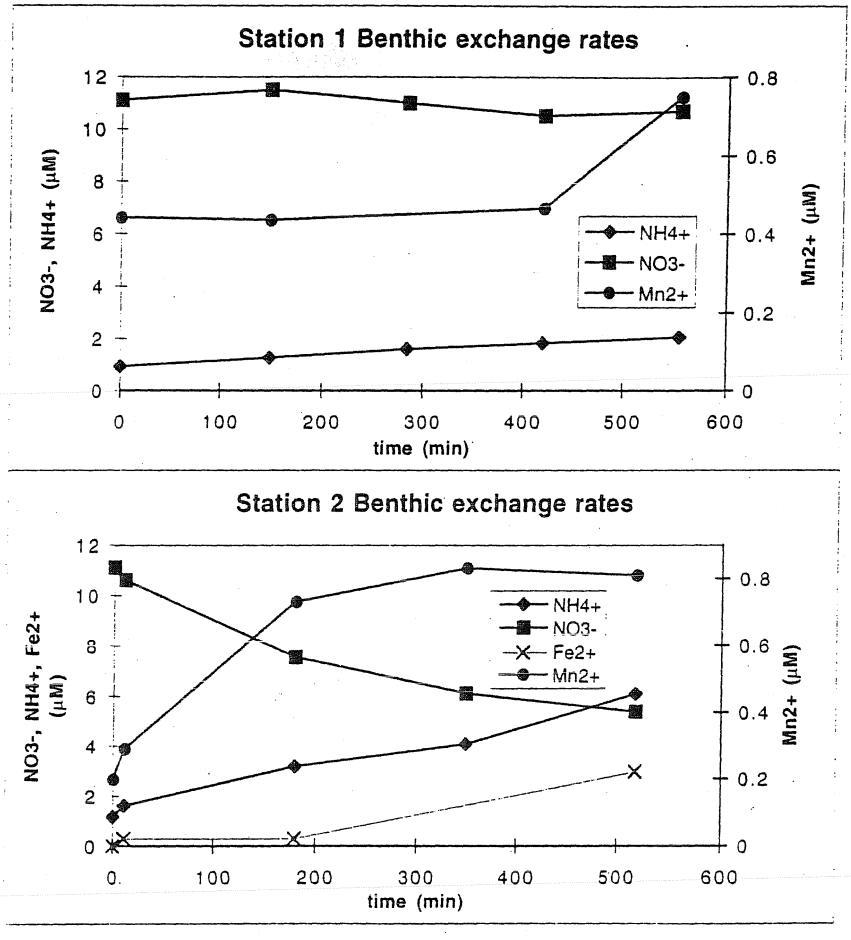

Fig. 4: Data from the chamber lander ELINOR from Stations 1 and 2. Only those parameters are depicted where a calculation of a linear regression was reasonable. The fluxes calculated from the concentration changes in the chamber are listed in Table 2b.

from insignificant 3 µmol C m^{-2} d^{-1} at Station 1 to 330 µmol C m^{-2} d^{-1} at Station 4. Contrary to Mn^{2+}, calculated fluxes of ferrous iron towards the sediment surface first increased with water depth from ca. 90 µmol m^{-2} d^{-1} (Station 1) to about 500 µmol m^{-2} d^{-1} at Station 3, but no significant amounts of ferrous iron were present in the pore water of Station 4. There, ferrous iron was only found in the bottom water, and an Fe^{2+} flux into the sediment of 4.2 mmol m^{-2} d^{-1} was calculated. Peak concentrations of ferrous iron in the pore or bottom water at all stations occurred closer to the sediment surface as compared to the manganese peaks (Fig. 3).

Sulfate reduction rates

The measured sulfate reduction rates (SRR) of Stations 1 to 4 are presented in Fig. 5. The laboratory incubations from all stations showed the maximum activity at the sediment surface and a rapid decline over depth. From ca. 15 cm sulfate reduction activity became negligible in all cores except for minor subsurface peaks. This pattern was not due to sulfate limitation at any station in the deeper sediment strata, as concentrations were always > 2 mM (data not shown). The depth-integrated SRR activity (0-15 cm) was highest in cores from Station 2 (115 m) and lowest at Station 3 (155 m) (Table 3). The activity profiles obtained *in situ* were comparable to those of the laboratory incubated cores at Stations 2 and 3 evenn though the depth-integrated rates were slightly lower. However, at Station 1 and 4, differences were observed. The *in situ* profile from Station 1 showed a distinct subsurface peak between 4 and 10 cm, which could not be found in the laboratory profile. As a result of this, the depth-integrated rate from Station 1 was higher by a factor of 2 as compared to the laboratory rates (Table 3). Station 4, however, exhibited the opposite picture in all *in situ* cores: rates at a given horizon derived from *in situ* incubations were lower by a factor of up to 9 than the corresponding laboratory incubations. Again, this was expressed in the depth-integrated rates, which differed by a factor of 6 (Table 3).

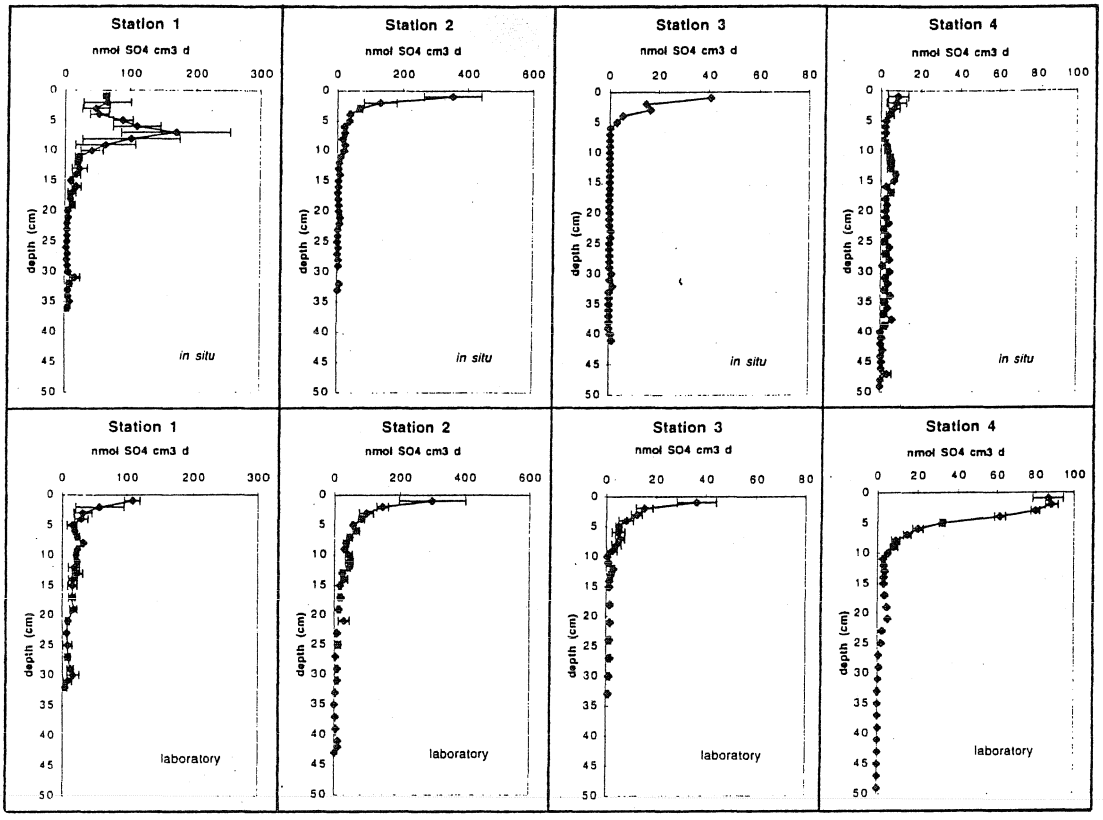

Fig. 5: Sulfate reduction rates of sediments from Gotland Basin. Upper panel shows results from *in situ* incubations, lower panel those from laboratory incubations of all stations. Each data point represents triplicate measurements. The errorbar indicates the standard error of the mean value (= mean value/(SQR(n)). For information on incubation time and calculation method see text.

Determination of total reducible inorganic sulfur (TRIS)

The results of the measurements of the content of total reducible inorganic sulfur (TRIS, comprises FeS, FeS_2, H_2S, S^0) in the sediment are presented in Fig. 6. For reasons of comparability the sulfur contents as determined by CNS analysis are also depicted in this figure. While the profiles at Stations 1 and 4 were rather scattery and showed an increase of sulfur over the length of the retrieved cores, Station 2 had decreasing sulfur contents to ca. 16 cm and very little amounts below. Only a sharp subsurface peak at ca. 31 cm at this station is conspicuous and

Table 3: Overview of the depth-integrated sulfate reduction rates (0-15 cm) of Stations 1 to 4 as determined by *in situ* and laboratory whole core incubations. Values in mmol m^{-2} d^{-1}. Standard deviation (n=3) given in parentheses.

Station	*in situ* incubations (± std. dev.)	laboratory incubations (± std. dev.)
1	8.99 (2.36)	4.66 (0.82)
2	7.52 (1.46)	10.55 (1.93)
3	0.80 (0.39)	1.01 (0.18)
4	0.69 (0.15)	4.21 (0.60)

was related to a sandy layer in the freshwater deposits that made up the deeper strata of the sedimentary column at Stations 2 and 3. Station 3 exhibited decreasing values with depth.

Sulfur inventories

Corrected for the contribution of sea water sulfate (2 to 22% of total S, data not shown), the sulfur inventories of the Stations as determined from both TRIS and CNS measurements are listed in Table 4. Station 4 had the highest amounts of sulfur buried in the sediment column, followed by Station 1, while the two stations whose deeper strata consisted of freshwater deposits had the lowest values (ca. one order of magnitude difference between the extreme values). It is obvious that the TRIS measurements yielded total sulfur contents comparable to the sulfur stock as calculated from CNS determinations; only at Station 4 was the sulfur inventory ca. 80% larger when measured by CNS analysis, as compared to TRIS analyses.

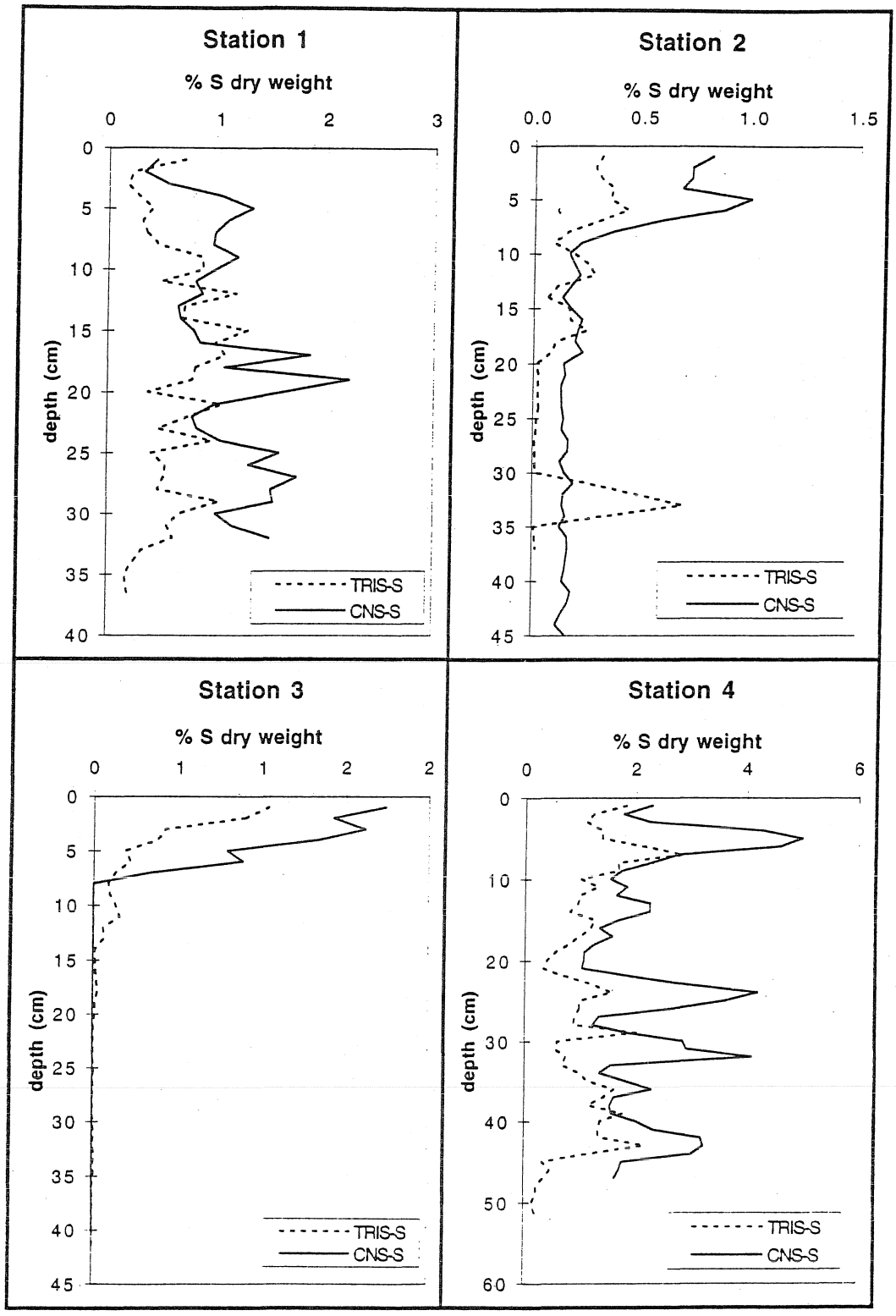

Fig. 6: Depth profiles of total reducible inorganic sulfur (TRIS) and total sulfur as measured by CNS analysis of Stations 1 to 4.

Table 4: Overview of the sulfur inventories of the investigated stations as determined from CNS- and TRIS mesurements, respectively. Values are given on a wet weight basis in mg S cm^{-2} over the entire core length.

Station	core-length	Sulfur inventory as measured by		Factor difference
	cm	TRIS	CNS	
1	32	135.4	153.6	1.1
2	37	38.6	30.2	0.8
3	40	11.5	12.1	1.1
4	47	140	247.9	1.8

CNS profiles

The depth profiles of the CN analyses are shown in Figs. 7 and 8, along with the molar ratios of C:N and C:S, the latter being calculated from the sulfur contents measured by CNS analysis. A simplified stratigraphy is included in these figures. Carbon was almost only of organic origin, and the surface concentrations increased with water depth from ca. 5% dw (Station 1) to ca. 10% dw (Station 4). Only at at Station 4 inorganic carbon was present in the diagenetically active surface sediments in concentrations of up to 1% dw (Fig. 8). Concentrations of nitrogen were low (< 1% dw) and varied according to carbon, causing roughly constant (around 10, Stations 1 and 4) or even decreasing C:N profiles (Stations 2 and 3; Figs. 7, 8). At Station 2 and 3, the freshwater deposits below ca. 10 cm showed very low contents of all compounds, and no sulfur was detected in these sediments at Station 3. Molar C:S ratios at all stations decreased from high values at the sediment surface to lower ones below, reflecting the decrease in organic carbon and increasing amounts of sulfur. The mean values of the strata below the diagenetically active horizon (= below 15 cm) were between 4.5-5.4 (Stations 1 and 4) and 7.3 (Station 2). No C:S ratios were calculated for Station 3, as no sulfur was measured below ca. 10 cm, where the C:S ratio was not yet stable (Figs. 7-8).

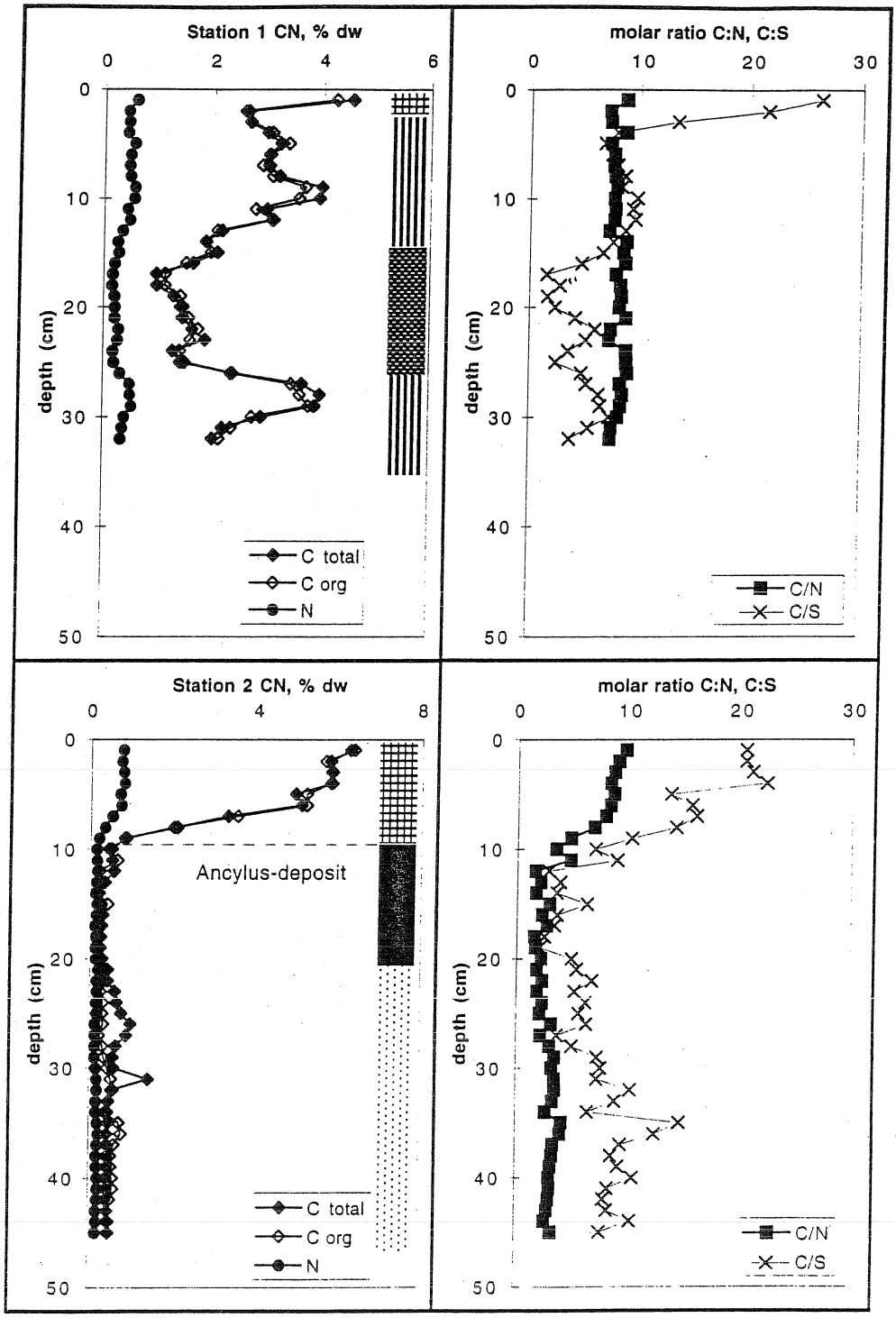

Fig. 7: Depth profiles of CN-contents of Stations 1 (upper panel) and 2 (lower panel). The molar C:N and C:S ratios that were calculated from the profiles are shown in the panels on the right. A simplified stratigraphy is shown. Dotted: cream coloured freshwater clay; crossed: soft black (fluffy) sediment layers; vertically striped: dark sediment with occasional black patches; dark gray: sandy layers; horizontally striped: black and light gray laminated layers.

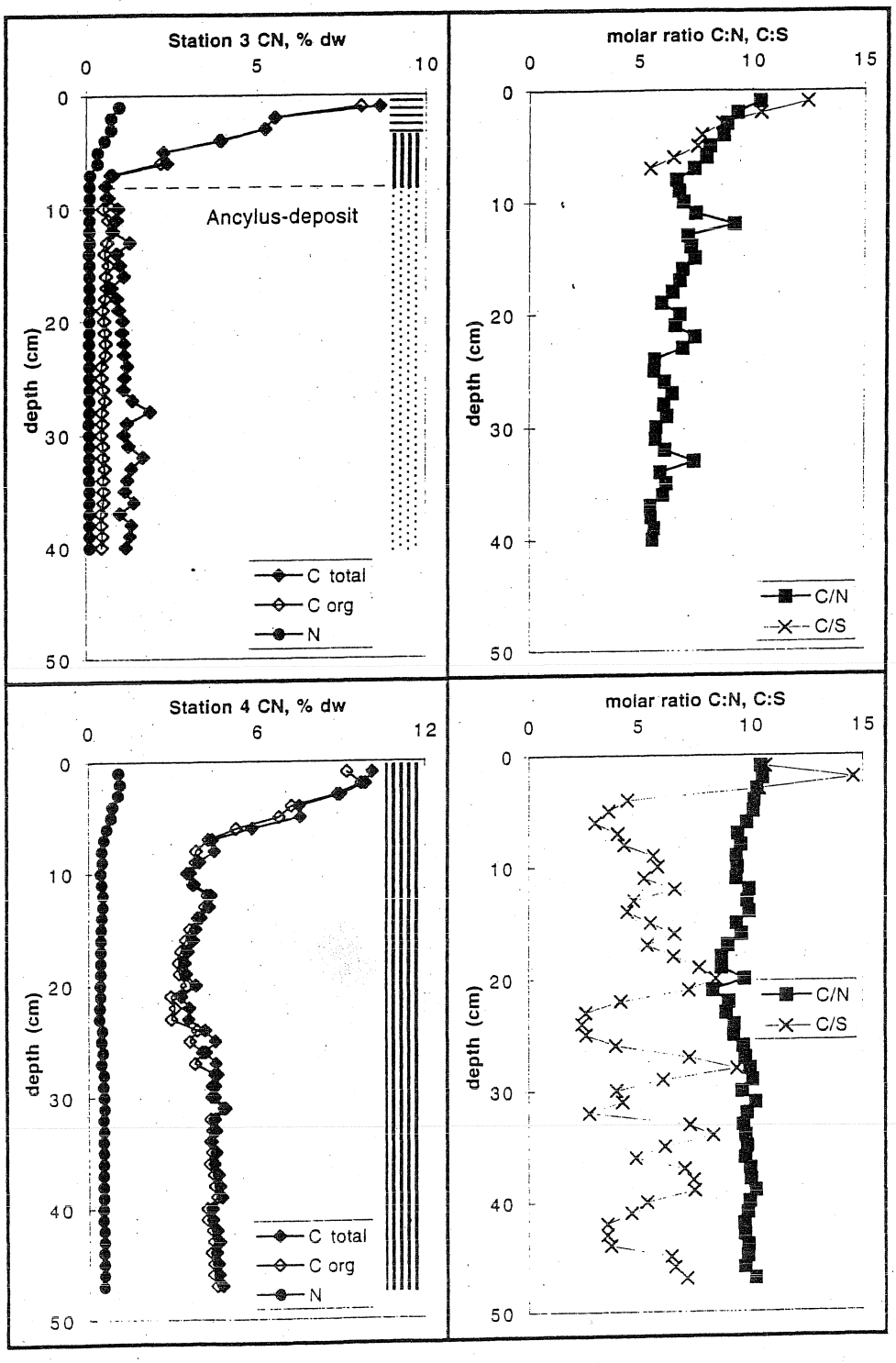

Fig. 8: Depth profiles of CN-contents of Stations 3 (upper panel) and 4 (lower panel). The molar C:N and C:S ratios that were calculated from the profiles are shown in the panels on the right. A simplified stratigraphy is shown, for legend see Fig. 7.

^{137}Cs profiles

Profiles of ^{137}Cs are shown in Fig. 9. Except for Station 4, the measured activities decreased with sediment depth; Station 1 exhibited a linear profile between 5 and 10 cm, and Station 2 showed a zone of roughly constant activity at the sediment surface, probably indicating bioturbation. Detectable activities of ^{137}Cs were found to the lowest marine horizons in the deeper layers of Stations 2 and 3 (stratigraphy in Figs. 7, 8). At Station 4 the ^{137}Cs activities first increased to a depth of 3 cm and decreased further below. This station also had the highest peak activities (ca. 5 Bq g^{-1} dw) among the visited locations. The observed peaks could not easily be attributed to either the Chernobyl-fallout (1986) or the nuclear tests in the sixities.

Discussion

CNS analyses and sulfur inventories

The maximum carbon contents increased with water depth and were almost only of organic origin, except for Station 4. Here the existence of up to 1% dw inorganic carbon is probably related to the ongoing formation of mixed authigenic Mn-carbonates (Carman and Rahm, 1997). Coastal sediments often show increasing C:N ratios over depth in the active surface layers (nitrogen limitation) (e.g. Blackburn, 1979), but constant or even slightly decreasing values have also been reported from the European Arctic Ocean (Wagner, 1993). Blackburn (1987) suggested that C:N ratios of marine sediments tend to stabilize at values around 10, irrespective of the input matter. Our observed C:N ratios in the surface sediments generally confirmed this assumption as they were around 10 and thereby higher as compared to the "Redfield-ratio", which lies at ca. 6-7 and relates to marine plankton (Redfield *et al.*, 1963). The freshwater deposits (Stns. 2a and 3), which represent transitional sediments between the glacial and post-glacial phases of the Baltic Sea (Winterhalter *et al.*, 1981) showed lower values than the diagenetically active surface horizons and remained stable over depth (Figs. 7, 8). C:N ratios of sedimented matter of around 10 indicate a preferential degradation of nitrogen over carbon in the water column and at the sediment surface, while in the sediment both compounds appear to be mineralized with similar rate constants.

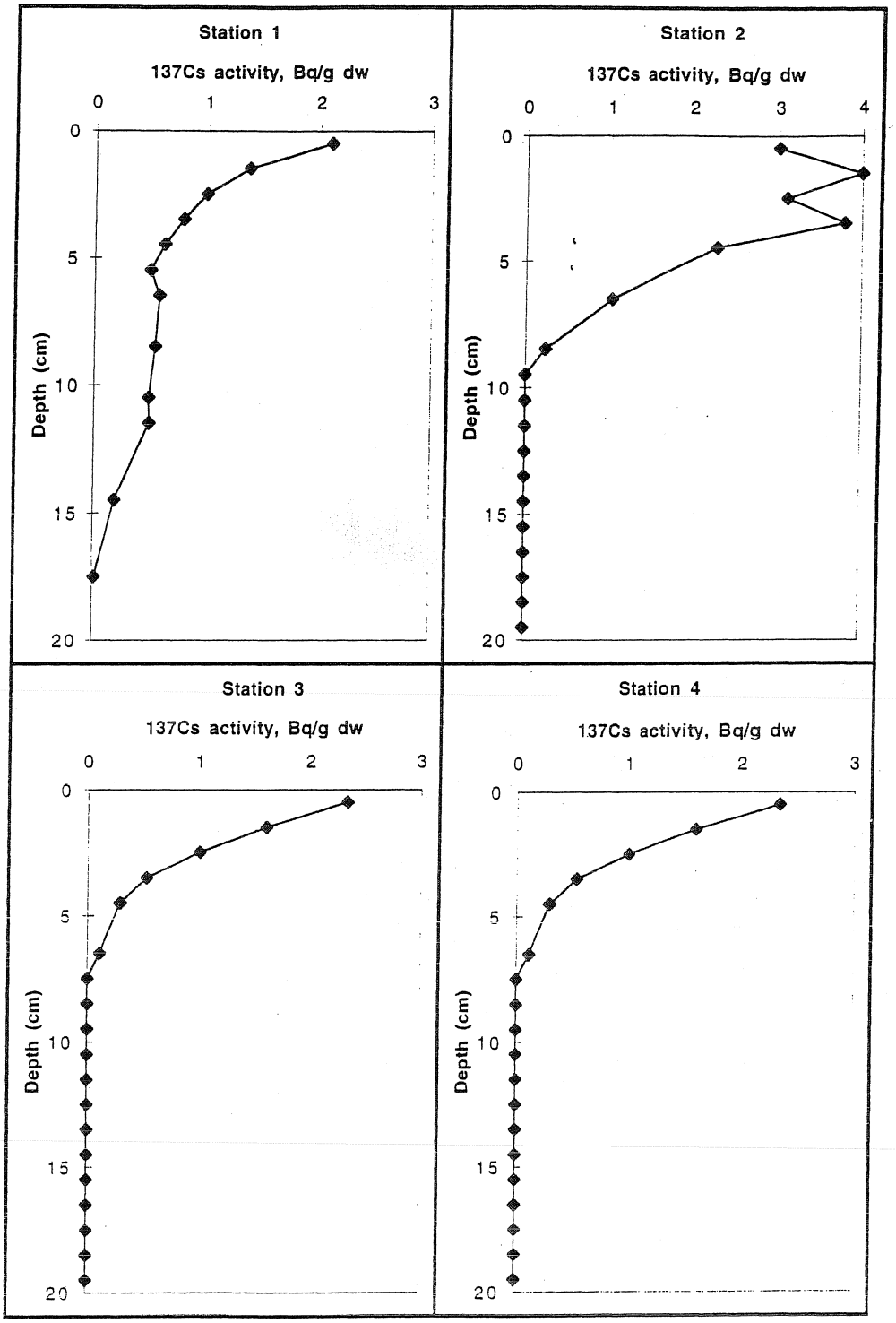

Fig. 9: Depth profiles of the activities of ^{137}Cs of all stations. Values are in Bq g^{-1} dw. Upper panel shows Stations 1 and 2, lower panel shows Stations 3 and 4. The error bars indicate the counting error.

SedimentaryC:S records have been used to classify depositional environments into categories as normal marine, euxinic or freshwater (Berner, 1982; Berner and Raiswell, 1983; Berner and Raiswell, 1984). Normal marine sediments were found to have a molar ratio of 7.5 ± 2.1, and lower values were determined in anoxic settings, indicating higher sulfur contents. Our findings at anoxic Station 4, however, did not show lower C:S ratios compared to the other stations, which also fell into the category normal marine sediments; this finding is supported by the normal C:S ratios reported by Boesen and Postma (1988) for Gotland Basin sediments. The freshwater sediments at Station2 and 3 did not exhibit high C:S ratios as predicted by Berner's model (1982), probably because these sediments are poor in organic carbon (Boesen and Postma, 1988) and cannot be compared to present-day freshwater sediments. Measurements of sulfur inventories by CNS and sulfide (TRIS) analysis revealed a good match of the two assays for oxygenated stations 1, 2 and 3 with discrepancies between 10 and 20% left (Fig. 6, Table 6). Station 4, on the other hand, contained 80% more CNS-sulfur, pointing to a considerable part of the sulfur stock being fixed in organosulfur or other compounds that are not measured by TRIS analysis. This is in good agreement with a hypothesis suggesting that reactive organic matter settling in anoxic environments can form organic sulfur compounds (OSC) upon contact with high concentrations of pore water H_2S (Kohnen *et al.*, 1991; Kohnen *et al.*, 1989; Sinninghe Damsté *et al.*, 1993; Wakeman *et al.*, 1995). The newly formed molecules are extremely resistant to biogenic degradation and thus may add to enhanced carbon preservation in euxinic settings.

^{137}Cs profiles

The absence of Chernobyl-derived ^{134}Cs ($t_{1/2}$=2.1 a) due to its decay in the sediments since the accident prevents a clear attribution of the observed peaks to 1986. A considerable mobility of radio-caesium was found in shallow Baltic Sea sediments (Holby and Evans, 1996) and in lake sediments (Knof, 1992), and Sholkovitz and Mann (1986) reported a preferential diffusional downward transport of ^{137}Cs in sediments of Buzzards Bay, Massachusetts. Our finding of detectable activities down to the lowest marine horizon on top of the freshwater deposits supports this idea. This indicates that caesium, which is preferably bound to clay minerals, especially illite (Brouwer *et al.*, 1983), in the case of the brackish Baltic Sea cannot be safely

used to determine sediment accumulation rates. However, the profiles gave an indication of bioturbation at Stations 1 and 2 (Fig. 9). Supportive evidence for bioturbation at this station can be obtained from the ^{210}Pb profile that showed distinct subsurface peaks to a depth of 14 cm. The presence of macrofauna at Station 1 agreed well with this finding, but the depth of bioturbation as indicated by the radionuclide profiles (4-12 cm, Fig. 9) is surprising and our data are insufficient to prove that the fauna we found caused the shape of the profile. Bioturbation at Station 2 extended to 4 cm depth, and although we did not find macrofauna at the sampling date, it is probable that in preceeding years bioturbating species were present and caused the observed distribution of ^{137}Cs. The activity peak at 3 cm depth at Station 4 is more difficult to explain (Fig. 9). The center of Gotland Basin, in our study represented by Station 4, acts as a trap for fine-grained material, and thus receives the largest amounts of radio-caesium. This is reflected in the observed highest peak activities of ^{137}Cs. In case this peak originated from weapon-fallout, it hence would indicate a sedimentation rate of ca. 0.73 mm a^{-1}, which is not unrealistic for Gotland Basin. Values of 1-1.3 mm a^{-1} are reported in the literature (Winterhalter *et al.*, 1981). If the above assumption was true, where then is the peak of the Chernobyl-accident? A possible explanation grounds in the extremely high water contents and softness of the sediment at Station 4, where even a controlled sampling with the multiple corer may have caused the fluffy layer on top of the sediment - containing the Chernobyl peak - to be dispersed in the overlying water.

Oxygen dynamics

The *in situ* oxygen penetration depths of around 1 mm were caused by a rapid consumption of oxygen in the surficial sediment, coupled to reoxidation and degradation. The gradients of the profiles indicated fluxes of 7-8 mmol m^{-2} d^{-1} that are on the lower end of the range reported from comparable coastal environments (Jørgensen and Revsbech, 1989). While penetration depths decreased with bottom water oxygen concentration, this was not the case for DOU. Station 2 exhibited the highest DOU, despite lower bottom water oxygen concentration compared to shallow Station 1 (Table 1, 2a). Comparing the *in situ* diffusive and total oxygen uptake of the stations (Table 2a/b) showed a higher TOU value for Station 1 (+20%), which probably is an indication to the influence of the observed benthic fauna that supplied oxygen to the

sediment via bioirrigation. At the deeper Station 2 (115 m), where no fauna was found, DOU and TOU measurements agreed closely. At Station 3 TOU was lower by 56% as compared to DOU measurements by *in situ* microelectrode profiles. Probably this is due to a high spatial variability caused by local erosions at the slope of Gotland Basin.

The simple model used to calculate the degree of reoxidation by oxygen of the sulfide produced by sulfate reduction showed that the largest part of the produced sulfide must be reoxidized to maintain the existing conditions (93% at Station 1, 99% at Station 2, 79% at Station 3 and 89% at Station 4, respectively). The sediment accumulation rates necessary for a complete burial of sulfide (= no oxygen consumed in the reoxidation of sulfide) were between 5 and 50 mm a^{-1}, which is unrealistically high for Gotland Basin (Winterhalter *et al.*, 1981). Thus we assume the calculated rates of reoxidation to be in a realistic range. At all stations, sulfide was quantitatively the major reductant for oxygen; the calculated complete reoxidation of ammonium, Mn^{2+} and Fe^{2+} together consumed only ca. 10% of the DOU at each station (the TOU value was used at Station 1). According to our calculations, the reductive capacity of reduced metabolic compounds diffusing upwards even exceeded the oxidation potential of the TOU at Station 1 (by factor 3) and the DOU at Station 2 (by factor 7), so theoretically no oxygen would be available for oxic respiration at those stations. This trend did not change significantly even when the release rates of ammonium, Mn^{2+} and Fe^{2+} measured in the benthic chamber were used to show that in fact a release - and thus no complete oxidation - took place; additionally bioturbation at Station 1 significantly increased the supply of oxygen to the sediment which in turn increased both oxic respiration and reoxidation in the thin oxygenated layers surrounding the burrows (Glud *et al.*, 1994; Hansen *et al.*, 1996). While this model gives reasonable trends for the reoxidation of reduced metabolic compounds, it is of course simplified. For example, the observed fauna and also microorganisms are in a competition for oxygen with the chemical process of reoxidation. Another factor which played a role is the precipitation of a fraction of the sulfide as FeS or FeS_2. This process decreases the amount of sulfide available for reoxidation and thus leaves more oxygen for oxic respiration. But the significance of this process was not determined in our study. As oxygen is the terminal electron acceptor for all reduced compounds, indirect reoxidation of sulfide through iron-or manganese oxyhydroxides,

which also are known to oxidize Fe^{2+} (e.g., Burdige, 1993), should not affect the validity of our assumptions. Hence, the results of our calculations probably reflect a non-steady-state situation in the balance of sulfide production and -reoxidation in Gotland Basin during the time of investigation.

Comparison of benthic in situ exchange rates vs. flux calculations

Fluxes of **ammonium** that were determined from pore water profiles exhibited a linear decrease with increasing water depth from ca. 400 µmol m^{-2} d^{-1} at Station 1 to ca. 100 µmol m^{-2} d^{-1} at Station 4 (Table 2a). The exchange rate of ammonium measured *in situ* in the benthic flux chamber at Station 1 agreed closely with the calculated flux, while at Station 2 it was higher by factor 2. Generally the observed release rates are in the range reported from coastal or shelf sediments (Thamdrup and Canfield, 1996). The observed peak concentrations of **nitrate** in the pore waters of Stations 1, 2 and 3 were very high considering the narrow oxic layer where nitrate production could occur. Pore water studies in coastal environments showed that such high nitrate concentrations usually occur along with deeper oxygen penetration depths (Jensen *et al.*, 1994). In the literature nitrate concentrations up to 4000 fold higher than ambient sea water in the vacuoles of marine *Beggiatoa* and *Thioploca* sulfur bacteria are reported (Fossing *et al.*, 1995; McHatton *et al.*, 1996; Schulz *et al.*, 1996). Along with these findings, our observation of sulfur bacteria on the sediment surface of Station 2 led us to speculate that these bacteria may have been the source of the nitrate peak we measured at Stations 2 and 3. In case bacteria were responsible for the high nitrate concentrations, this would also explain the observed high nitrate uptake from the enclosed water in the *in situ* chamber studies (Stations 1, 2), revealing that this phenomenon might not be related to direct denitrification. An estimation of the bacterial cell volume necessary to result in the measured nitrate concentration of ca. 20 µM in the uppermost sediment layers of Stations 2 and 3 (Fig. 3) yielded ca. 0.1 mm^3 cm^{-3} wet sediment, when a conservative value for the intracellular nitrate concentration of 0.2 M was assumed (e.g., Fossing *et al.*, 1995) reported values of up to 0.5 M). A cell volume of 0.1 mm^3 cm^{-3} wet sediment is rather low and can already be caused by inconspicuous numbers of bacteria present in the sediment (H. Schulz, MPI, pers. comm.).

The measured **iron** gradients were low and indicated that iron reduction was generally unimportant in the degradation of organic matter (Fig. 3, Table 2a). *In situ* measurements of benthic iron release rates showed that iron was liberated only from the sediments of Station 2 (Table 2b). Possibly the observed layer of a microaerophilic iron oxidizing bacterium prevented the release of ferrous iron from the sediment at Station 1. It remains unclear why no indication of iron release at Station 3 was found, as this station showed the highest diffusive efflux of Fe(II) as inferred from pore water gradients. Possibly iron oxidizing bacteria were present at that station, but we observed no matlike structure as at Station 1. An interesting finding at Station 4 was that the calculated flux of Fe^{2+} ions into the sediment (4.2 mmol m^{-2} d^{-1}, Table 2a, Fig. 3) exactly balanced the sulfide production measured in the laboratory cores (4.2 mmol m^{-2} d^{-1}, Table 3), showing that all available ferrous iron in the pore water was immediately precipitated. Whether FeS or FeS_2 was the product of this reaction cannot be said. As Gotland Basin is known to have sulfidic deep water masses for years (e.g.; Grasshoff and Voipio, 1981), not all sulfide produced can be precipitated as iron sulfide, but partly escapes into the bottom water. Boesen and Postma (1988) found evidence for direct formation of FeS_2 without the intermediate FeS step in Gotland Basin. We interpret our results as reflecting iron limitation in the process of iron sulfide formation in the anoxic sediments at Station 4. Accordingly, no signs of iron release were found in the *in situ* flux chamber measurements at that location. **Manganese** was released by the sediment with increasing water depth when calculated from pore water gradients; however, *in situ* exchange rates measured at Stations 1 and 2 by the benthic flux chamber pointed to a Mn(II) release that was higher by an order of magnitude (Table 2a/b). While in the literature similar findings have been reported and explained by an intense release of Mn^{2+} from the topmost sediment horizon (Johnson *et al.*, 1992), where microbially mediated reduction of manganese oxides can occur in the presence of low oxygen concentrations (Tebo *et al.*, 1991), we regard our calculated fluxes from the pore water analyses to probably underestimate the real *in situ* fluxes, as the steep gradients of Mn^{2+} within the topmost millimeters of the sediment were below the resolution of our pore water studies. Furthermore, bioturbation probably enhanced the benthic exchange rates at Station 1.

At all stations the peak concentrations of ferrous iron were underlain by the peak concentration of dissolved manganese, which agrees with recent data from the Gotland Deep published by Carman and Rahm (1997). Often this sequence is found to be vice versa, and a reduction of manganese oxides by dissolved ferrous iron has been proposed to explain the observed Mn(II) peaks without assuming that manganese reduction is coupled to organic matter degradation (Nealson and Myers, 1992). However, for widespread organisms capable of both metabolisms the redox potential for iron reduction makes this process energetically more favourable than manganese reduction (Nealson and Myers, 1992). In this case, iron reduction and the resulting peak of ferrous iron should occur higher in the sediment column than manganese reduction; in the light of these findings, our results are interpretable as a hint to the coupling of manganese reduction to the degradation of organic matter in Gotland Basin. However, reduction of manganese(hydr)oxides by sulfide is also possible (Burdige, 1993; Burdige *et al.*, 1992; Van Cappellen and Wang, 1996).

Sulfate reduction

Investigations comparing *in situ* measurements of benthic exchange rates of nutrients to laboratory results pointed to systematic variations in the determined parameters as a consequence of transient heating and decompression during the retrieval of samples, yet the extent and direction of these changes is still under discussion (Deming and Colwell, 1985; Jahnke *et al.*, 1989; Jannasch and Wirsen, 1982). Heating and decompression (the latter is assumed to be of minor importance at depths < 1000 m) may be lethal to psychro- and barophilic organisms (Smith and Hinga, 1983; Turley *et al.*, 1988; Yayanos, 1986), while possibly enabling growth of mesophilic bacteria, so that *in situ* measurements in deep-sea environments generally are expected to yield lower results than comparable laboratory experiments (Glud *et al.*, 1994). However, in coastal environments exchange rates are enhanced due to the activity of benthic animals (Devol and Christensen, 1993; Glud *et al.*, 1994). The rates are normally underestimated due to the underrepresentation of active benthic fauna in small sampling devices, an artifact that is compensated for by larger *in situ* chambers. In our case, decompression most probably did not play a significant role. The temperature difference between the bottom and the surface waters was around 15°C, and with known Q_{10}-values for sulfate reducing bacteria of around 3 (Isaksen and

Jørgensen, 1996; Jørgensen, 1977; Skyring *et al.*, 1983; Westrich and Berner, 1988), the time the samples were exposed to increased temperatures (ca. 1 h) did not suffice to stimulate fast growth and/or enhanced metabolic activity of a significant fraction of the sulfate reducing bacterial population. The depth-integrated SRR determined in this study are in the middle to low range of rates known from coastal and shelf sediments (overview in Skyring, 1987). A comparison of the laboratory vs. *in situ* sulfate reduction rates revealed a general tendency of lower depth-integrated rates *in situ* (Table 3); at two sites the difference was however not statistically significant: Station 1 showed a subsurface peak in the *in situ* profile that was absent in the laboratory cores, causing a higher *in situ* depth-integrated rate at this site. The observed peak is most probably due to sediment heterogeneity, which was particularly pronounced at that station (Fig. 7, stratigraphy). Results from Station 4 represent the opposite end in the range of our values, where the integrated *in situ* sulfate reduction rate was found to be only one third of the laboratory value. However, the transient heating during ca. 1 hr (recovery and fixation) combined with Q_{10}-values for sulfate reducing bacteria of 3 would not have been enough to cause the observed threefold difference between *in situ* and laboratory rates at that station, only a maximum increase of 11-15% could have taken place (data not shown). A possible explanation could be that the bow wave of the sinking lander caused the topmost layers of the exceptionally soft sediment at Station 4 to be dispersed, so that the profiles from that station are offset compared to the laboratory profiles and the topmost values do not represent the original sediment surface. The fact that the landers sunk about 50 cm into the sediment at this station may serve as a hint that the above explanation is probably true.

Total mineralization

The carbon degradation rates calculated for the individual metabolic processes are shown in Table 5, along with their percent-wise contribution to overall degradation. Overall degradation rates were calculated from the sum of the carbon equivalents of the pore water nutrients plus the depth-integrated rates of sulfate reduction measured in the laboratory cores. We chose to use the laboratory results of sulfate reduction measurements as they were affected in the same manner as the multicorer samples from which the pore water profiles were obtained. It is

Table 5: Rates of carbon degradation in µmol C m^{-2} d^{-1} for the various electron acceptors. Values of oxygen are calculated from *in situ* microprofiles and corrected for the reoxidation of the reduced upward diffusing species NH_4^+, Mn^{2+}, Fe^{2+} and HS^-. Values for sulfate reduction are calculated from the depth-integrated rates of the laboratory incubations at the respective station. Values of ammonium, nitrate, iron and manganese are based on calculated fluxes (see Table 2a). No carbon degradation due to denitrification is given for Station 2, as we assume the measured nitrate to stem from bacteria (see text for details). The carbon equivalent of the nitrate flux at Station 3 was calculated from the nitrate production during oxic respiration. The ammonium flux was converted to carbon equivalents by multiplication by the C:N ratio of the respective sediment layer used for the flux calculation. The row "NH_4^+ supp." represents the given flux of ammonium into the bottom water supported by the calculated ammonium production due to oxygen respiration in the first mm of sediment where oxygen was present and not consumed in the reoxidation. The row "C-flux" represents the overall amount of organic carbon (in mol m^{-2} a^{-1}) degraded at the respective station on an annual basis. nc = not calculated. *= all oxygen is consumed by the reoxidation of reduced species in the pore water. See text for details.

	Station							
	1	%	2	%	3	%	4	%
O_2	0*	**0***	0*	**0***	3386	**53.7**	0	**0**
NO_3^-	168	**1.4**	0	**0**	488	**7.7**	0	**0**
Mn^{2+}	7	**0.06**	3	**0.01**	104	**1.7**	330	**3.6**
Fe^{2+}	22	**0.2**	nc	**nc**	122	**1.9**	0	**0**
SO_4^{2-} lab.	11400	**98.3**	23200	**99.9**	2200	**34.9**	8800	**96.4**
SO_4^{2-} *in situ*	18200		15800		1800		3000	
SUM (lab.)	**11597**		**23203**		**6300**		**9130**	
NH_4^+	3319		3571		2840		1122	
NH_4^+ supp.	3319*		3571*		3625		1122	
C flux (mol m^{-2} a^{-1})	**4.2**		**8.5**		**2.3**		**3.3**	

obvious that sulfate respiration was the dominant degradation process. Even though oxygen was taken up by the sediments of Stations 1, 2 and 3, our calculations show that oxic respiration played a quantitatively less important role in the degradation of organic matter, as most of the available oxygen was consumed in the chemical reoxidation of sulfide to maintain the sedimentary sulfur balance. This is in good agreement with results published by Canfield *et al.* (1993), who in a study on Kattegat sediments also found reoxidation processes of reduced metabolic products to be quantitatively more important in the consumption of oxygen than aerobic respiration. The nitrate uptake at Station 1 contributed ca. 1.4% to organic matter degradation (Table 2a), if the nitrate was reduced and not taken up by bacteria as we assume to have been the case at Stations 2 and 3. Denitrification of the nitrate produced during oxic respiration may have contributed to carbon degradation at Station 3; assuming that all produced nitrate was denitrified to N_2, ca. 8% of the overall degradation were contributed by dentrification at that station. However, it is more likely that this nitrate also was taken up by the bacteria. Manganese reduction as inferred from pore water gradients played a role only at anoxic Station 4 (3.6% of the total carbon degradation), but was quantitatively unimportant at the other stations. Reduction of ferric iron did not exceed ca. 1% of the overall degradation. Even if iron and manganese reduction occurred chemically (see above), the overall rates of carbon degradation would not change significantly at all stations. Carbon degradation as calculated from ammonium fluxes gave slower rates of organic matter degradation as compared to overall degradation. The difference was by factors of 3 to 9, depending on the station (Table 5). Only when the ammonium production due to oxic respiration in the thin oxic layer of Station 3 (ca. 1 mm, below the resolution of our laboratory pore water profiles) was calculated and added to the measured ammonium flux, this factor decreased (Table 5).

Our overall degradation rates show that the total carbon remineralization rate did not differ significantly between oxic and anoxic stations, confirming the findings of other authors (Canfield, 1989; Henrichs, 1992; Henrichs and Reeburgh, 1987). Assuming no temporal variation in mineralization, the annual benthic degradation was calculated to be ca. 2.5-4 mol C m^{-2} a^{-1} (Stations 1, 3 and 4) and ca. 8.5 mol C m^{-2} a^{-1} (Station 2; Table 5), which is equivalent to

Table 6: Carbon degradation and burial in Gotland Basin. All numbers are given as percentages of a mean primary production of 15 mol C = 180 g C m^{-2} a^{-1} (PP_{180}; Lassig *et al.*, 1978; Schulz *et al.*, 1992), except last row, which indicates the burial efficiencies (buried carbon as percentage of carbon flux to the sediment). Benthic remineralization numbers were calculated from the sum of laboratory sulfate reduction rates plus the summed carbon equivalents of the measured pore water nutrient fluxes. Carbon burial was calculated from the mean organic carbon content of sediment strata below the diagenetically active surface and sediment accumulation rates of 0.5 mm a^{-1} (Stations 1 and 2) and 1 mm a^{-1} (Stations 3 and 4). The degradation in the water column necessary to maintain the existing conditions was calculated by subtracting the sum of burial plus benthic degradation from the primary production.

%	Station 1	Station 2	Station 3	Station 4
Benthic remineralization	28	57	15	22
Burial	4	1	2	7
Water column degradation	68	42	83	61
Burial efficiency	14	2	16	21

between 15% (Station 3) and 57% (Station 2) of the annual primary production estimated for that area (ca.15 mol C m^{-2} a^{-1}; Lassig *et al.*, 1978; Schulz *et al.*, 1992) (Table 6). However, since the benthic response to sedimenting organic matter (phytoplankton blooms) in spring and autumn is known to be very rapid in both deep-sea and shallow marine sediments (often a matter of days to weeks, Graf, 1989; Graf, 1992), even higher benthic remineralization rates could be assumed for the short time periods following the input of fresh organic debris; consequently, benthic overall annual degradation will be probably slightly higher than the extrapolated value of our findings suggest. Together with our calculated carbon burial rates of between 0.2 mol C m^{-2} a^{-1} (ca. 1% of the primary production, Station 2) and 1 mol C m^{-2} a^{-1} (ca. 7%, Station 4), this left ca. 40-80% of the primary production to be degraded in the water column.

Consequently, the carbon burial efficiency (the amount of carbon buried expressed as the percentage of the carbon flux to the sediment; Henrichs and Reeburgh, 1987) was calculated to be between 2.4% (Station 2) and 21% (Station 4, Table 6). Carbon burial efficiency was found to correlate directly with sediment accumulation rate (Hedges and Keil, 1995), and our values were in the known range for sediment accumulation rates around 0.1 cm a^{-1} (Hedges and Keil, 1995; Canfield, 1993). Again, no major difference between the stations with oxygenated bottom water and the anoxic station were found, although Station 4 exhibited a slightly higher carbon burial efficiency compared to the other stations (Table 6).

When instead of the laboratory sulfate reduction rates the results of the *in situ*-measurements of sulfate reduction were used to calculate total degradation rates, the overall amount of remineralized carbon varied, according to the importance of sulfate reduction as the most dominant degradation pathway. Sediment variability between the laboratory and the *in situ* cores probably was the reason for an increase in total remineralization (+57%) at Station 1. Station 2 showed slower *in situ* sulfate reduction rates, leading to a decrease of 32% in the total amount of mineralized carbon. The amount of sulfide produced *in situ* was still enough to theoretically consume all available oxygen through reoxidation. While Station 3 remained roughly constant (the increase of 10% was due to a slightly lower *in situ* sulfate reduction rate, leaving more oxygen for oxic respiration), anoxic Station 4 showed slower *in situ* rates of organic matter oxidation (-64%), which apparently was an artifact due to LUISE's landing on the exceptionally soft sediment (see above). In the light of these explanations, slightly lower sulfate reduction rates appear to be probable when determined *in situ* (Greeff *et al.*, subm., chapter 2.1 of this thesis), but sediment heterogeneity and sampling/investigative artifacts may add to produce a complex picture, in which the true differences between *in situ* and laboratory measurements are hard to disclose.

Conclusions

The presented results from Gotland Basin give rise to the following conclusions:

- Of a primary production of ca. 15 mol C m^{-2} a^{-1}, between ca. 15 and 57% were degraded by benthic activity; ca. 1-7% were permanently buried below the active surface layer, and ca. 40-80% were degraded during the settling of the particles through the water column. Carbon burial efficienies varied between 2.4% and 21%.
- Sulfate reduction was generally the most important process in the benthic degradation of organic matter. At two out of three stations with oxygenated bottom water (Stations 1 and 2) the rates of sulfide production were calculated to be high enough to completely consume the DOU in the reoxidation. The observed results from the calculations do not reflect steady-state conditions of sulfide production and reoxidation in Gotland Basin. The general tendency indicates that in Gotland Basin direct carbon degradation by oxic respiration is by far outbalanced by sulfate reduction and contributes only minor percentages to overall decomposition. Thus, total benthic carbon remineralization was approximated by sulfate reduction.
- Sulfate reduction rates determined *in situ* were generally comparable to but at three out of four stations lower than laboratory rates, but the differences were statistically not sgnificant.
- Denitrification and metal reduction as inferred from the pore water fluxes did not play a significant role in the mineralization of organic matter at all stations, when metal reduction was assumed to be coupled to organic matter degradation.
- The formation of sedimentary iron sulfide in the anoxic part of Gotland Basin is iron limited.
- The deep waters of Gotland Basin are a source for dissolved Mn^{2+}.
- Mn-reduction was probably coupled to organic matter degradation instead of proceeding chemically by Fe^{2+} diffusing upwards, as is the case in many marine sediments (Nealson and Myers, 1992).
- A considerable fraction of sedimentary sulfur appeared to be fixed in organosulfur compounds (OSC), as revealed by the comparison of sulfur inventories determined by CNS and

TRIS analysis. This may support the notion of enhanced carbon preservation in environments rich in hydrogen sulfide (e.g. Kohnen *et al.*, 1989), where readily degradable organic matter is supposed to form resistant OSC upon contact with hydrogen sulfide.

- All stations showed C:S ratios in the range of "normal marine sediments" (e.g. Berner, 1982) and no clear difference was noticeable between the stations with oxygenated bottom water and the anoxic station. This is in contrast to the general finding that anoxic sediments should have lower C:S ratios (Berner and Raiswell, 1983).

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2.3

Temperature dependence and rates of sulfate reduction in cold sediments of Svalbard, Arctic Ocean.

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Abstract

Sediments of permanently cold areas around Svalbard and northern Norway were examined for their sulfate reduction activities and the degree of adaptation of their bacterial communities towards low temperatures. Depth distributions of sulfate reduction rates were obtained from whole-core incubations with sulfur-35 labeled sulfate as tracer. The integrated rates from the sediment surface to a depth of 15 cm ranged between 0.9 and 4.1 mmol m^{-2} d^{-1} comparable to rates in shelf sediments of temperate climates. The temperature dependence of sulfate reduction was investigated by incubation of anoxic sediment slurries in a temperature gradient block at -5°C to +40°C. Sulfate reduction rates increased 4 to 10-fold from *in situ* temperature to the optimum temperature and highest measured rates reached nearly 200 mmol ml^{-1} d^{-1} at 27°C. The optimum temperatures, 25°C to 30°C, indicated a mesophilic community of sulfate-reducing bacteria and were at least 20°C higher than the *in situ* temperatures of -1.7°C to 2.6°C. Arrhenius-plots were linear from the lowest temperatures nearly to the optimum temperatures and activation energies fell in the range from 40 to 75 kJ mol^{-1}, i.e. at the lower end of previously reported values. Samples from depths below 15 cm showed enhanced rates as a result of

substrate addition, whereas the optimum temperatures did not change. The high rates at *in situ* temperatures and the low activation energies are indications of a cold-adapted population of mesophilic or moderately psychrophilic sulfate-reducing bacteria in these sediments.

Introduction

More than 90% of the ocean and most of the seafloor are permanently below 5°C (Morita 1975, Russell 1990), which implies that bacteria living in these habitats should be adapted to low temperatures. Most studies of cold-adaptation have been on aerobic psychrophilic bacteria from the water column (Harder & Veldkamp 1967, 1968, McMeekin 1988, DeLille & Perret 1989) and from food materials such as milk (Ratkowski *et al.* 1982a, b). Only few psychrophilic sulfate-reducing bacteria have been described (Isaksen & Jørgensen 1996) and the adaptational advantage of obligate psychrophilic marine bacteria to grow better at low temperatures than do facultative psychrophiles was examined by Harder & Veldkamp (1971).

The physiology of cold adapted bacteria and their potential role for biotechnology were discussed by Gounot (1991). She emphasised the importance of psychrophilic bacteria in natural environments and regretted the limited knowledge about their adaptation to low temperature. Wiebe *et al.* (1992, 1993) reported an enhanced substrate requirement for bacterial growth at low temperatures. A diminished affinity for substrate uptake was shown for two psychrotolerant Antarctic bacteria by Nedwell & Rutter (1994). The temperature dependence of the energy demand of anaerobic bacteria was discussed by Conrad & Wetter (1990), who reported that hydrogen metabolism is thermodynamically favoured by low temperatures.

Sulfate reduction is considered to be the most important process of organic material degradation on the continental shelves (Jørgensen 1982, Canfield 1993) and therefore of great significance for the global carbon cycle. The importance of sulfate reduction for carbon turnover in cold climates is still poorly understood. A psychrophilic response of sulfate reduction in sediment samples was shown only once (Isaksen & Jørgensen 1996). The general question of temperature limitation of mineralization rates in Arctic regions will be discussed further.

The feasibility to accurately measure rates of sulfate reduction with radiotracers without temperature artifacts was a second reason to focus on the sulfate reduction process. Whole core incubations gave information about the depth distribution of sulfate reduction in intact sediment cores at *in situ* temperatures. For the determination of the temperature dependence of the sulfate-reducing community in these sediments slurries were incubated in a temperature gradient block.

Psychrophilic bacteria are very sensitive to high temperatures (Morita 1975) and the transport through a warm water column may reduce the number of living psychrophiles in sediment samples. Therefore Svalbard had been chosen for permanently cold sediments and water column. Low air temperatures at the time of the cruise, September / October 1995, were also advantageous for the handling of cold sediments on deck. Additionally, Svalbard is well accessible from northern Norway.

The adaptation of isolated bacteria or of bacterial communities to different temperatures may be interpreted from Arrhenius plots (Harder & Veldkamp 1968, 1971, Innis 1975, Mohr & Krawiec 1980). These are made by plotting the logarithm of a rate of bacterial growth or metabolism versus the inverse absolute temperature. A linear part of the plot is considered a good temperature adaptation of the bacteria in this interval (Guillou & Guespin-Michel 1996). The slope of this line can be used to calculate an "activation energy" which is not a well-defined thermodynamic unit but rather an integrated measure of the temperature response of the overall microbial community (Westrich & Berner, 1988). We tried to distinguish between the temperature response of the sulfate reducers and the substrate formers by adding surplus substrate in some experiments.

Materials and methods

Coastal sediments were sampled with a multiple corer during a cruise with RV "Jan Mayen" from Tromsø, northern Norway, to Svalbard in the Arctic Ocean (Figure 1). Sampling sites were Malangen Fjord (1a, 1b) near Tromsø (Norway); Hornsund (2 + 4) , Van-Mijenfjord (3)

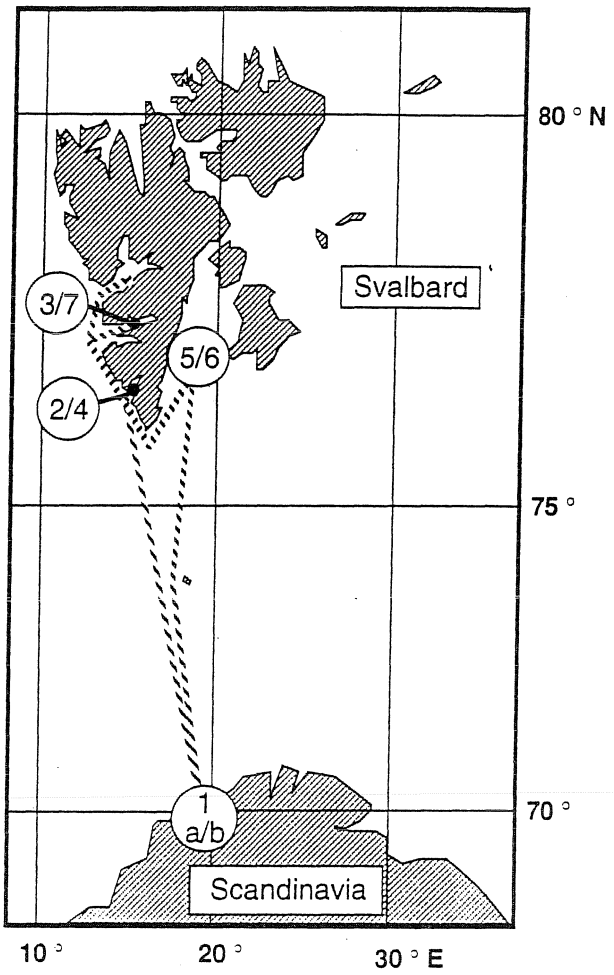

Fig. 1: Cruise route and sampling sites.

and its outer part called Bellsund (7) at the south-west coast of Svalbard and Storfjord (5 + 6) at the south-east coast (Table 1). The bottom water temperatures decreased northwards along the west coast of Svalbard with decreasing Gulfstream intensity (Table 1). The lowest bottom water temperature of -1.7°C was recorded at Storfjorden at the east coast of Svalbard. This extremely low temperature is caused by the Barents Current which transports cold water from the Barents Sea southwards. All sampled sediments were silty sands with variable proportions of clay, silt and sand. Small stones indicated ice-transport of terrestrial material whereas shell debris and worm tubes were of marine origin. Water depths were between 78 m and 329 m (Table 1).

Table 1: List of stations

Station number / name	Coordinates	Date	Water depth (m)	Bottomwater temp. (°C)	Areal SRR * (mmol m-2 day-1)
1a/bMalangenfjorden	69° 29.4 N 18° 07.5 E	09.25.1995 10.09.1995	329	7.0	0.99
2 Hornsund	76° 58.2 N 15° 34.5 E	09.28.1995	155	2.6	4.15
3 Van Mijenfjorden	77° 45.7 N 15° 03.9 E	10.01.1995	115	0.2	0.90
4 Hornsund (Lander)	76° 33.0 N 15° 00.2 E	10.04.1995	138	2.8	1.97
5 Storfjorden	77° 33.0 N 19° 05.0 E	10.05.1995	175	-1.7	1.22
6 Storfjorden (Lander)	77° 30.0 N 18° 26.9 E	10.06.1995	78	1.5	0.91
7 Bellsund	77° 38.2 N 14° 25.1 E	10.01.1995	145	3.2	2.41

* The areal sulfate reduction rate is calculated by integration of the sulfate reduction rates from the sediment surface to a depth of 15 cm.

Sulfate reduction measurements

Whole core incubations

Subcores of 25 to 35 cm length were taken from intact sediment cores with perspex tubes of 25 mm i.d. immediately after core retrieval. Along the sides of the tubes silicone rubber ports at intervals of 1 cm allowed the injection of tracer (ca. 5 µCi of $^{35}SO_4^{2-}$, Amersham) without disturbing the sediment (Jørgensen 1978). The cores were incubated for 8-12 hours at *in situ* temperature in the dark. The sediment was cut into slices of 1 cm thickness, thoroughly mixed with 10 ml of 20% (w/v) zinc acetate to stop the reaction, and subsequently frozen for the transport.

Temperature gradient incubations

A thermally insulated solid aluminum block of 2 m length and a square size of 15 x 15 cm was heated electrically to +40°C ±0.1°C at one end and cooled to -5°C ±0.1°C with a refrigerated circulation thermostat at the other end. Samples of about 10 ml slurries were incubated in stoppered glass test tubes (Venoject), which were placed in holes in the aluminum block. It contained thirty rows of four holes each along the block so that 120 samples could be incubated simultaneously at temperature intervals of 1.5°C with a maximum of four replicates at each temperature.

For the preparation of sediment slurries, segments of 5 cm thickness from two different depths were collected from intact cores at Stations 1a, 2, 3 and 5. One sample was taken just below the colour transition zone from brown to black or grey which occurred in nearly all cores. A lower sample was taken just below the first one (Table 2). The slurries were made with oxygen-free bottom water. The *in situ* temperature was maintained at all times from sampling to incubation. The samples were preincubated in the temperature-gradient block for one hour to reach steady temperatures of 0.1°C, after which 100 µl tracer containing 8 to 16 µCi of $^{35}SO_4^{2-}$ (Amersham) was added. Short incubation times of 4 to 5 hours were chosen to prevent significant growth of the bacteria during incubation. The samples were treated after incubation in the same way as for whole core incubations. The temperature gradient experiments were carried out either without or with substrate addition. As substrate 100 µl neutralized solution of mixed Na-salts of acetate, butyrate, formate, lactate and propionate plus ethanol were added. Final concentration was approximately 1 mM of each component.

All samples were distilled with a solution of hydrochloric acid and chromium (II) chloride to convert reducible sulfur compounds into H_2S (Canfield *et al.* 1986). The H_2S was subsequently trapped in 10 ml of 5% (w/v) zinc acetate solution and counted in a scintillation counter (Packard). The ratio between added ^{35}S-Sulfate and formed ^{35}S-Sulfide was used to calculate the sulfate reduction rate (Fossing and Jørgensen 1989). The detection limit was about 0.2 nmol ml^{-1} day^{-1}. The rates of sulfate reduction for slurried samples are calculated per volume undilu-

ted sediment to enable comparison between sulfate reduction in natural sediments and in slurries.

Arrhenius plots

The Arrhenius equation provides a link between bacterial growth rate (often metabolic or respiratory parameters are used as well) and energy demand of the cells. The equation is written as (f. i.: Westrich & Berner 1988):

$$v = A * e^{\frac{E_a}{R*T}}$$

with: v = rate (growth, metabolism or respiration)

A = constant

R = gas constant (8.31 J K^{-1} mol^{-1})

T = absolute Temperature (K)

E_a = "activation energy" (kJ mol^{-1}).

Results

Results of whole core incubations

Sulfate reduction rates were in the range between 0.5 and 250 nmol ml^{-1} day^{-1} (Figure 2a/b). The mean sulfate reduction rates of 2 - 4 replicate measurements are plotted together with minimum and maximum values to display the range of variations between cores. All profiles exhibited low values near the sediment surface and below 15 - 20 cm depth. The highest rates in each core usually occurred between 3 and 10 cm depth. The highest rates of all measurements were found at Station 2, with almost three-fold higher rates than at all other stations. The depth

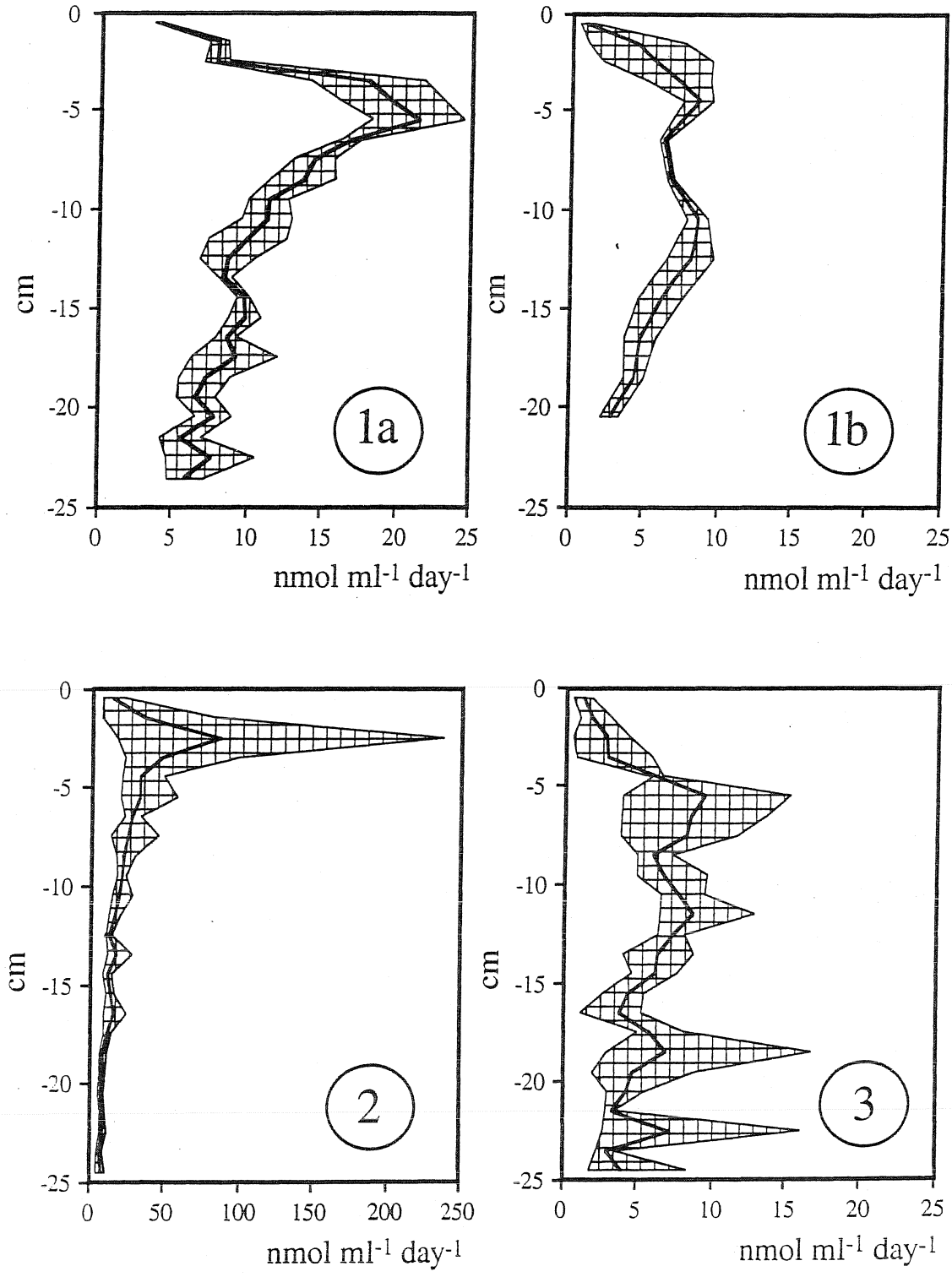

Fig. 2a: Sulfate reduction rates of Stations 1 to 3, measured with whole-core incubations at *in situ* temperatures. The solid line represents mean values of four (Station 3) and two cores (Station 1a/b, 2). The chequered areas cover minimal and maximal values. Note different scales for sulfate reduction rates.

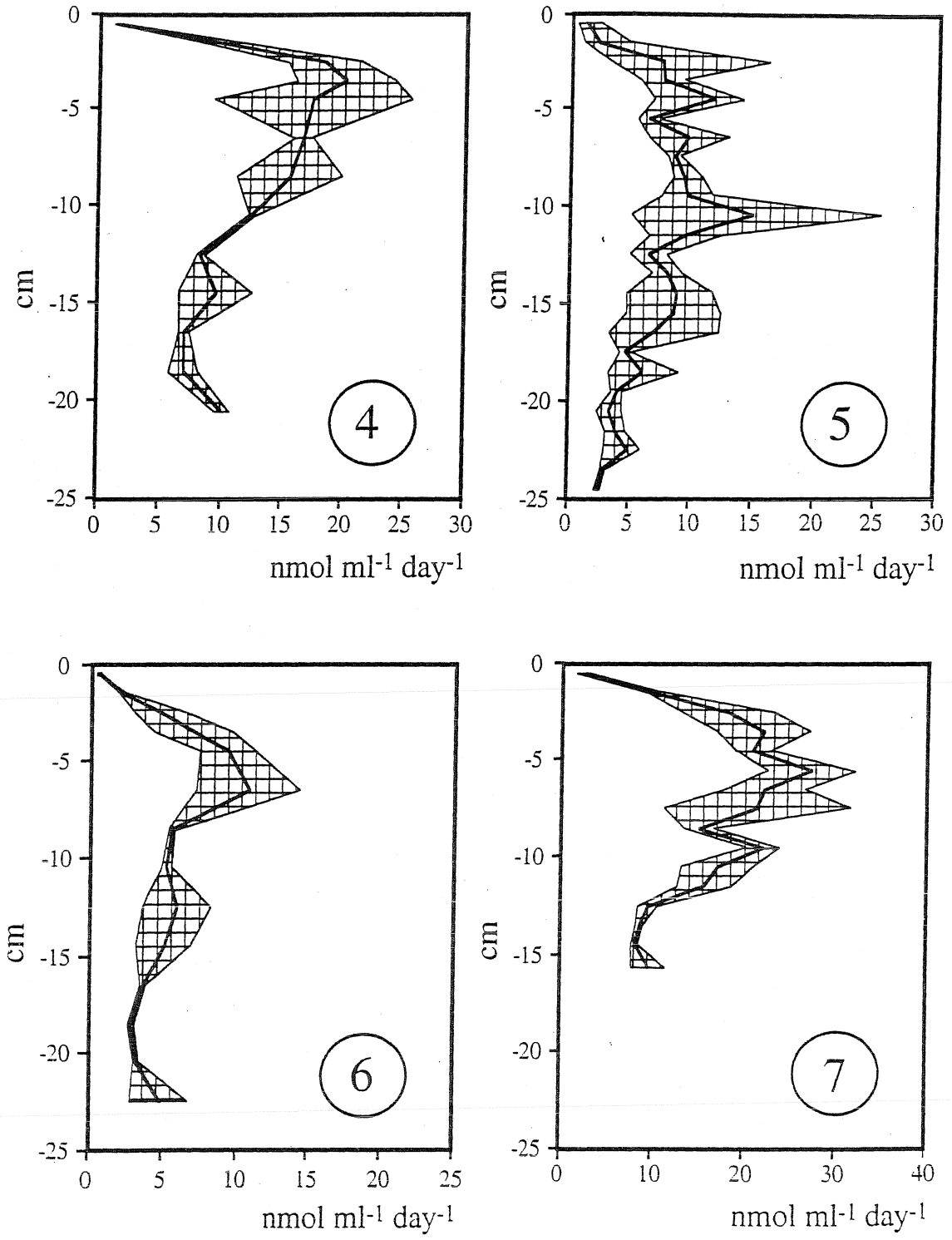

Fig. 2b: Sulfate reduction rates of Stations 4 to 7, measured with whole-core incubations at *in situ* temperatures. The solid line represents mean values of four (Station 4, 5) and two cores (Station 6, 7). The chequered areas cover minimal and maximal values. Note different scales for sulfate reduction rates.

integrated rates to a sediment depth of 15 cm (Table 1) are used for comparison between different sites. They ranged between 0.90 and 4.15 mmol m^{-2} day^{-1} and again Station 2 showed the highest rate by far.

Results of temperature gradient incubations

Temperature gradient incubation experiments were made at Stations 1a, 2, 3 and 5, resulting in sixteen temperature profiles for the cruise. Here we present the profiles of Station 5 which are representative examples (Figure 3). Typical for the Svalbard sediments were relatively high rates at *in situ* temperatures. At these temperatures the calculated rates of the slurry incuba-

Table 2: Results of temperature gradient incubation experiments. n.d. = not determined.

Station, depth (cm)	Substrate	$T_{opt.}$ (°C)	Sulfate reduction rate (nmol ml^{-1} day^{-1})		Linear range* (°C)	"Activation energy" (kJ/mol)
			at *in situ* Temp.	at opt. Temp.		
1a, 15-20	-	24	6	16	-2, +23	47
1a, 15-20	+	23	5	15	-2, +23	48
1a, 20-25	-	n. d.	n. d.	n. d.	n. d.	n. d.
1a, 20-25	+	n. d.	n. d.	n. d.	n. d.	n. d.
2, 8-13	-	26	20	185	-2, +25	74
2, 8-13	+	27	11	115	-2, +25	68
2, 15-20	-	27	8	37	-2, +25	54
2, 15-20	+	27	10	61	-2, +25	57
3, 9-14	-	27	6	34	-2, +25	46
3, 9-14	+	26	9	43	-2, +25	49
3, 15-20	-	28	1.5	7	-2, +27	46
3, 15-20	+	28	4	21	-2, +27	48
5, 9-14	-	27	5	52	-2, +26	57
5, 9-14	+	27	8	49	-2, +26	55
5, 15-20	-	28	2	10	-2, +26	49
5, 15-20	+	30	4	19	-2, +27	38

* The term "linear range" designates the linear part of the Arrhenius plot.

tions compared well to the results of the whole core incubations for the same depth intervals. All profiles showed an increase of the rates towards the optimum temperatures which were between 25°C and 30°C. Above 30°C all profiles exhibited a rapid decline of the rates with further increasing temperatures. The *in situ* rates, optimum temperatures and maximum rates for all slurry-experiments are summarized in Table 2.

The effect of substrate addition was different between the stations and the sampled sediment depths. Sulfate reduction rates in the upper sediment layer generally increased less with substrate addition than seen in the deeper layer. The optimum temperatures did not change significantly after substrate addition. Only the upper Hornsund sample (Station 2) showed decreasing sulfate reduction rates after addition of substrate. The rates in the lower sample of Station 1 were always below 2 nmol ml^{-1} day^{-1}, even after substrate addition, and had an irregular distribution without a clear trend. Therefore, the results of these two experiments are marked as "not detectable" (Table 2).

Arrhenius plots

The Arrhenius plots were made by plotting the logarithm of the measured rate versus the inverse absolute temperature, again Station 5 is used as example (Figure 4). The activation energies were calculated from the slope of the linear part of the plots. The calculated activation energies for our experiments and the ranges of linearity are shown in Table 2. Activation energies were in the range between 38 and 74 kJ mol^{-1} and the majority of the values are around 50 kJ mol^{-1}. For nearly all experiments, the range of linearity extended from the *in situ* temperature, or even below, and up to near the optimum temperature.

Discussion

The depth profiles of the whole core incubations show similarities to previously reported results of marine sediments with oxic surfaces where sulfate reduction rates are low but not necessarily zero near the sediment surface and increase strongly to a maximum below the

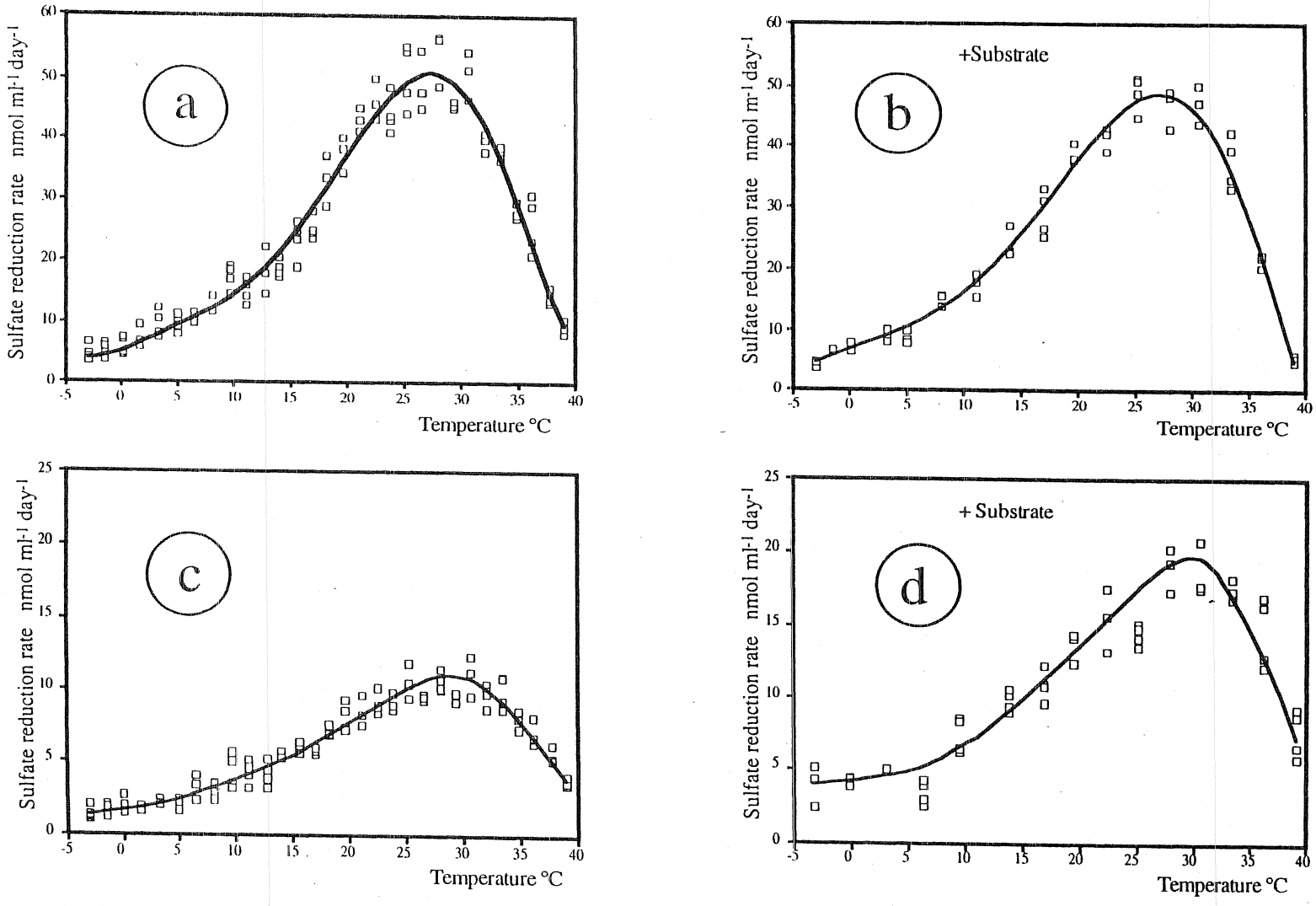

Fig. 3: Sulfate reduction rates from temperature gradient incubations of sediment slurries from Station 5: sediment depth 9-14 cm without (a) and with substrate (b), sediment depth 15-20 cm without (c) and with substrate (d).

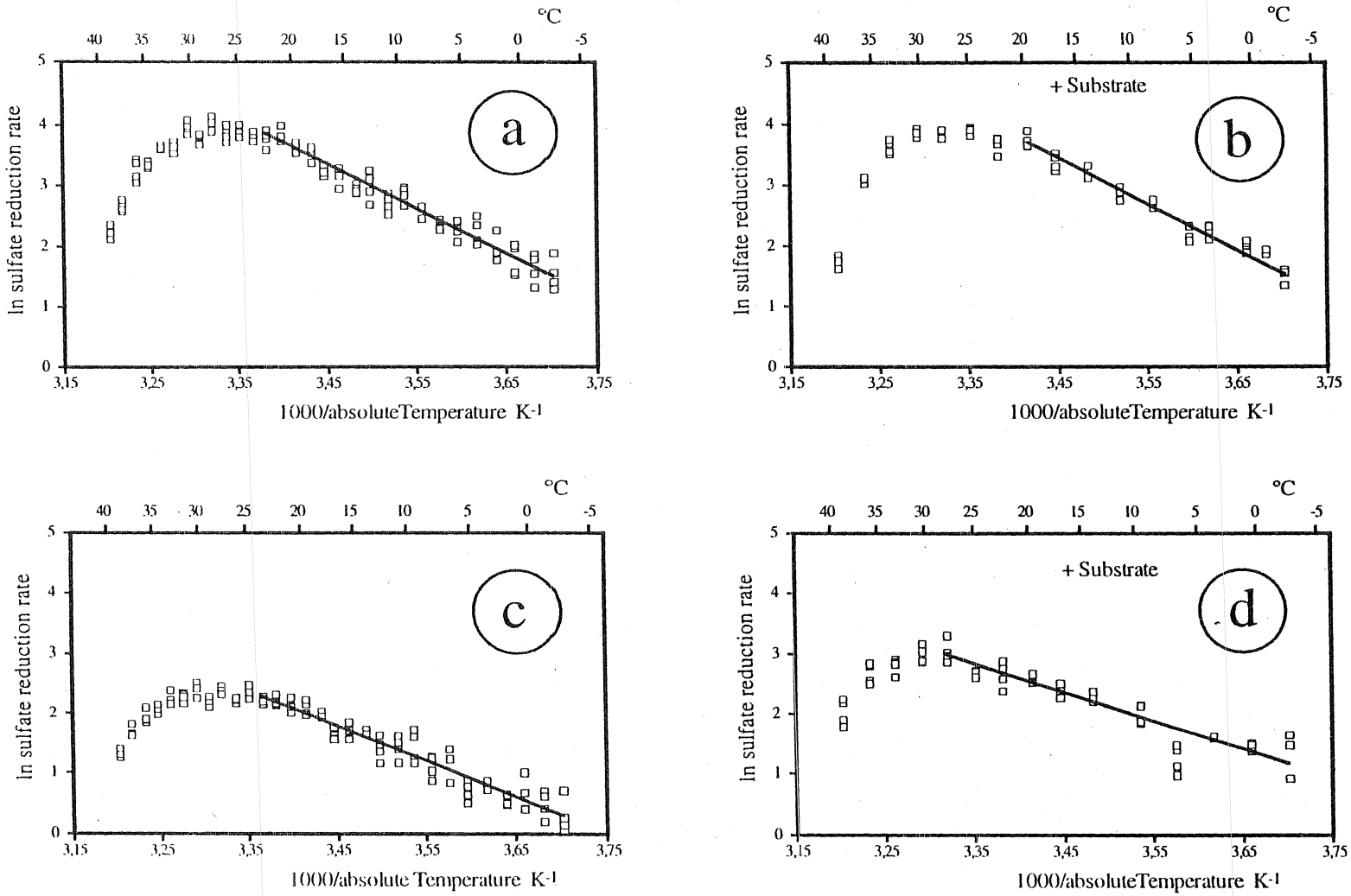

Fig. 4: Arrhenius plots of the results shown in Fig. 3: sediment depth 9-14 cm without (a) and with substrate (b), sediment depth 15-20 cm without (c) and with substrate (d).

penetration depth of nitrate and the Fe- and Mn-reduction zone (Jørgensen 1977). The rates decrease again with increasing depth presumably because the available substrate is gradually depleted deeper in the sediment. The measured rates of up to 200 nmol ml^{-1} day^{-1} for the Hornsund sediment (Station 2) are of similar magnitude as rates of coastal sediments (Fossing & Jørgensen 1989, Howarth & Jørgensen 1984, Moeslund *et al.* 1994, Skyring 1987, Sørensen & Jørgensen 1987). Rates below 20 nmol ml^{-1} day^{-1}, comparable to Storfjorden (Station 5, 6) results, were found in Kattegat sediments at a temperature of 5.5°C and 33 m water depth (Jørgensen & Bak 1991).

Although the Malangen Fjord sediment in Norway (Station 1a, b) experienced the highest temperature of 7°C the sulfate reduction rates were here lower than the rates in the Storfjorden in Svalbard (Station 5) with a bottom water temperature of -1.7°C. The more coarse grained, sandy Malangen Fjord sediments were lowest in organic content of all the stations studied (D. E. Canfield, pers. comm.). Thus, the availability of organic substrate was more important for the limitation of sulfate reduction than the temperature.

Also the areal sulfate reduction rates (0.90 - 4.15 mmol m^{-2} day^{-1}; 0-15 cm) were comparable to rates of more temperate coastal sediments (North Sea and Baltic Sea: 4.7 mmol m^{-2} day^{-1}, Thamdrup *et al.* 1994; between 1.07 and 3.84 mmol m^{-2} day^{-1}, Århus Bay, Thode-Andersen & Jørgensen 1989; different locations: Skyring 1987). Even higher rates of 5.4 mmol m^{-2} day^{-1} (0-8 cm) were reported for a permanently (between -1.8°C and +0.5°C) cold Antarctic station (Nedwell *et al.* 1993). These authors calculated that 32% of the mineralization of organic material took place through sulfate reduction.

The importance of sulfate reduction in Arctic sediments is further evident from a comparison with other processes of organic mineralization. During our cruise free-falling landers were used to investigate benthic fluxes of oxygen, nitrate and other substances. The sulfate reduction rates accounted for 28% (Station 5) to 42 % (Station 2) of the *in situ* release rates of organic carbon (Glud *et al.* in prep.).

The role of nitrate in Arctic sediments around Svalbard was investigated by Blackburn *et al.* (1996), who reported efflux of dissolved organic nitrogen up to 0.93 mmol m^{-2} day^{-1}. Oxygen consumption rates of 1.85 to 11.2 mmol m^{-2} day^{-1} were measured by Hulth *et al.* (1994) in Svalbard sediments. Pfannkuche & Thiel (1987) reported benthic total oxygen consumption of 134 to 499 µmol m^{-2} h^{-1} corresponding to 3.2 to 12 mmol C m^{-2} day^{-1} for sediments of the eastern Barents Sea. A sulfate reduction rate of 4 mmol m^{-2} day^{-1} as for the Hornsund samples is comparable to 8 mmol C m^{-2} day^{-1}. These data clearly show that sulfate reduction can constitute an important metabolic process in cold marine sediments.

The nature of bacterial adaptation to low temperature is still poorly understood. The optimum temperature for sulfate reduction in the investigated Arctic sediments was at least 20°C higher than the *in situ* temperatures of -1.7 to +7°C. An optimum between 25 and 35°C is usually described as mesophilic, however, such bacteria generally do not grow below 0°C (Morita 1975). Bacteria active below 0°C, but with an optimum temperature of over 20°C, may be called moderately psychrophilic or cold-adapted mesophiles.

The interpretation of Arrhenius plots is not clear (Mohr & Krawiec 1980, Ratkowsky *et al.* 1982b, Reichardt & Morita 1982). A linear part of the plot may indicate a temperature range over which the bacteria are well adapted (Guillou & Guespin-Michel 1996). The Arrhenius plots of the Svalbard and northern Norway samples of this cruise have broad linear intervals ranging from the lowest incubation temperatures to near the optimum temperatures. The low slopes of the Arrhenius plot, corresponding to low "activation energies", and the broad linear ranges both indicate adaptation of the bacterial community in Actic sediments towards low *in situ* temperatures.

Sulfate reducers are dependent on extracellular degradation of macromolecular organic compounds and their subsequent partial fermentation, as they can only take up small organic molecules (Widdel 1988, Hansen 1994). Arnosti *et al.* (submitted) reported that extracellular polymer hydrolysis in sediments of different locations showed adaptation to different *in situ* temperatures. To determine a potential difference between the temperature responses of sub-

strate formation and sulfate reduction, the temperature gradient experiments were conducted either without, or with, substrate addition. The optimum temperatures and "activation energies" did not change significantly with increased substrate concentrations (Table 2). Either the substrate formation processes had a similar temperature response as sulfate reduction or their change with temperature was only small in Svalbard sediments.

The different responses of slurries from upper and lower sediment layers to the addition of substrate may indicate a stronger substrate limitation deeper in the sediment. This may also be seen in sulfate reduction rate versus depth profiles of the whole core incubation experiments in a rapid decline of the rates with increasing depth below an optimum at around 3-10 cm depth. Wiebe *et al.* (1992, 1993) described enhanced nutrient demand at low temperatures for facultative psychrophilic *Vibrio sp.* strains and for two psychrotolerant Antarctic bacteria. Nedwell & Rutter (1994) showed a diminished affinity for substrate uptake at low temperatures. Therefore, it may be concluded that bacterial life at low temperatures is much more dependent on substrate concentration than it is at higher temperatures. The higher increase of sulfate reduction rates after substrate addition at *in situ* temperature (-1.7 °C) compared to the increase at optimum temperature (around 28 °C) of the Storfjord samples (Station 5) supports this hypothesis. The reaction of the upper Hornsund sample (Station 2) producing lower sulfate reduction rates after substrate addition is not yet explained.

Isaksen & Jørgensen (1996) reported a difference between the optimum temperatures of growth and sulfate reduction of a psychrophilic pure culture. The optimum temperature for growth was at 18°C, whereas the optimum for sulfate redution was found at 27°C. A similar difference may occur in natural sediments. Psychrophilic sulfate-reducing bacteria were isolated successfully from subsamples of the Svalbard sediment cores of this study (Knoblauch *et al.* in prep). Their ecological significance has to be investigated further.

In summary it can be stated that sulfate reduction rates in cold polar regions are of magnitudes comparable with rates in sediments of more moderate climate. The sulfate reducing community and the substrate producers are well adapted to low *in situ* temperatures, even below 0°C.

It is more likely that substrate availability, not temperature, limits sulfate reduction in cold sediments.

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3 Zusammenfassung und Ausblick

Messungen der Sulfatreduktionsraten in verschiedenen marinen Sedimenten wurden ausgeführt. Zum Zweck der *in situ*-Inkubation der Proben wurde ein freifallender benthischer Lander (LUISE) von mir entwickelt, konstruiert und erprobt. Ergebnisse verschiedener Labor- und Freilandexperimente trugen zur erfolgreichen Realisation des Gerätes bei. Das Instrument wurde intensiv getestet und schließlich, im Sommer 1996, auf einer Forschungsausfahrt ins Gotlandtief (Ostsee) zusammen mit den bereits existierenden Landern des MPIs (PROFILUR und ELINOR) erfolgreich eingesetzt. Benthische Mineralisationsraten entlang eines Transektes vom flachen Rand in die tiefen Bereiche des Beckens wurden gemessen. Die den Lander vorstellende Veröffentlichung (Kapitel 2.1) kombinierte beispielhaft die Ergebnisse einer der Stationen mit detaillierten Beschreibungen des technischen und wissenschaftlichen Hintergrundes. Eine neue Methode, die während der Aufstiegsphase des Gerätes durch Druckentlastung sowie Erwärmung der Proben entstehenden Artefakte zu kompensieren, wurde erstellt und erfolgreich angewendet. Dieses Verfahren ist prinzipiell auch bei anderen Landern anwendbar, deren Einsatz ähnliche Probleme mit sich bringt.

Die auf der Gotlandausfahrt gewonnenen Ergebnisse wurden in einer weiteren Veröffentlichung zusammengefaßt (Kapitel 2.2), die die unterschiedliche Bedeutung der verschiedenen Abbauwege organischer Substanz im Gotlandtief zum Thema hat. Es wurde gezeigt, daß die *in situ*-Daten der Sulfatreduktion generell eine leichte Tendenz zu niedrigeren Raten aufwiesen als die vergleichend ausgeführten Laborinkubationen, wenn Sedimentheterogenität als Ursache für die Unterschiede ausgeschlossen werden konnte. Jedoch war diese Tendenz statistisch nicht signifikant. Weiterhin konnte gezeigt werden, daß Sulfatreduktion in den Sedimenten des Gotlandtiefs der dominierende Abbauprozeß war, obwohl das Bodenwasser von drei der vier Stationen Sauerstoff enthielt. Der überwiegende Teil des diffusiven Sauerstoffflusses in das Sediment wurde den Berechnungen zufolge bei der chemischen Reoxidation der reduzierten Abbauprodukte anaerober Stoffwechselwege verbraucht. Dentrifikation und die Metallatmungen (Eisen- und Manganreduktion) spielten im Allgemeinen quantitativ keine große Rolle beim Abbau organischen Materials. Vergleichende Analysen der sedimentären Schwefelgehalte

mittels zweier verschiedener Methoden erbrachten den Hinweis, daß in den permanent anoxischen Sedimenten des tiefen Gotlandbeckens ein signifikanter Anteil des Gesamtschwefels in Form von schwer abbaubaren Organosulfiden gebunden ist. Dies steht in Übereinstimmung mit den Ergebnissen neuerer Forschungen auf diesem Gebiet (z. B. Kohnen *et al.*, 1991; Wakeman *et al.*, 1995).

Ein weiteres Projekt, das zeitlich vor der Komplettierung des Landers lag, war die Betrachtung der biogeochemischen Vorgänge in permanent kalten Sedimenten, die auf einer Ausfahrt im Herbst 1995 bei Nordnorwegen und der Inselgruppe Svalbard (N) beprobt wurden (Kapitel 2.3). Die Sulfatreduktionsraten dieser Proben wurden mittels der herkömmlichen Inkubationsmethode im Labor ermittelt. Die gewonnenen Daten zeigten dabei generell keinen nennenswerten Unterschied zu den von temperierten Sedimentationsräumen bekannten Werten. Untersuchungen zur Temperaturabhängigkeit der sulfatreduzierenden Bakterienpopulationen erbrachten den Hinweis auf ausgeprägte Kälteadaptation. Diese zeigte sich anhand der Tatsache, daß die gemessenen Aktivierungsenergien für die enzymatischen Reaktionen mit verfügbaren Substraten einerseits am unteren Ende des bekannten Bereichs lagen, vor allem aber auch noch bei den *in situ*-Temperaturen zwischen +7°C und -1.7°C linear blieben. Permanent kalte Sedimente (<5°C) bedecken ca. 95% des Weltmeerbodens; den Ergebnissen dieser und anderer (Isaksen und Jørgensen, 1996) Studien zufolge sind die dort lebenden (sulfatreduzierenden) Bakterien hervorragend an die *in situ* herrschenden Temperaturbedingungen angepaßt und können daher effektiv am Abbau organischer Substanz mitwirken.

Zukünftige Anwendungen des Landers LUISE werden zeigen, ob der beschriebene Trend zu niedrigeren *in situ*-Sulfatreduktionsraten auch bei Proben aus der Tiefsee festzustellen ist. Diesbezüglich ist eine Ausfahrt ins Schwarze Meer im Herbst diesen Jahres (1997) geplant, die sich insbesondere mit dem Schwefelkreislauf der dortigen Sedimente befassen wird. Desweiteren sind Forschungsfahrten in Vorbereitung, die einerseits biogeochemische Untersuchungen an Gasaustrittsstellen in der Ägäis zum Schwerpunkt haben (METEOR-Fahrt 40/2), andererseits die Sedimente des Auftriebsgebiets vor Angola zum Gegenstand biogeochemischer Studien haben werden (METEOR-Fahrt 41/1).

Wie aus den vorausgegangenen Kapiteln hervorgeht, habe ich mich in meiner Dissertation mit dem marinen Schwefelkreislauf befaßt und durch die Entwicklung und Erprobung des Landers LUISE vor allem den Grundstein für *in situ*-Messungen von Sulfatreduktion gelegt. LUISE ist aber ein Instrument, das generell die Injektion von Flüssigkeiten in das zu beprobende Sediment erlaubt. Neuartige Ansätze zur Bestimmung benthischer Sulfatreduktionsraten beinhalten den Einsatz sauerstoffmarkierter ($S^{18}O_4^{2-}$) Sulfatlösungen, mittels derer ein besseres Verständnis des Effekts der Reoxidation reduzierter Schwefelverbindungen ermöglicht wird (Ferdelman, 1997). Sollte sich diese Technik weiterhin als erfolgversprechend herausstellen, wäre eine Anwendung mit LUISE durchaus denkbar. Jedoch ist der Lander auch für andere biogeochemische Untersuchungen geeignet. Gegenwärtig wird das Gerät mit einem Sensor ausgerüstet, der Temperaturprofile bis zu 60 cm Tiefe erfassen kann; die Kenntnis der *in situ*-Temperaturverhältnisse ist bei Untersuchungen bakterieller Aktivität in hydrothermal beeinflussten Sedimenten von besonderer Bedeutung, da mikrobielle Stoffwechselraten temperaturabhängig sind. Einsatz finden wird dieses System während der bereits erwähnten Fahrt in die Ägäis bei der Beprobung von heißen Gas-vents. Überdies sind zum Beispiel Injektionen von ^{15}N-markiertem Nitrat in Tiefseesedimenten denkbar, um *in situ*-Denitrifikationsraten zu bestimmen. Andere Einsatzmöglichkeiten könnten die Injektion Fluoreszenz-markierter Polysaccharide beinhalten, die erst kürzlich entwickelt und angewandt worden sind (Arnosti, 1995), um Hydrolyseraten extrazellulärer Enzyme in Sedimenten zu ermitteln.

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Übersicht der Zeichnungen im Anhang

Teil 1 - Rahmen -

1.1 Hauptrahmen

1.1.1 Seitliche Ansicht

1.1.2 Ansicht von oben

1.1.3 Bein und Fuss

1.1.4 Haltegestell für Batterie

1.1.4.1 Haltegestell

1.1.4.2 Stützstrebe

1.1.5 Verbindeklemmen für Rahmen

1.1.6 Verbinder für Rahmeneinzelteile

1.1.7 Stabilisatoren zwischen Beinen und Rahmenstreben

1.2 Auftriebsrahmen

1.2.1 Seitliche Ansicht

1.2.2 Ansicht von oben

1.2.3 Auftriebsrahmen, unterer Teil, Ansicht von oben

1.2.4 Seitlicher Auftriebskugelträger, oberer Teil des Rahmens

1.2.5 Oberer und unterer Auftriebskugelträger, unterer Teil des Rahmens

1.2.6 Träger für extra Auftriebskugel

1.2.7 Zwischenstück für Zentraleinheit

1.2.8 Aufhängevorrichtung des Landers

1.3 Ballastauslösesystem

1.3.1 Rahmen mit Ballastsystem in der Übersicht

1.3.2 Auslösehaken

1.3.3 Halterung für Auslösehaken

1.3.4Ballastgreifklemme

1.3.5 Fassung der Greifklemme im Fuss

1.3.6 Drahtseilrolle im Bein

1.3.7 Rollschäkel am Rahmen

1.3.8 Rolle des Auslösesystems

1.3.9 Halterung für Rolle

Teil 2 - Zentraleinheit -

2.1 Tragende Teile

2.1.1 Verbindende Stahlrohre

2.1.2 Endplatten der verbindenden Stahlrohre

2.1.3 Obere Ebene

2.1.4 Untere Ebene

2.1.5 Spacer für Zentraleinheit

2.2 Bewegliche Teile

2.2.1 Corer-Ebene

2.2.1.1 Corer-Ebene

2.2.1.2 Deckplatten der Ebene

2.2.2 Pistontragende Ebene

2.2.3 Gleiter an den beweglichen Ebenen

2.2.4 Blockiermechanismus der oberen Ebene

2.2.5 Stangen des Blockiermechanismus

2.3 Grosses Motorhaus

2.3.1 Ansicht von der Seite

2.3.2 Ansicht von oben/unten

2.3.3 Oberer Deckel

2.3.4 Unterer Deckel

2.3.5 Ummantelungen der Motoren

2.3.6 Halterung der Druckkompensationsmembrane

2.3.7 Motorenbefestigungsplatten oben/unten

2.3.8 Kupplung zwischen den Motoren

2.3.9 Statische Verbindung der Motoren

2.3.10 Überträgerwelle nach aussen

2.3.11 Kupplung zum Verbindungsrohr

2.3.12 Verbindungsrohr zur Gewindestange

2.4 Sensorhaus

2.4.1 Körper

2.4.2 Oberer Deckel

2.4.3 Unterer Deckel

2.4.4 Halterung der Druckkompensationsmembran

2.4.5 Halteklammer

2.5 Kleines Motorhaus und Zubehör

2.5.1 Einzelteile des kleinen Motorhauses und Schnitte (Fa. W. Pickl)

2.5.2 Obere Deckelplatte (Fa. W. Pickl)

2.5.3 Untere Deckelplatte (Fa. W. Pickl)

2.5.4 Motoraufhängung (Fa. W. Pickl)

2.5.5 Gewindestange (Fa. W. Pickl)

2.5.6 Achse (Fa. W. Pickl)

2.5.7 Bewegliche Kupplung

2.5.8 Spritzenhalterung (Fa. W. Pickl)

2.5.9 Spritzenauslöser (Fa. W. Pickl)

2.5.10 Vorgelege und Abstandhalter zur Nadelhalterung (Fa. W. Pickl)

2.5.11 Nadelhalterung

2.5.12 Führungsstangen für kleine Motorhäuser

2.6 Kernrohre und Zubehör

2.6.1 Kernrohr

2.6.2 Halteklemme für Kernrohr

2.6.3 Kolben

2.6.4 Ventilstift

2.6.5 Kolbenhaltestangen

2.7 Corecatcher

2.7.1 Körper des Corecatchers

2.7.2 Zwischenstück

2.7.3 Endstück und Verschlussplatte

2.8 Sonstige Teile

2.8.1 Sicherheitswanne

2.8.2 Halterung der Sicherheitswanne

2.8.3 Federnder Antennenträger

2.8.4 Antennenhalterung

2.8.5 Halterung des Elektronikzylinders

2.8.6 Halterung des akustischen Transducers

Teil 3 - Elektronik -

3.1 Elektronikzylinder

3.1.1 Seitliche Ansicht

3.1.2 Deckel

3.1.3 Positionen der Subconn Bulkheads

3.2 Belegungspläne der Steckverbindungen des Elektronikzylinders (V. Meyer, MPI)

3.2.1 Steckverbindungen im Deckel des Elektronikzylinders

3.2.2 Steckverbindungen im Boden des Elektronikzylinders

3.3 Kabelplan der Subconn Kabel

Teil 4 - Materialien und Lieferanten -

1) Akustischer Auslöser

Transducer Typ 1090ED

Auslöser Typ MR 5000B

Fa. Interocean, Vertrieb über Fa. Bornhöft Industriegeräte, Kiel.

2) Auftriebskugeln

12 (13) Stck. 17' Auftriebskugeln in Hardhats mit jeweils 25,4 kg Auftrieb.

Fa. Benthos, Vertrieb über Fa. Bornhöft Industriegeräte, Kiel

3) Ballast

je 3 Stck. Brennzuschnitte aus Stahl, 450 mm Durchmesser, 65 mm Stärke. Bezug über Fa. W. Schmidt, Thedinghausen-Dibbersen.

4) Batterien

1 Stck. 24V38Ah wiederaufladbare Blei-Gel Batterie, Fa. Deep Sea Power and Light

1 Stck. 12v/76Ah wiederaufladbare Blei-Gel Batterie, Fa. Deep Sea Power and Light

Vertrieb über Fa. Nautilus, Bremen

5) Druckkompensationsmembrane

Grosses Motorhaus:

3 Stck. Rollmembran Typ BFA 35-50-35 50 NBR 253, Fa. Simrit

Sensorhaus:

1 Stck. Rollmembran Typ BFA 35-30-35 50 NBR 253, Fa. Simrit, Bezug über Fa. Gottwald, Bremen

6) Endschalter

2 Stck. 1802-100 wasser- und druckdichte Schalter, Position normal geschlossen, Subconn ILM2M Steckverbindung am Kabel.
Fa. Hydracon, Anaheim, CA, USA

7) Gewindestangen

Hauptantrieb:

1 Stck. Trapezgewindespindel TR 36 x 6, 1gängig rechts, Material 1.4571, ca. 1m lang.
1 Stck. Nylatron GSM Mutter passend zu TR 36 x 6

Injektionsantriebe:

6 Stck. Trapezgewindespindel TR 12 x 3, 1 gängig rechts, Material 1.4571, ca. 1m lang
6 Stck. Nylatron GSM Mutter passend zu TR 12 x 3
alles Fa. Mädler, Hamburg

8) Kugellager

1 Stck. POM Lager mit Glaskugeln, Typ Haku 6006

9) Motoren

Motoren des Hauptantriebs:

2 Stck. Maxon 22.60.885.51.216-200 80W/24V gekoppelt
1 Planetengetriebe Maxon 2962.703-0100.0-000 100:1

Motoren der Injektionssysteme:

6 Stck. Faulhaber 1331T 012 S 2.7W/12V
6 Planetengetriebe 14/1 159:1

10) Nadeln

6 Stck. Hohlkanülen aus rostfreiem Stahl (1.4301). Abmessungen: 2.70 mm A.D., 1.1 mm I.D., 750 mm Länge. 4 Seitliche Auslassöffnungen 0.50 mm symmterisch um die Spitze angeordnet. Glaskeramikartige Beschichtung aussen (AMF-N (H)-Schicht). Die obersten 20 mm sind auf einen A.D. von 2 mm abgedreht.
Bezug von Fa. Möller Feinmechanik, Fulda.

Verbindung zur Spritze: Swagelock Fitting SS-2MO-9

11) O-Ringe

Druckzylinder Deckel aussen: 132.94 x 3.53 mm NBR 70 (Parker 2-252 N 674-70)

Druckzylinder Deckel innen: 120.24 x 3.53 mm NBR 70 (Parker 2-248 N 674-70)

Grosses Motorhaus oberer und unterer Deckel: 120.24 x 3.53 mm (Parker 2-248 N 674-70)

Sensorhaus oberer und unterer Deckel: 72.62 x 3.53 mm (Parker 2-233 N 674-70)

Kleines Motorhaus innen: 14.48 x 2.62 mm (Parker 5-239 N 674-70) und 42.52 x 2.62 mm (Parker 2-131 N 674-70)

Kolben: 31.42 x 2.62 mm (Parker 2-124 C 557-70)

Subconn-Einbaustecker /-buchsen 2- und 4-polig: 12.42 x 1.78 mm (Parker 2-014 C 557-70)

Subconn-Einbaustecker /-buchsen 6- und 8-polig: 17.17 x 1.78 mm (Parker 2-017 C 557-70)

12) Peilhilfen

ARGOS Satellitensender Typ SMM 6000/X, Firma SIS, Kiel

Blitzlicht Typ ST 400A, Fa. Novatech, Vertrieb über Fa. Nautilus, Bremen

Radiosender Typ RF 700A-1, Fa. Novatech, Vertrieb über Fa. Nautilus, Bremen

13) Sensoren

Drucksensor: Typ PA10-600, Fa. Keller (CH), Eichplatine und Vertrieb durch Fa. Meerestechnik Elektronik, Trappenkamp

Temperatursensor: modifizierter LM 35 (Selbstbau)

14) Simmerringe

Grosses Motorhaus: Typ Variseal 59041-0250-109-S

Kleines Motorhaus: Typ Variseal 59044-0060-109-S

Bezug von Fa. Gottwald, Bremen.

15) Spritzen

6 Stck. gasdichte MikrolitherspritzenTyp MS GLL 050, 500µl Volumen.

Bezug über Jürgens, Bremen (Best.Nr.:9.221 972)

Verbindung zu Nadeln über 18-gauge HPLC Teflonschlauch mit Luer-Lock Ansatz, Typ Z 11732-3, Fa. Aldrich. Bezug über Fa. Jürgens, Bremen.

16) Steckverbindungen und Kabel

2 Stck. 8 polige Einbausteckverbindungen Typ BH8MX

2 Stck 8 polige Einbaubuchsen Typ BH8FX

3 Stck. 6 polige Einbaubuchsen Typ BH6F

3 Stck. 4 polige Einbausteckverbindungen Typ BH4M

1 Stck. Kabelstecker Typ IL4M mit 17 m Kabel

1 Stck. 4 polige Einbaubuchse Typ BH4F

6 Stck. 2 polige Minieinbausteckverbindungen Typ BHM2M

8 Stck. 2 polige Minibuchsen Typ DCM2M

2 Stck 1 polige Ministecker Typ OMM1M

12 Stck. Muttern und Scheiben Typ BNWA

11 Stck. Muttern und Scheiben Typ BNWB

4 Stck. Sicherungshülsen Typ DLSA

7 Stck. Sicherungshülsen Typ DLSB

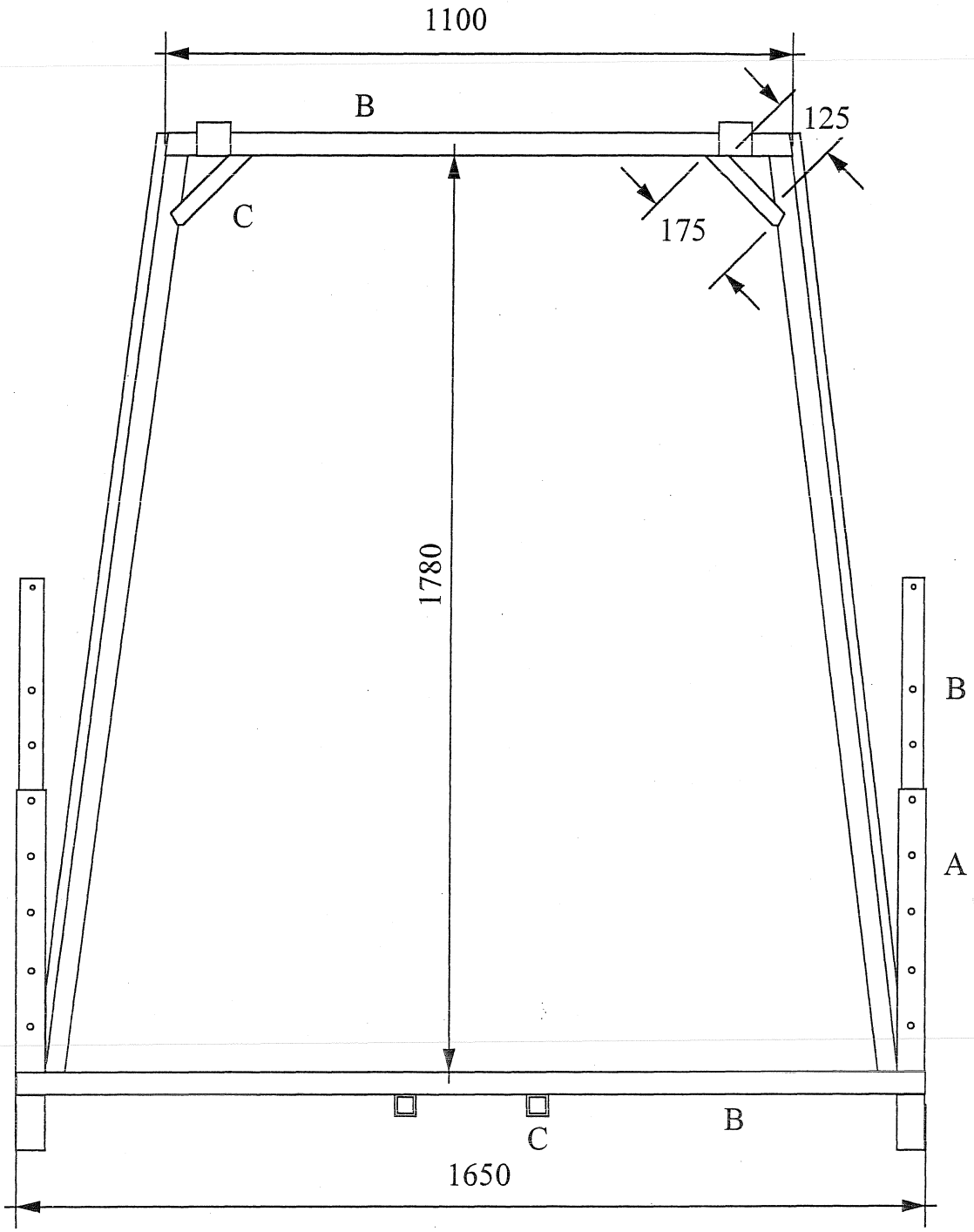
Kabel nach Zeichnung (Nr. 3.3)

Bezug von Fa. Subconn über Fa. Bornhöft Industriegeräte, Kiel.

17) Steuer- und Messelektronik

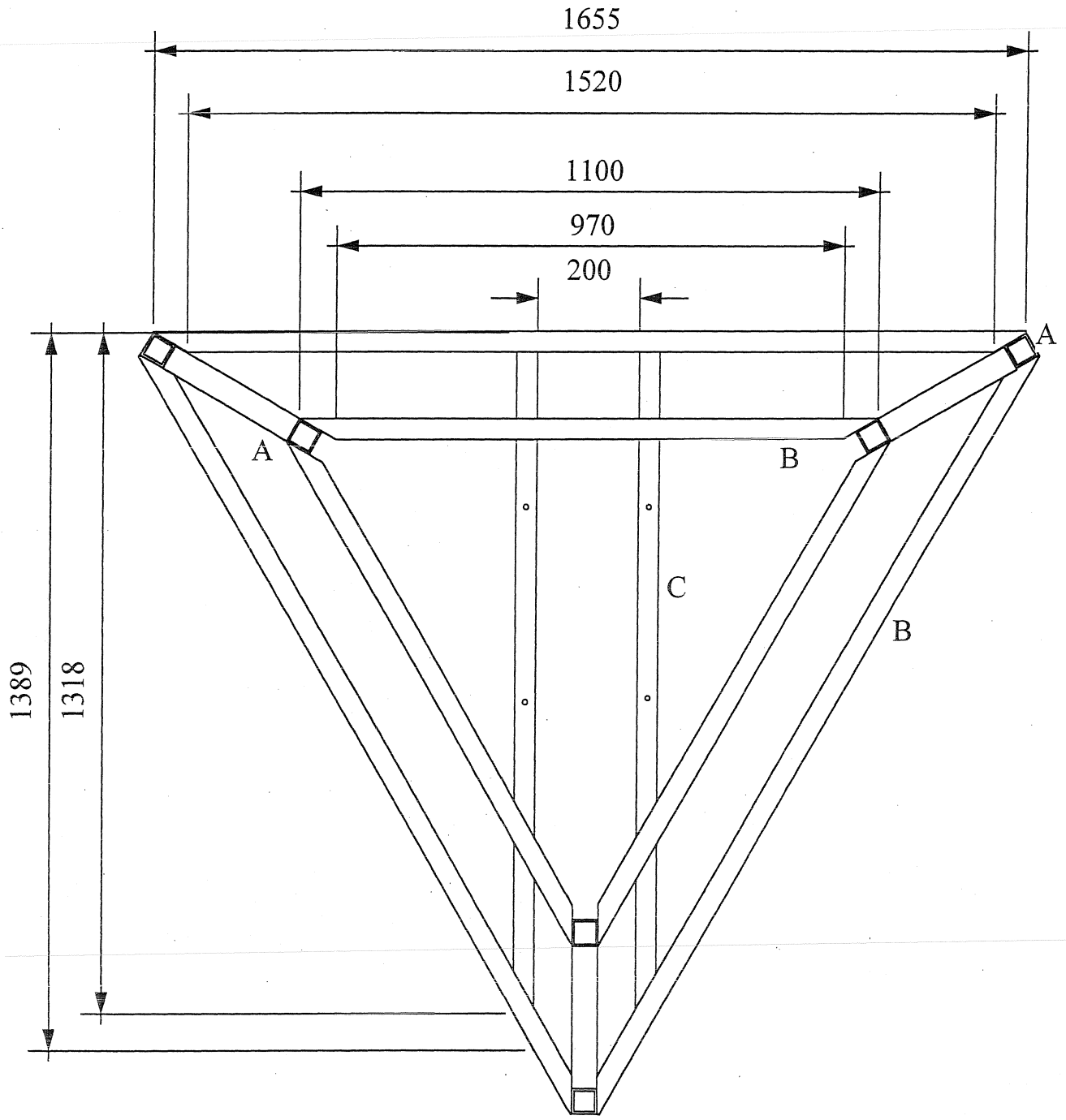
Aufragsbau für das MPI durch Fa. IBSO, Bremen.

Part: main frame		Nr: 1.1.1
Scale: 1:12	View(s): side	
Material: AlMg3 profiles		Date: 22.1.97



A: 50*50*5 mm, 1640 mm outside, 1870 mm inside
B: 40*40*4mm
C: 30*30*4 mm

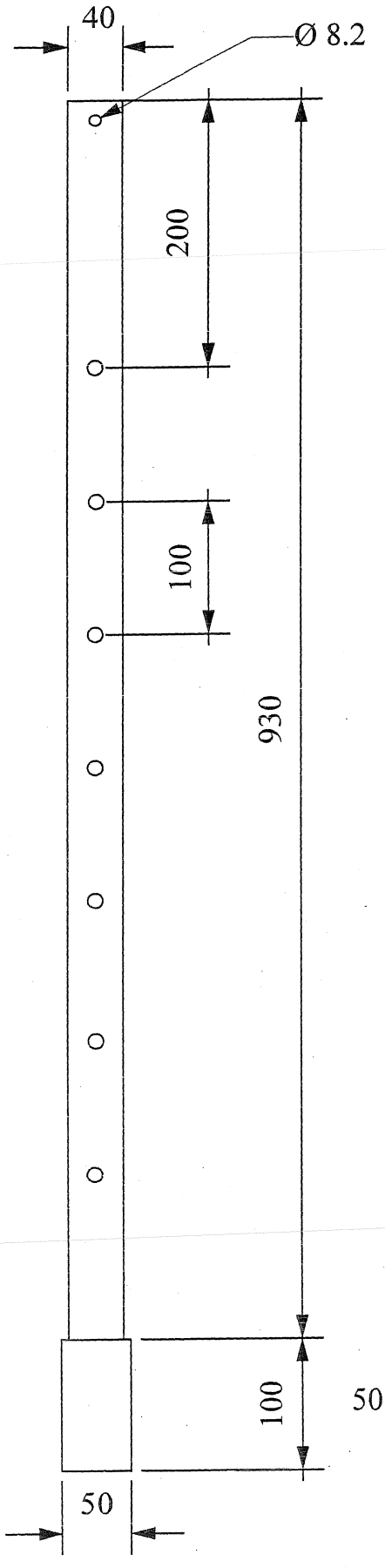
Part: main frame		Nr: 1.1.2
Scale: 1:12	View(s): top	
Material: AlMg3 profiles		Date: 22.1.97



A: 50*50*5 mm
B: 40*40*4 mm
C: 30*30*4 mm

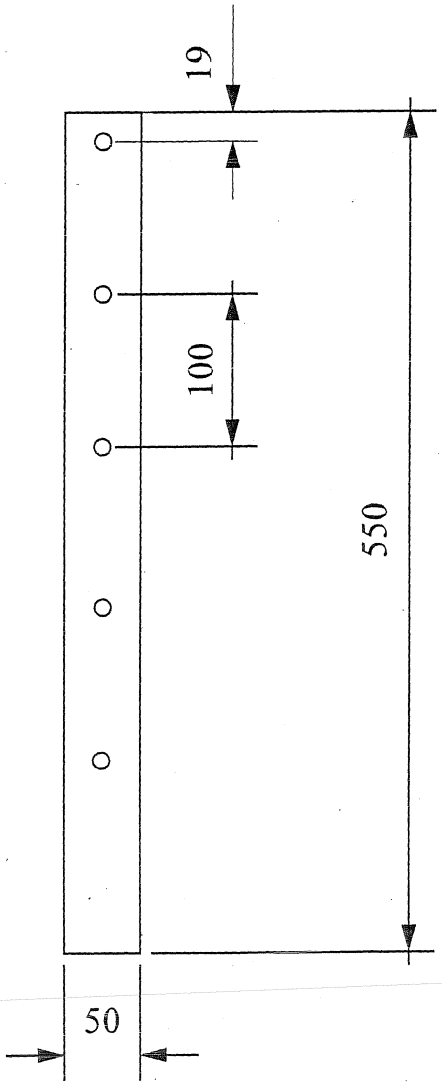
Part: leg and legholder		Nr: 1.1.3
Scale: 1:5	View(s): side	
Material: AlMg3 profiles		Date: 22.1.97

Leg 40*40*4 profile



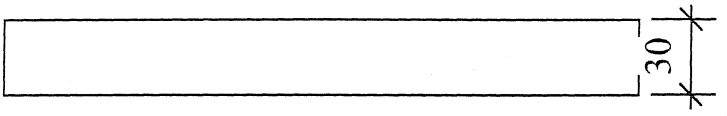
50*50*5 profile

Leg holder 50*50*5 profile

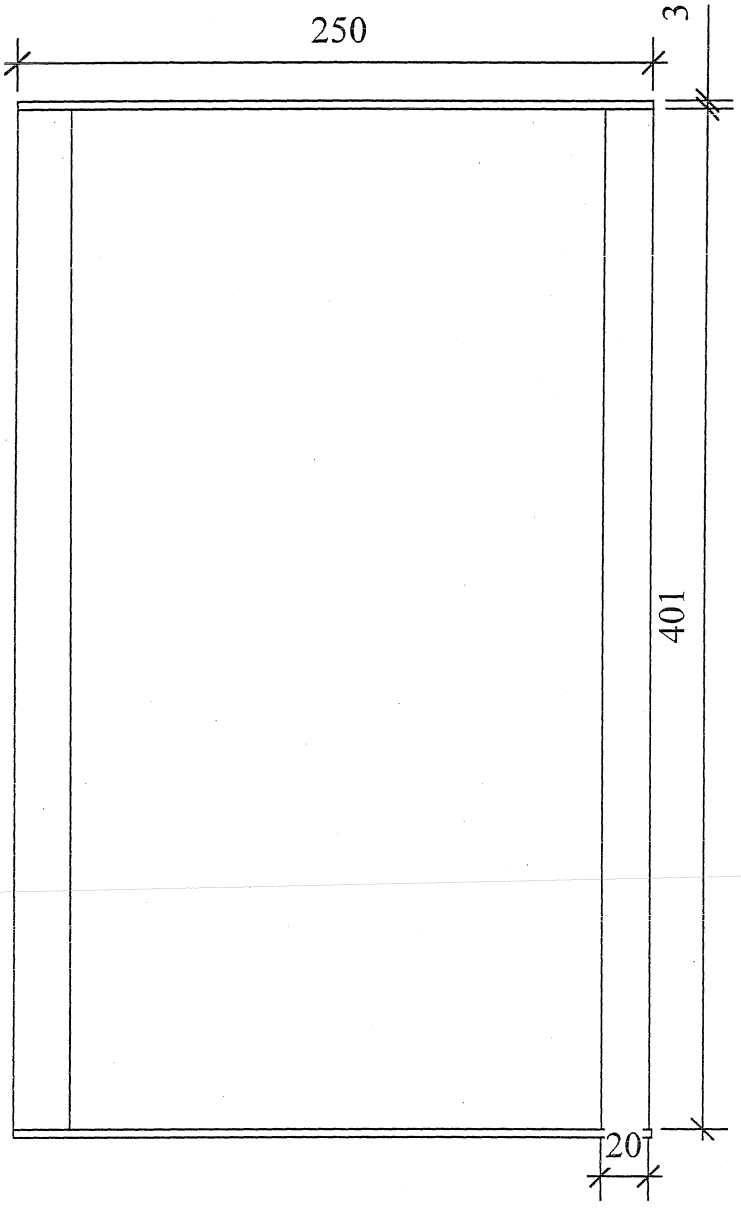


Part: Battery frame		Nr: 1.1.4.1
Scale: 1:3	View(s): all	
Material: AlMg3 Aluminium		Date: 27.11.96

Side view

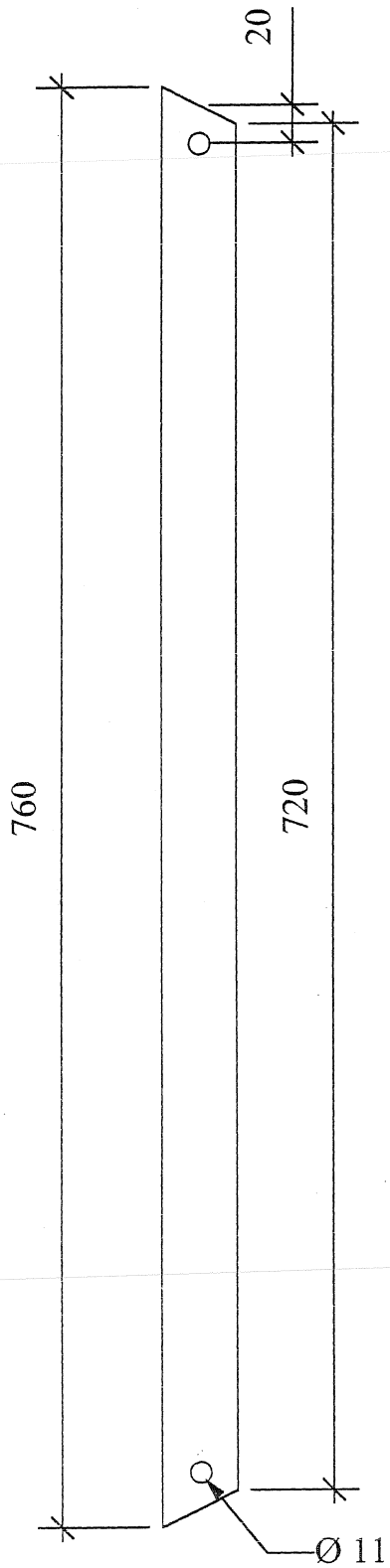


Top view



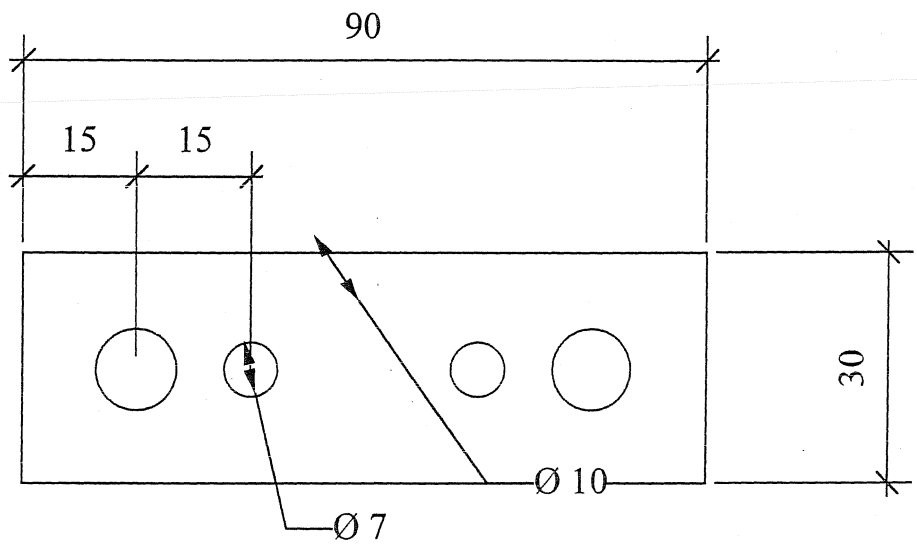
Part: Battery frame support		Nr: 1.1.4.2
Scale: 1:4	View(s): top	
Material: AlMg3 Aluminium		Date: 21.1.97

Top view

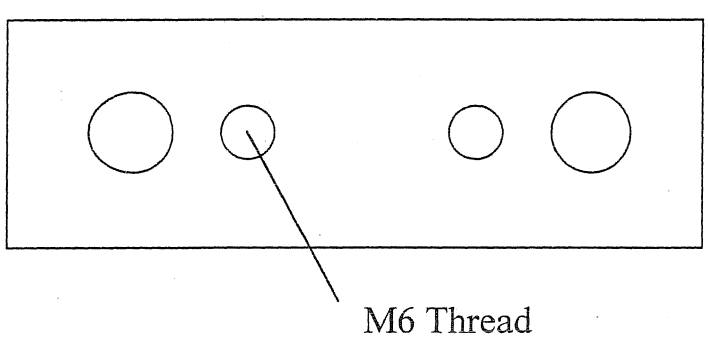


Part: Connectors for frames		Nr: 1.1.5
Scale: 1:1	View(s): all	
Material: 316-6 Steel / POM		Date: 27.11.96

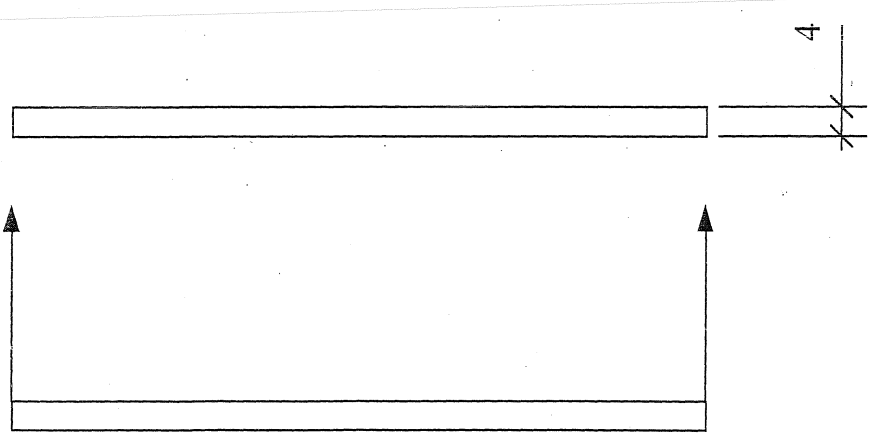
Steel plate, top view



POM plate, top view

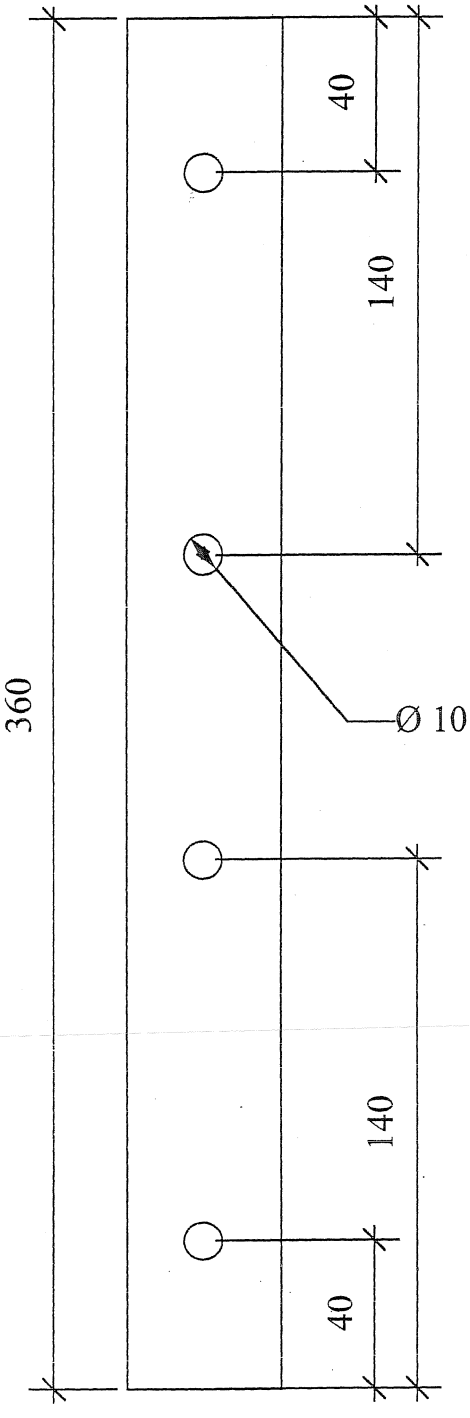


Side view

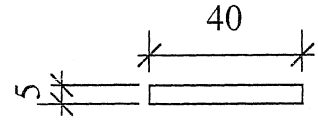


Part: Connectors for frame parts		Nr: 1.1.6
Scale: 1:2	View(s): all	
Material: 316-6 steel		Date: 27.11.96

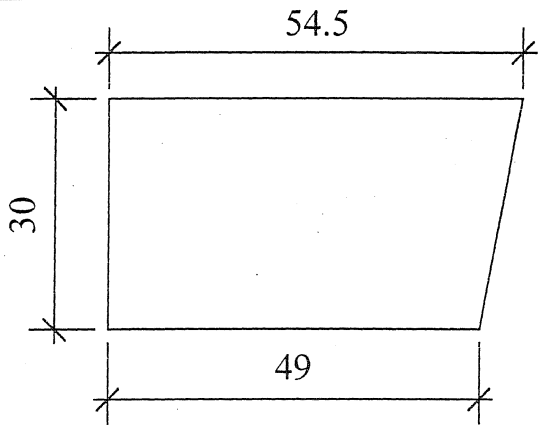
Top view

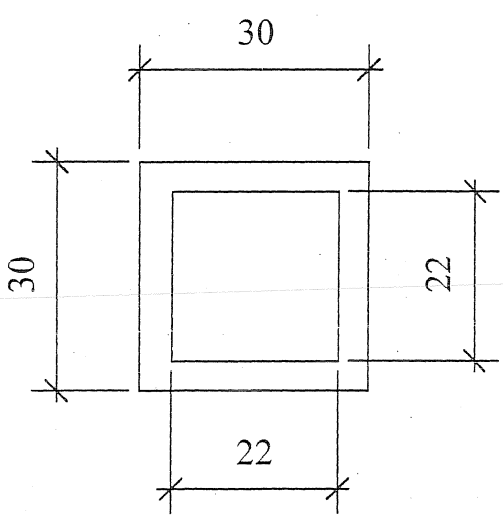


Side view

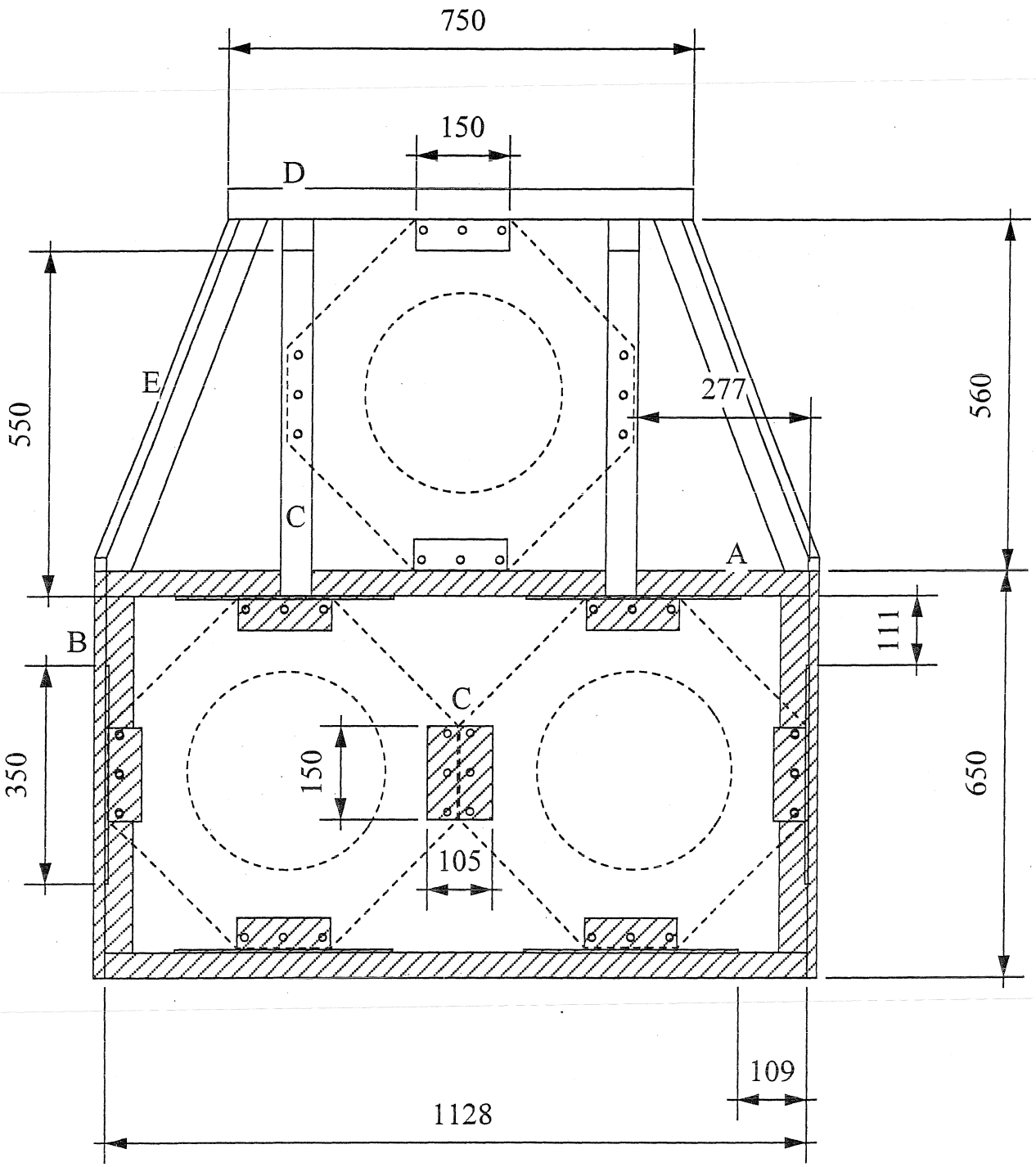


Part: Stabilizers for legs		Nr: 1.1.7
Scale: 1:1	View(s): all	
Material: AlMg3 Aluminium		Date: 27.11.96





Part: Floatframe		Nr: 1.2.1
Scale: 1:10	View(s): side	
Material: AlMg3 Aluminum	Date: 27.11.96	



A: 40*40*4 mm

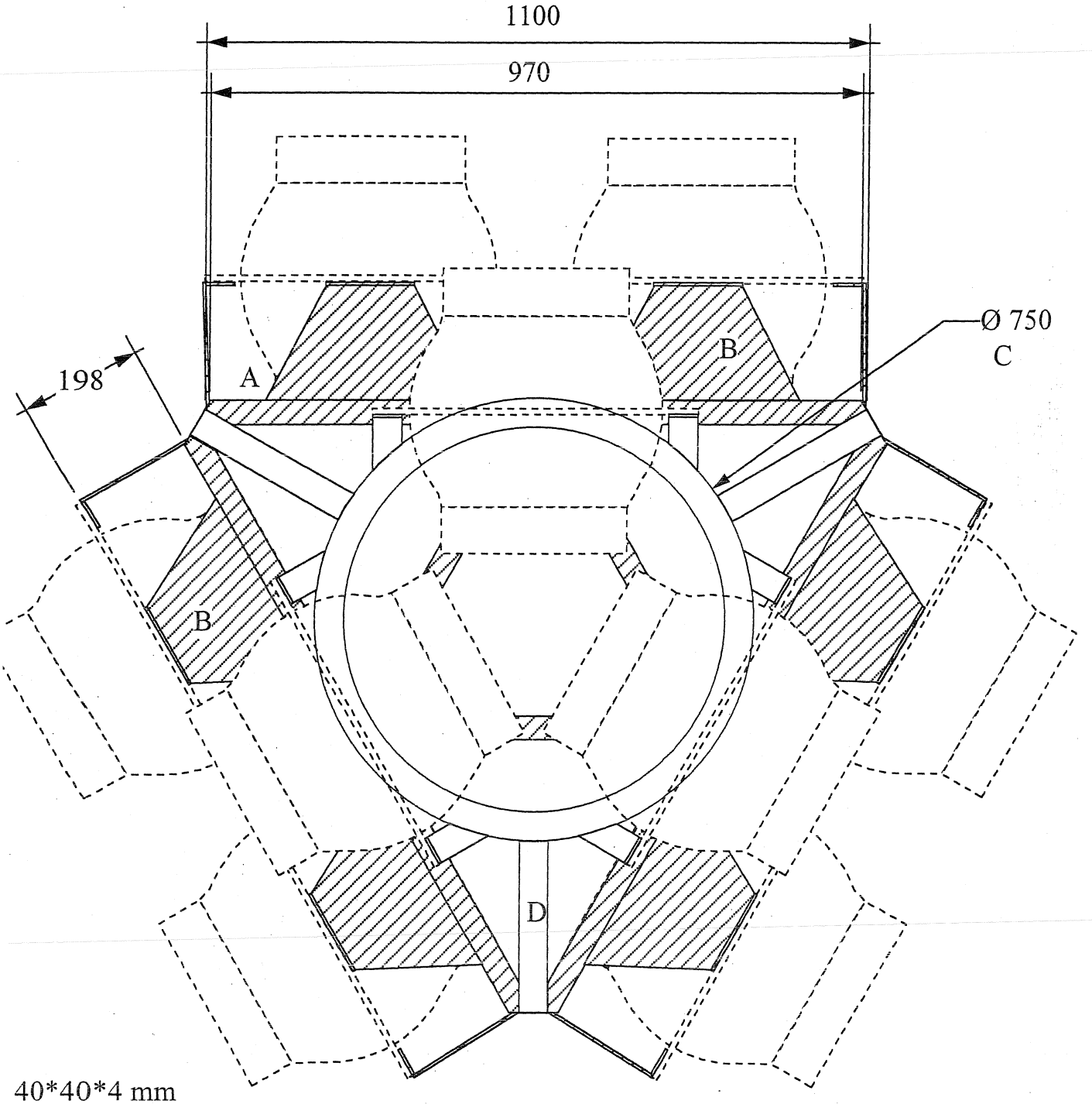
B: 50*50*4 mm

C: 5*50 mm

D: 49*5 mm, 750 mm Ø

E: 50*50*4 mm, 633 mm long

Part: Floatframe		Nr: 1.2.2
Scale: 1:10	View(s): top	
Material: AlMg3 Aluminium	Date: 27.11.96	



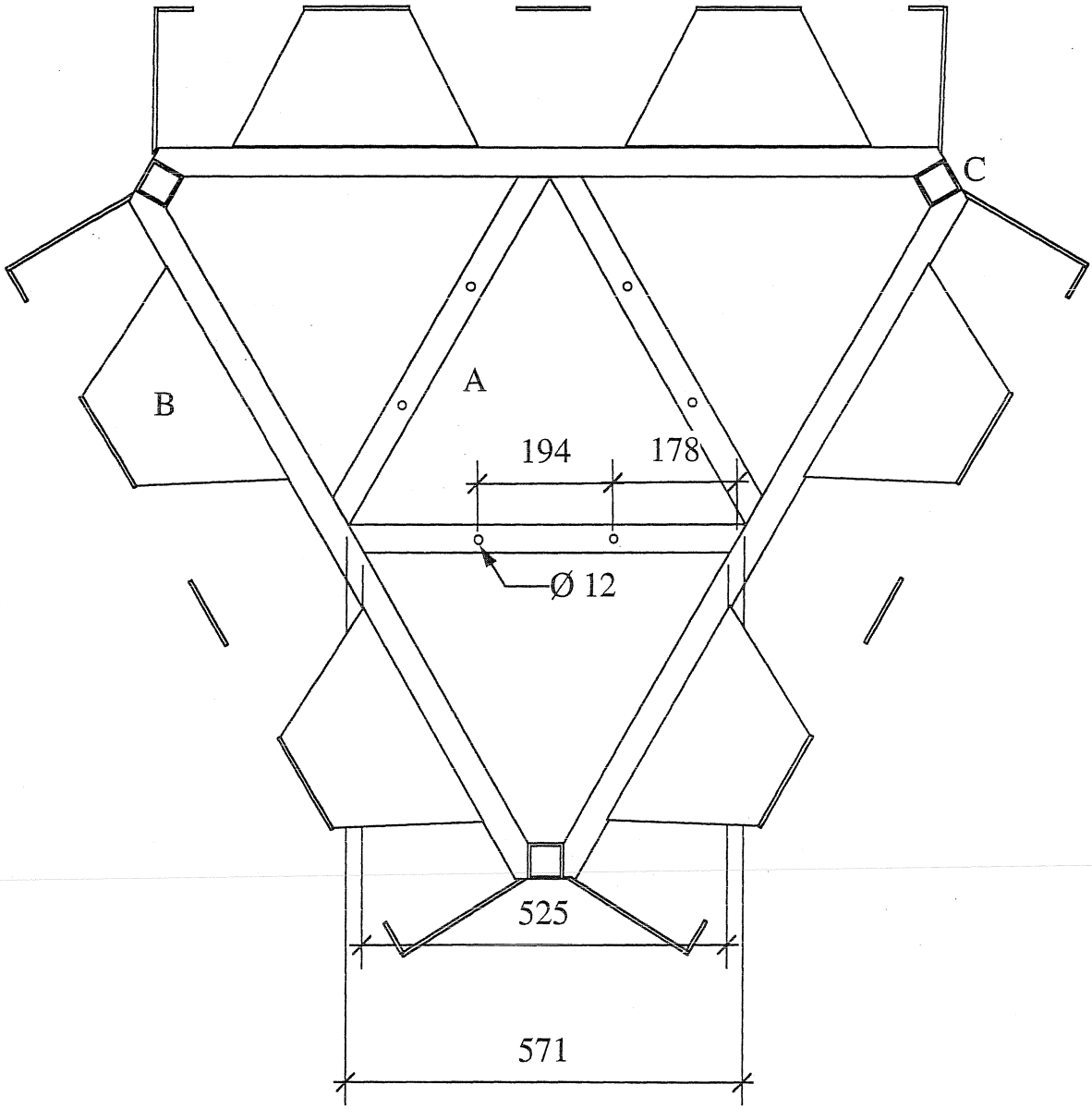
40*40*4 mm

5 mm

49*5 mm, 750 mm Ø

50*50*4 mm, 633 mm long

Part: Floatframe, lower part		Nr: 1.2.3
Scale: 1:10	View(s): top	
Material: AlMg3 Aluminium		Date: 27.11.96



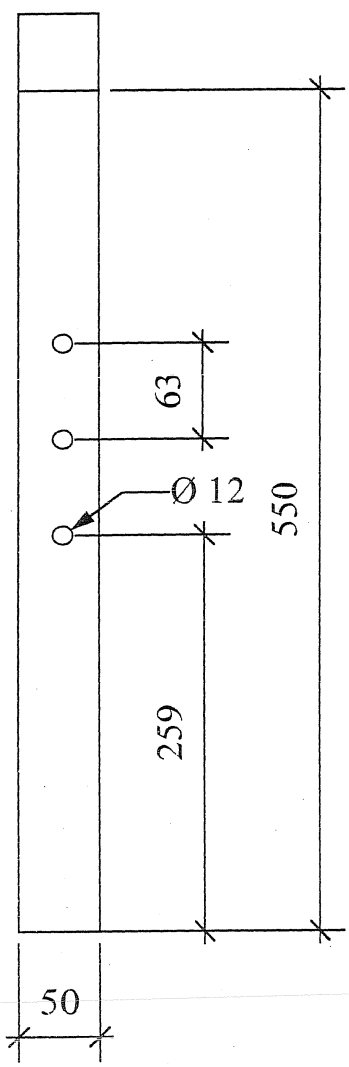
A: 40*40*4 mm

B: 5 mm

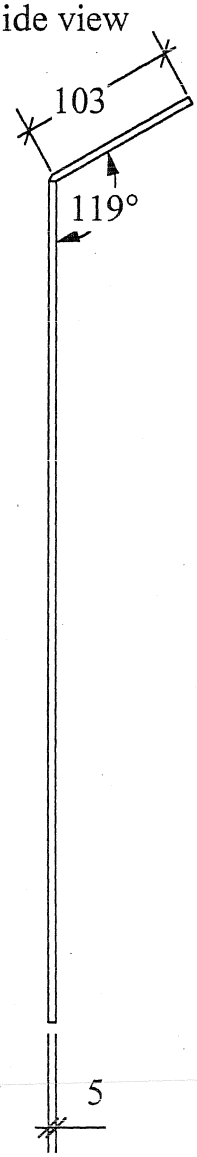
C: 50*50*5 mm

Part: Floatsupport top frame, side		Nr: 1.2.4
Scale: 1:5	View(s): all	
Material: AlMg3 Aluminium		Date: 27.11.96

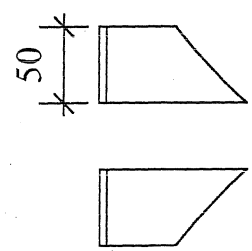
Front view



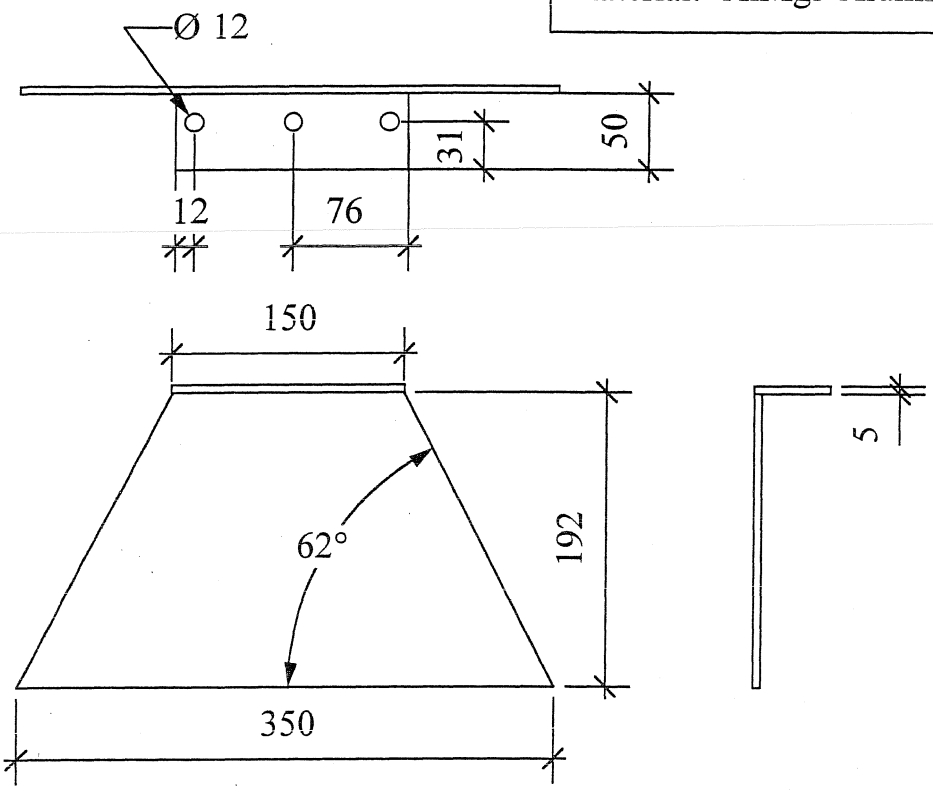
Side view



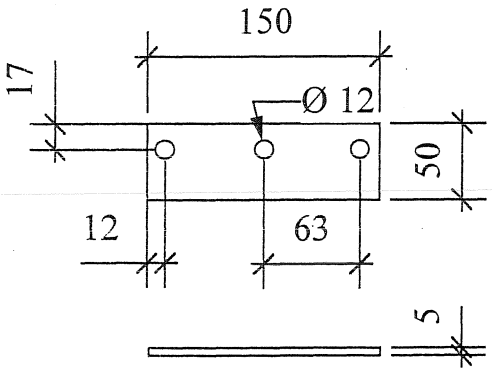
Top view



Part: Float support lower frame, top		Nr: 1.2.5
Scale: 1:5	View(s): all	
Material: AlMg3 Aluminium		Date: 27.11.96

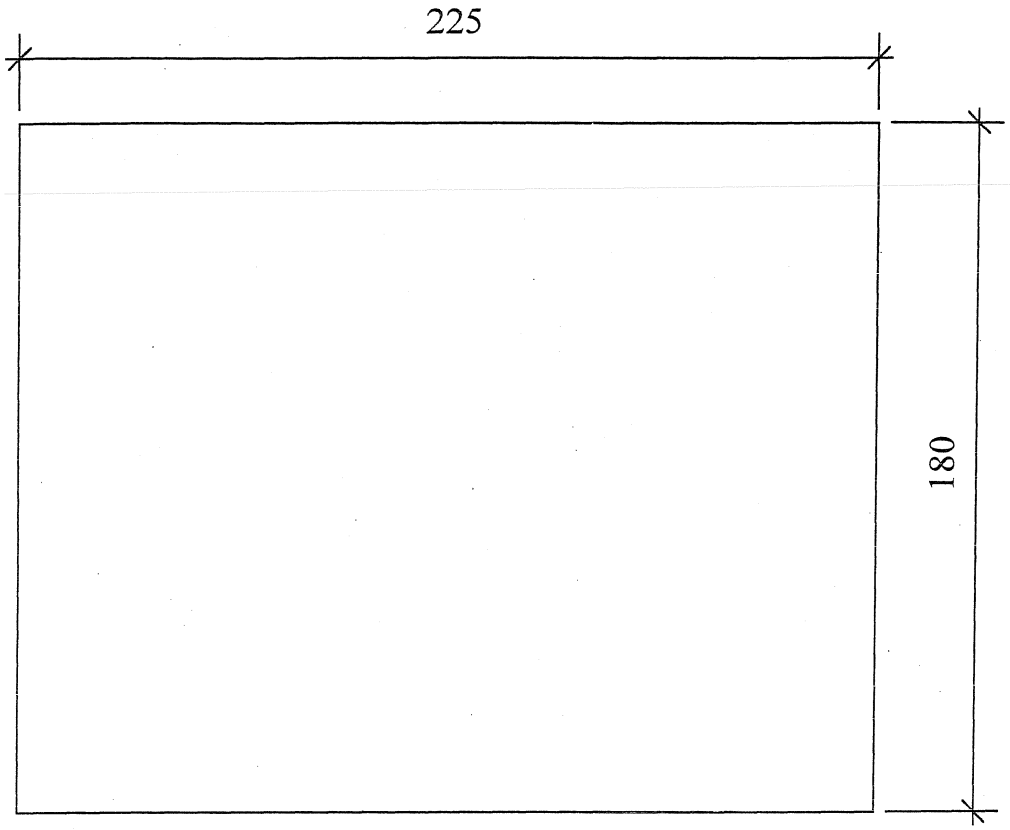


Part:Float supp. top frame, top & bottom		Nr: 1.2.5
Scale: 1:5	View(s): all	
Material: AlMg3 Aluminium		Date: 27.11.96

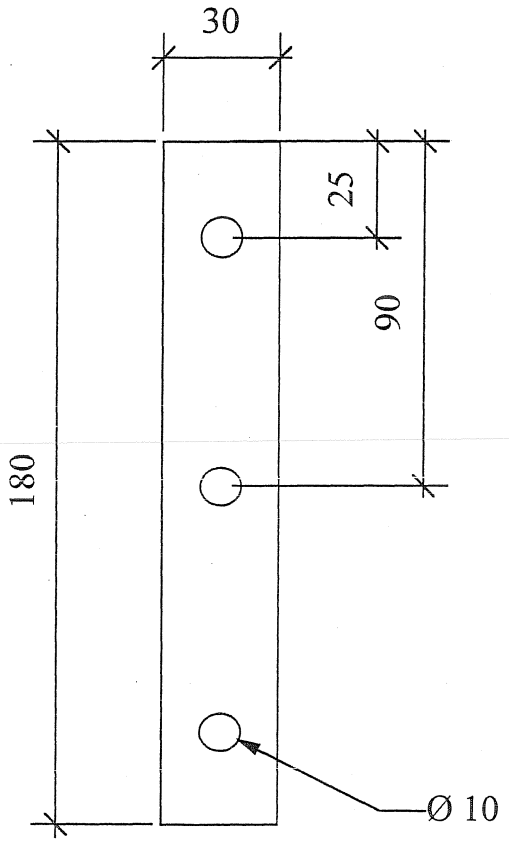


Part: Float support extra float sphere		Nr: 1.2.6
Scale: 1:2	View(s): all	
Material: AlMg3 Aluminium		Date: 27.11.96

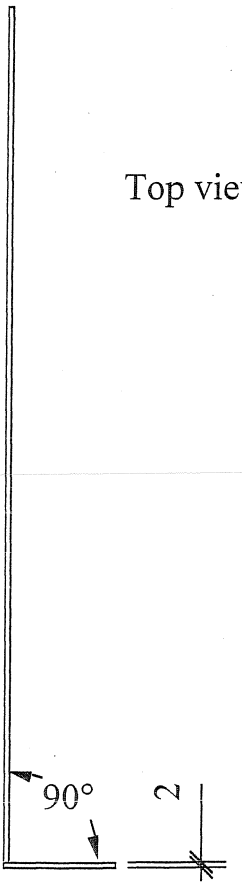
Side view



Front view

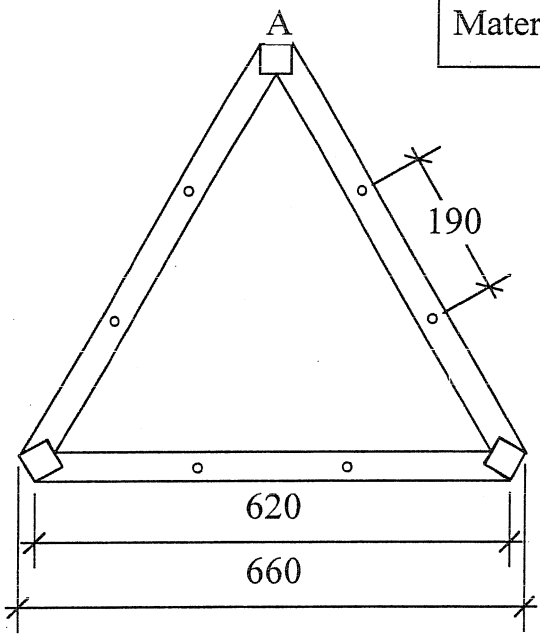


Top view



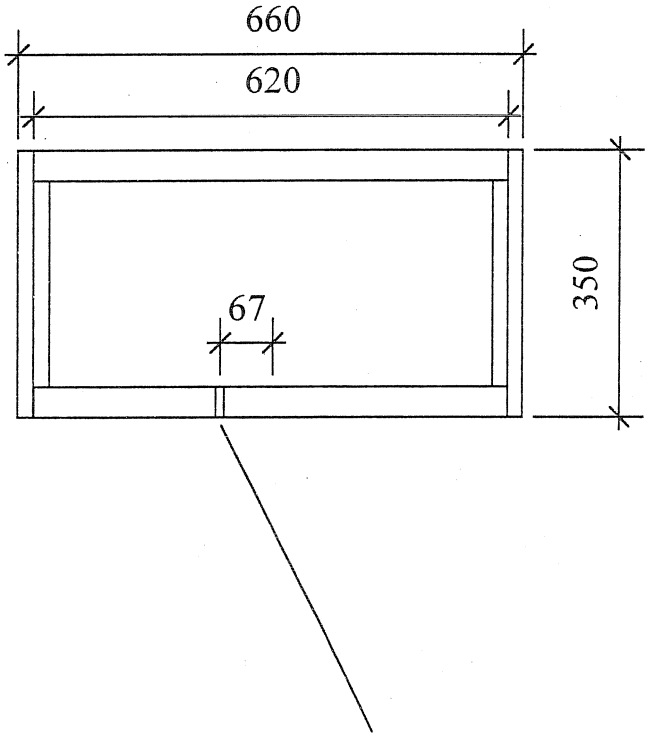
Top view

Part: Spacer for central unit		Nr: 1.2.7
Scale: 1:10	View(s): all	
Material: AlMg3 Aluminium		Date: 27.11.96



A: 40*40*4 mm

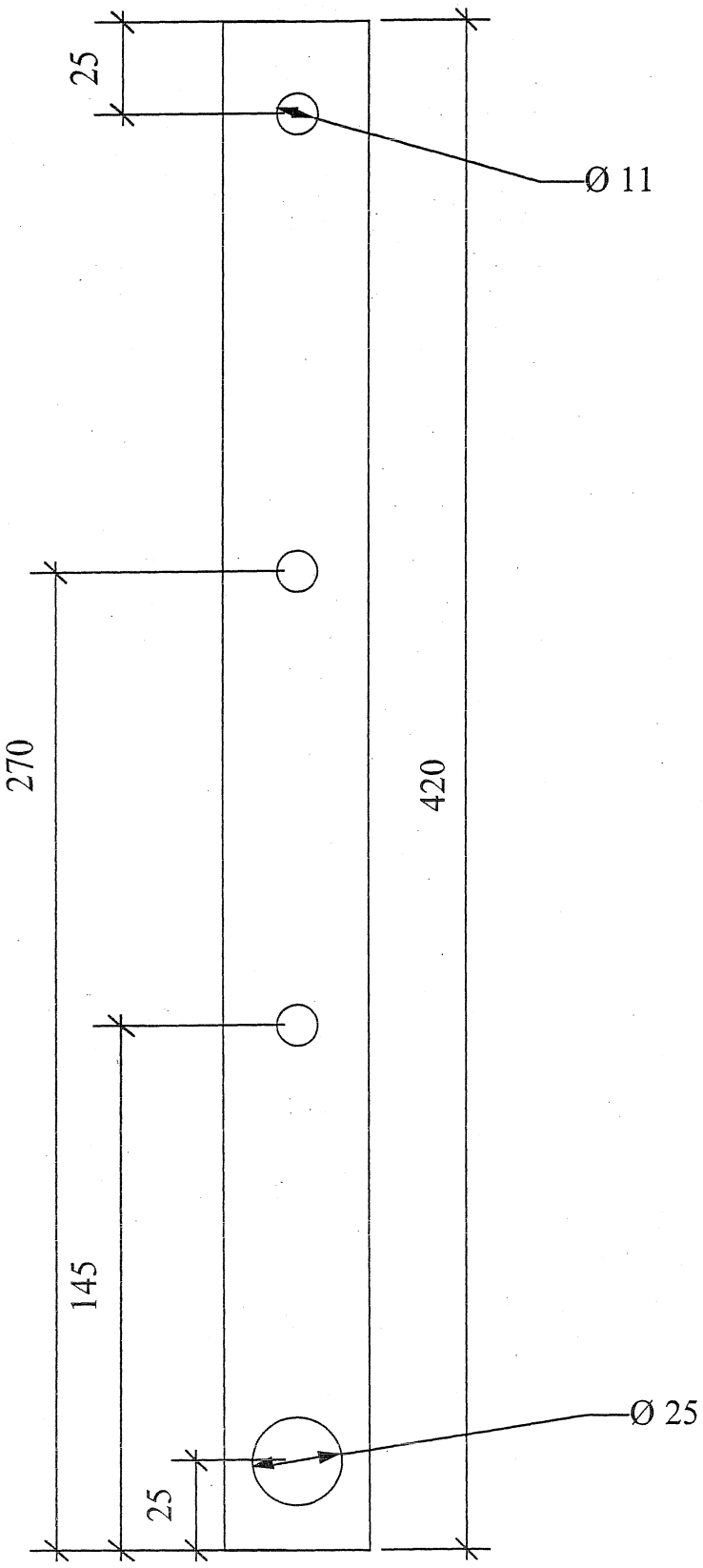
Side view



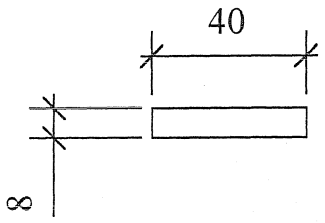
holes on bottom to fix central unit (10.5 dia)

Part: Attachment plate on float frame		Nr: 1.2.8
Scale: 1:2	View(s): all	
Material: 316-6 Steel		Date: 27.11.96

Top view

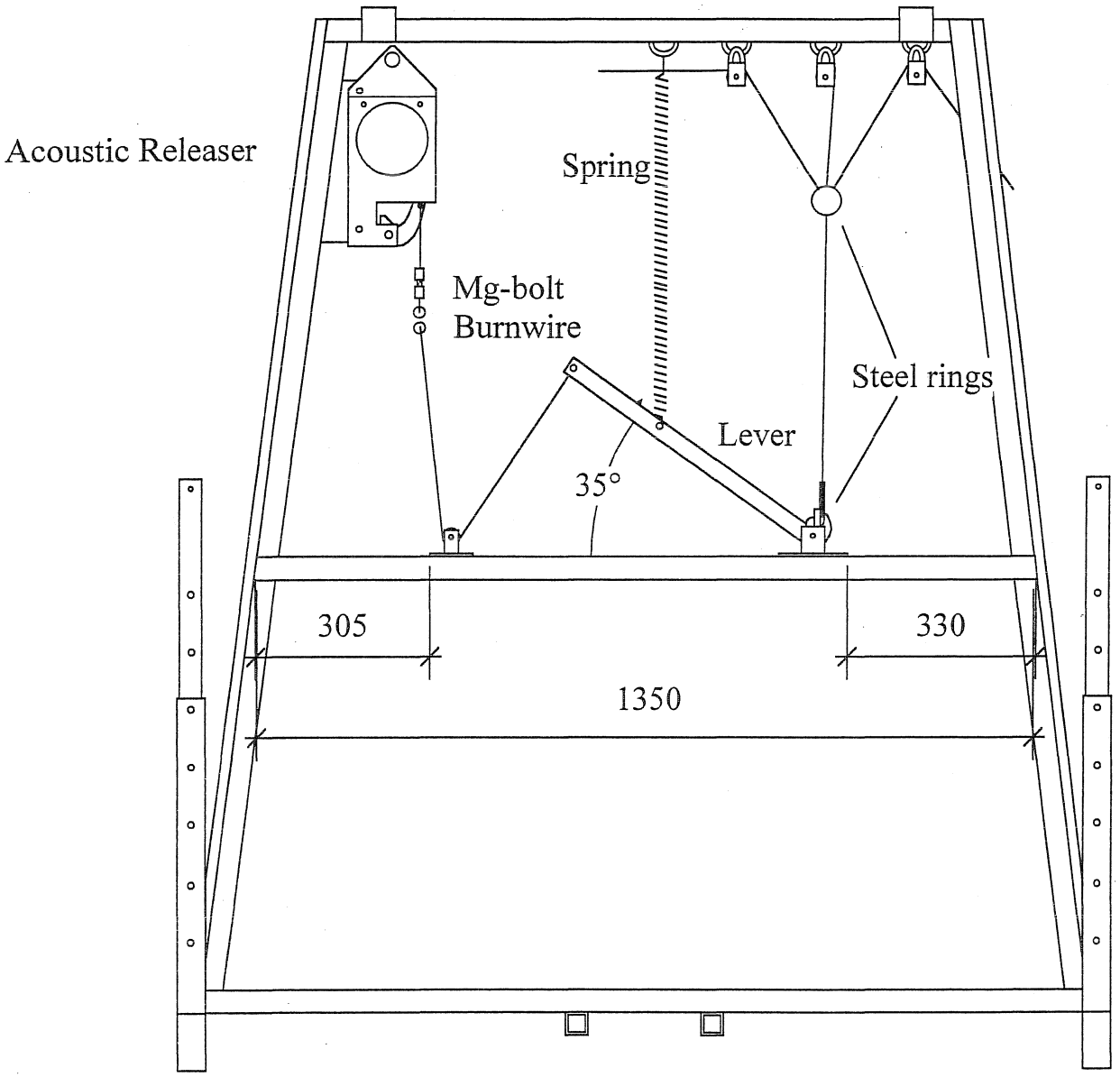


Side view

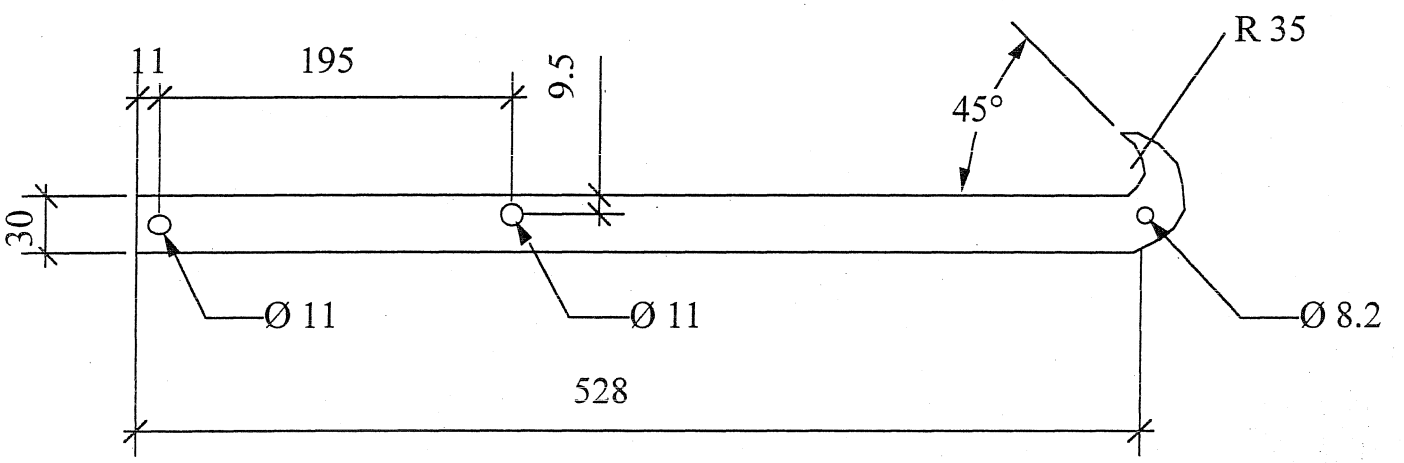


Schematic overview of the ballast release system of LUISE

Part: ballast release system overview		Nr: 1.3.1
Scale: 1:12	View(s): side	
Material: -		Date: 23.1.97

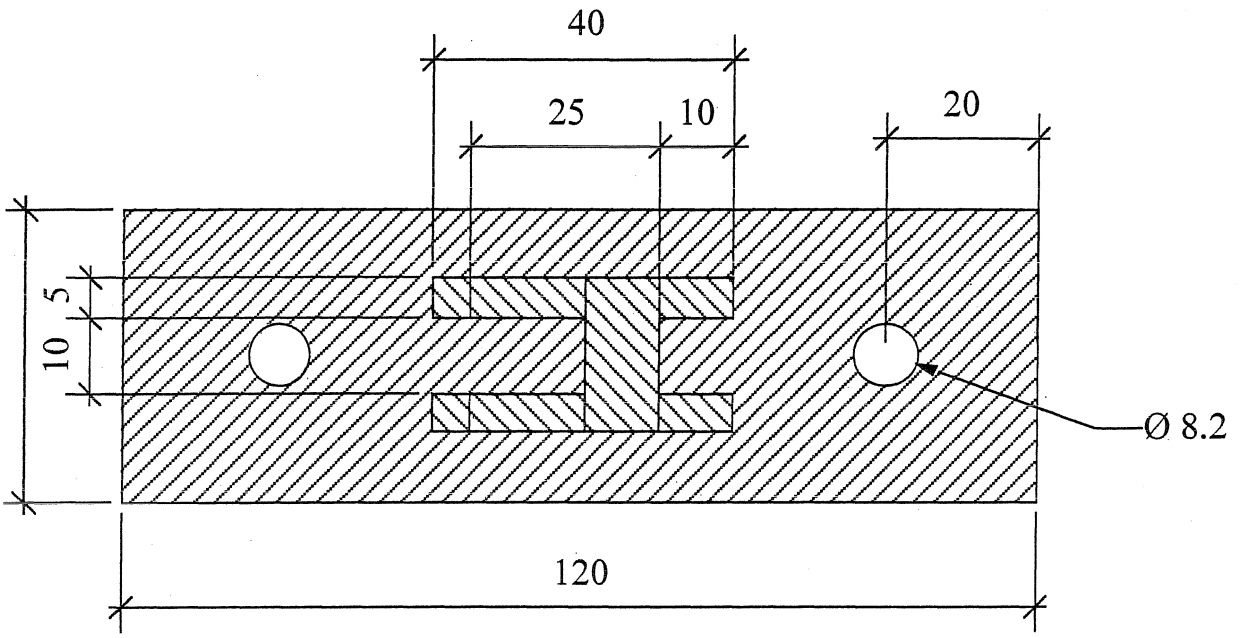


Part: releaser hook		Nr: 1.3.2
Scale: 1:4	View(s): side	
Material: 316-6 steel, 8 mm		Date: 23.1.97

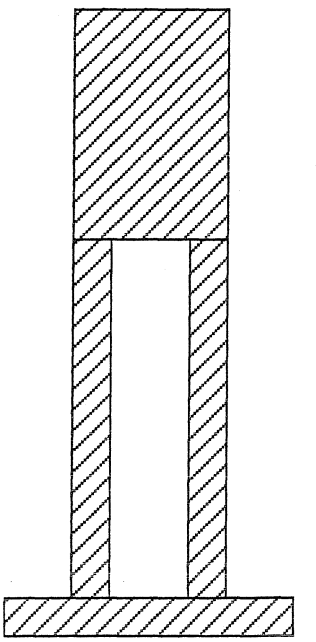


Part: release hook holder		Nr: 1.3.3
Scale: 1:1	View(s): all	
Material: 316-6 steel		Date: 23.1.97

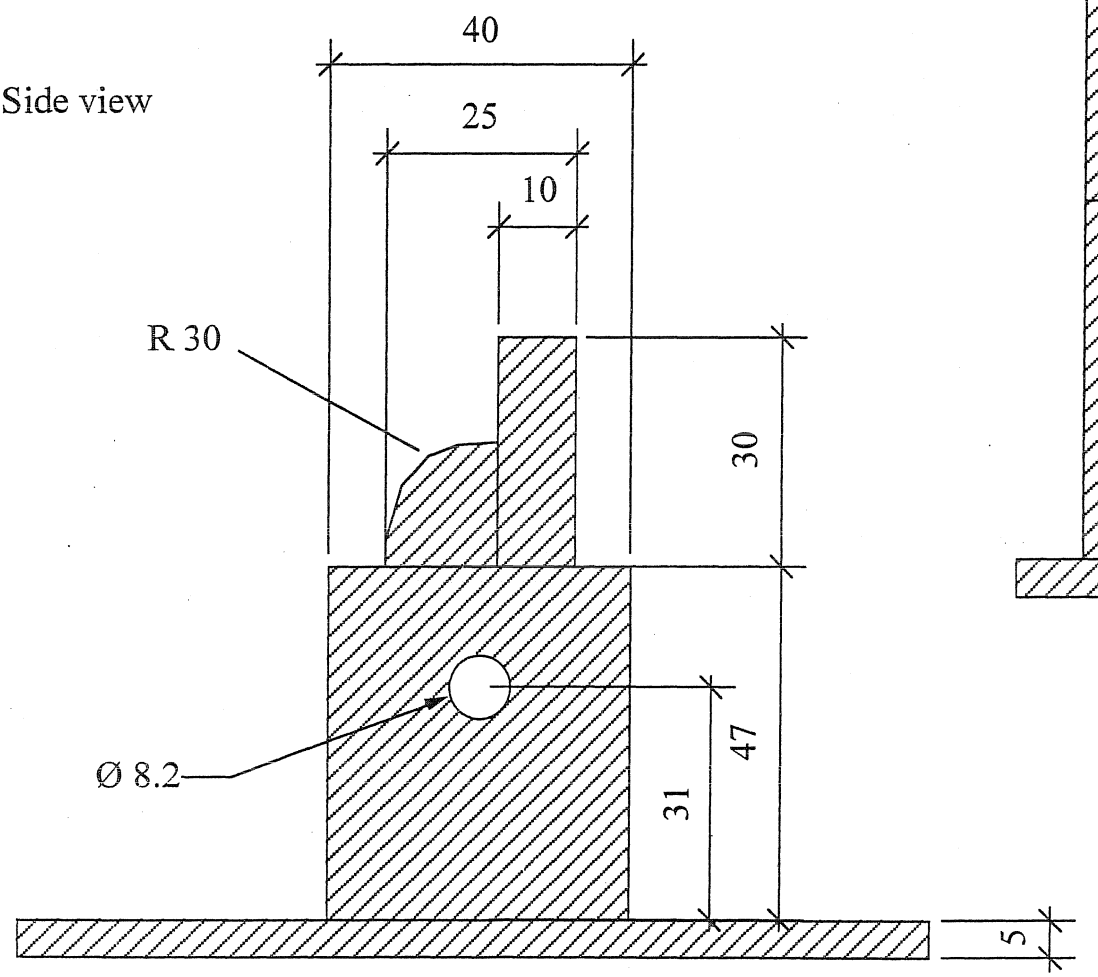
Top view



Rear view

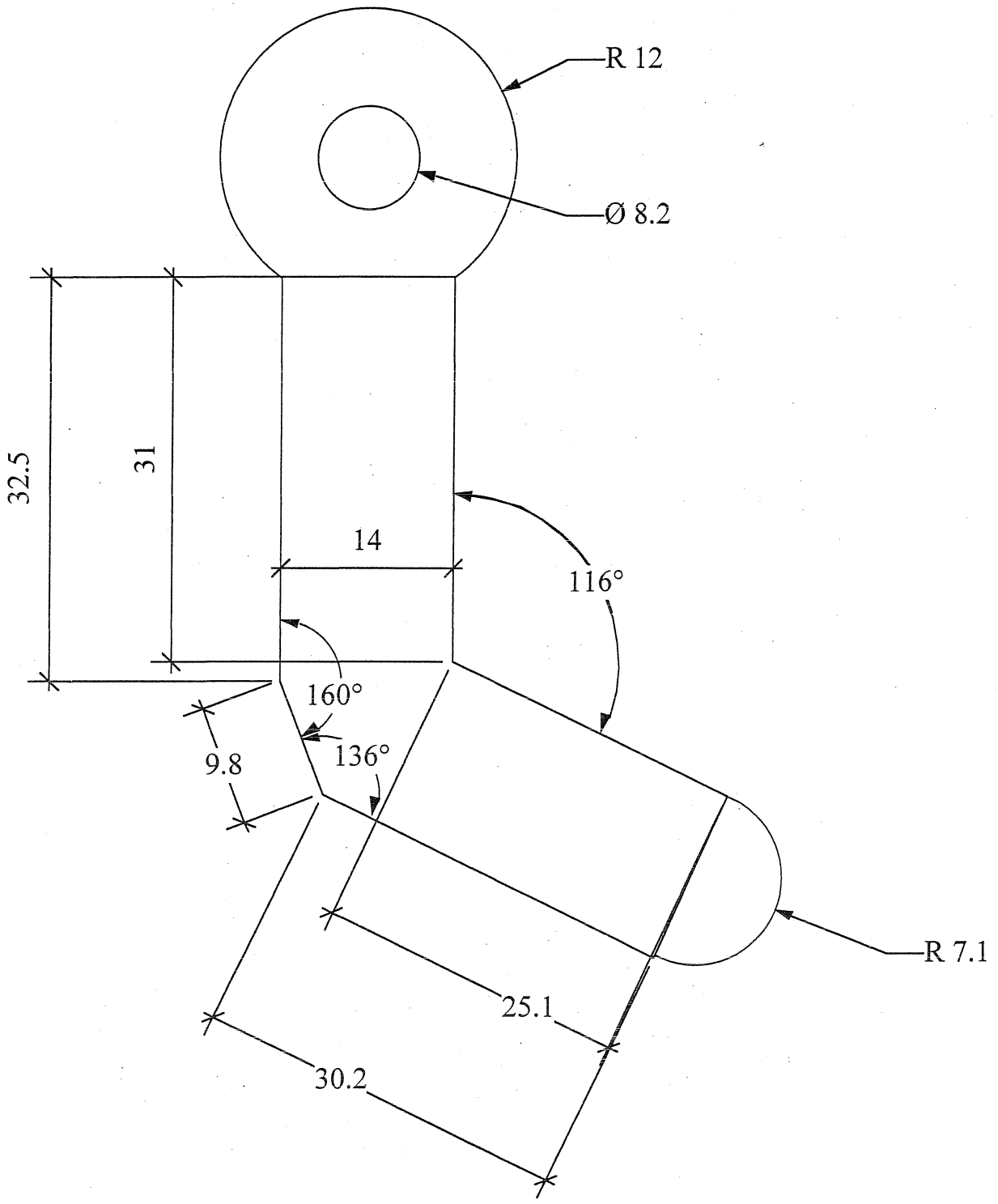


Side view



Part: Release clamp		Nr: 1.3.4
Scale: 2:1	View(s): side	
Material: 316-6 steel 8mm		Date: 22.1.97

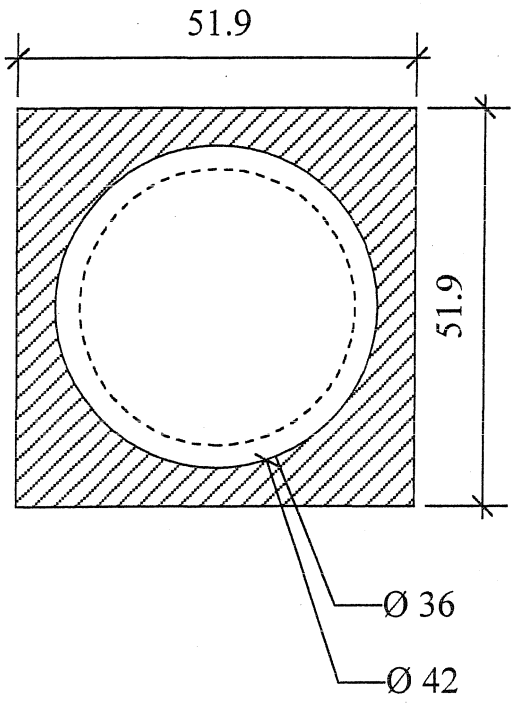
Side view



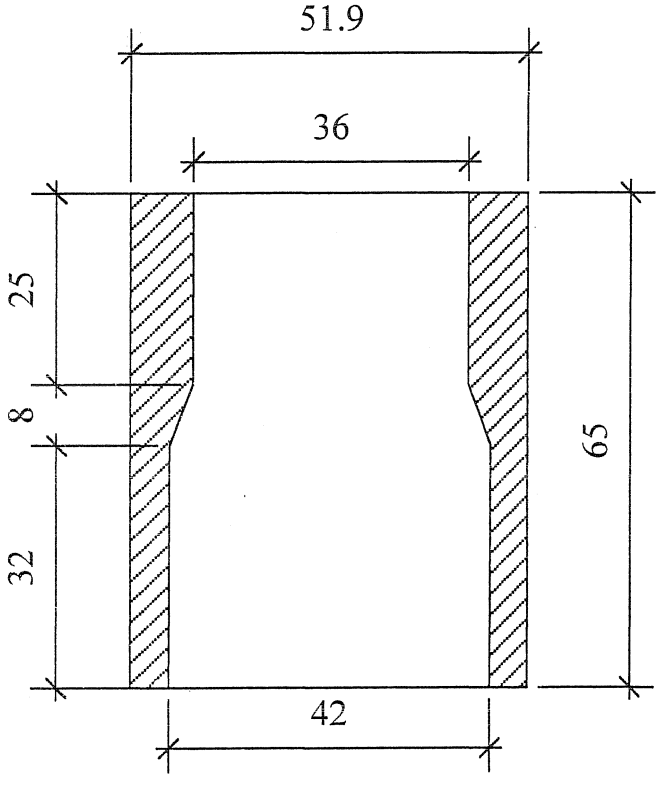
Note: round edges on all sides of the clamp

Part: Ballastrelease - clamp stopper		Nr: 1.3.5
Scale: 1:1	View(s): all	
Material:316-6 steel		Date: 22.1.97

Bottom view

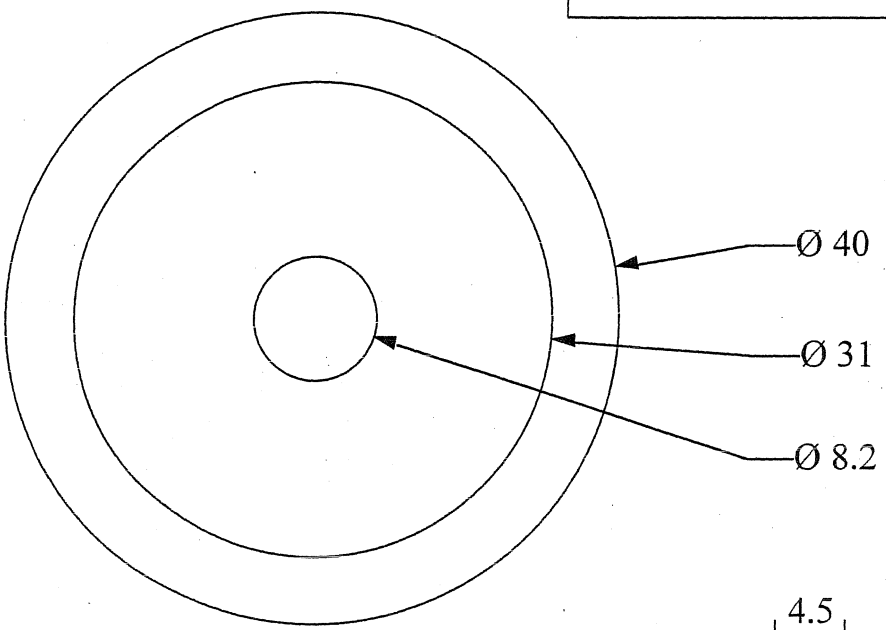


Center section

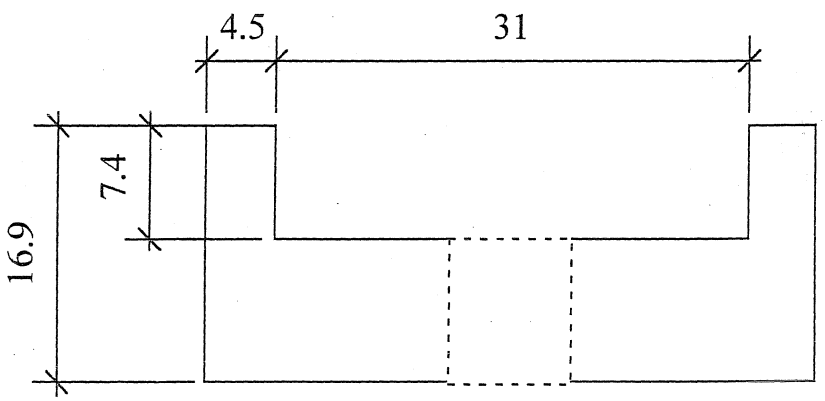


Part: cable roll for ballast wires (legs)		Nr: 1.3.6
Scale: 2:1	View(s): all	
Material: POM/316-6 steel		Date: 22.1.97

Bottom view

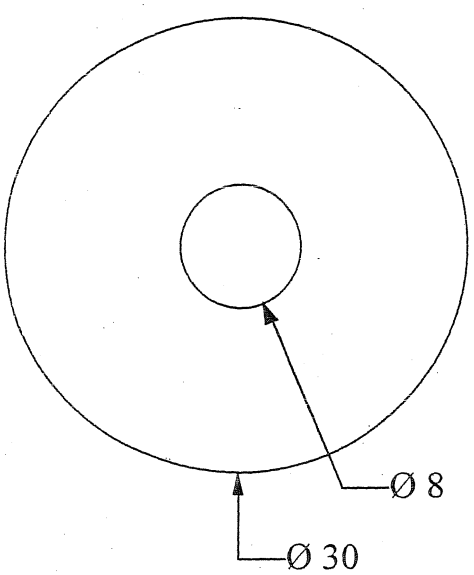


Side view

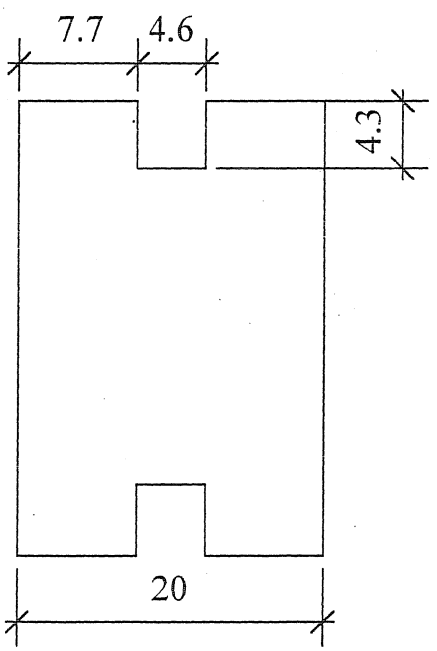


316-6 steel roll

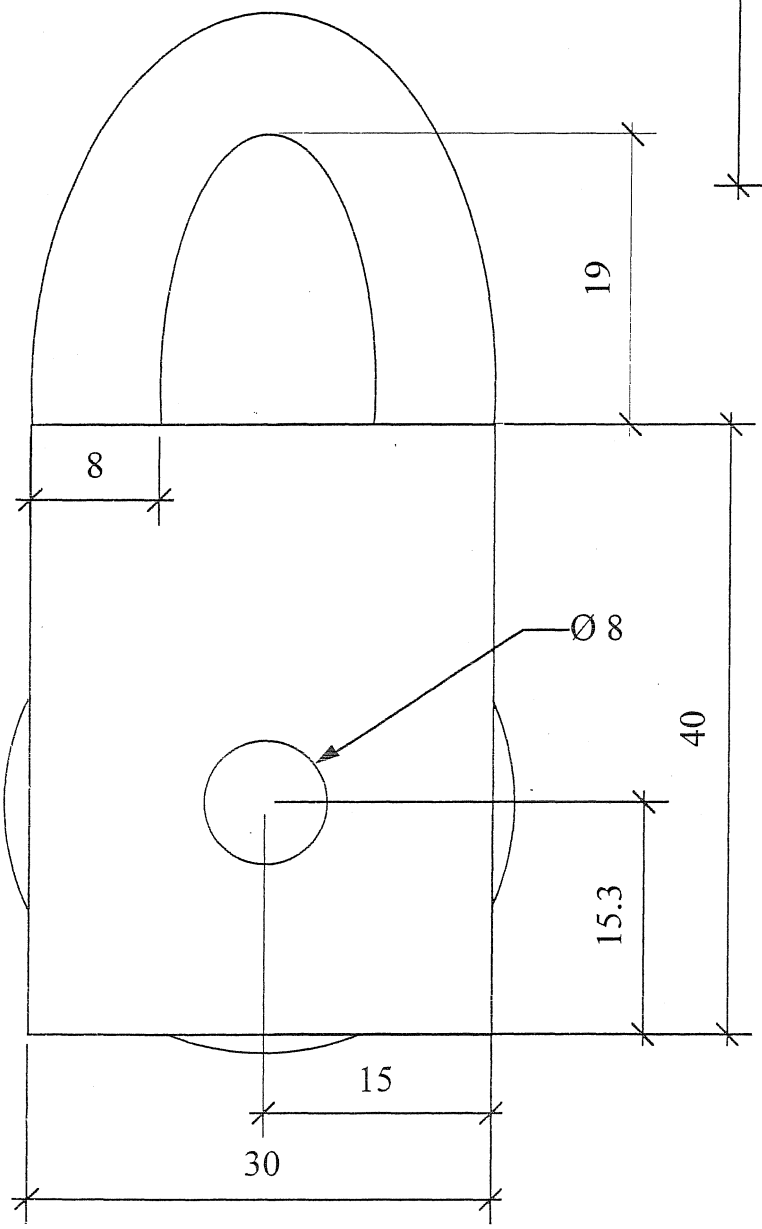
top view

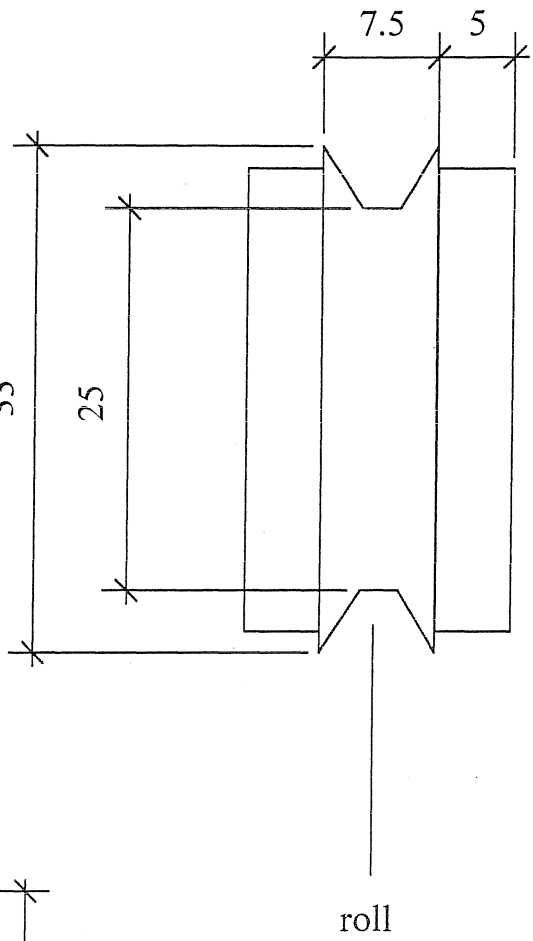


side view



Part: shackle roll for ballast wires		Nr: 1.3.7
Scale: 2:1	View(s): all	
Material: 316-6 steel		Date: 22.1.97

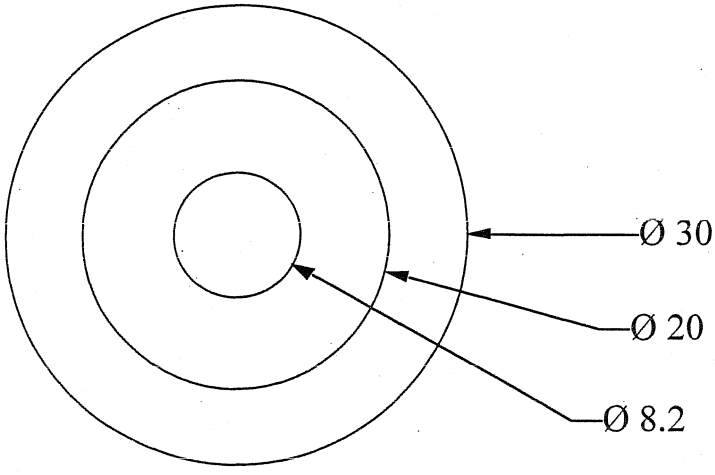




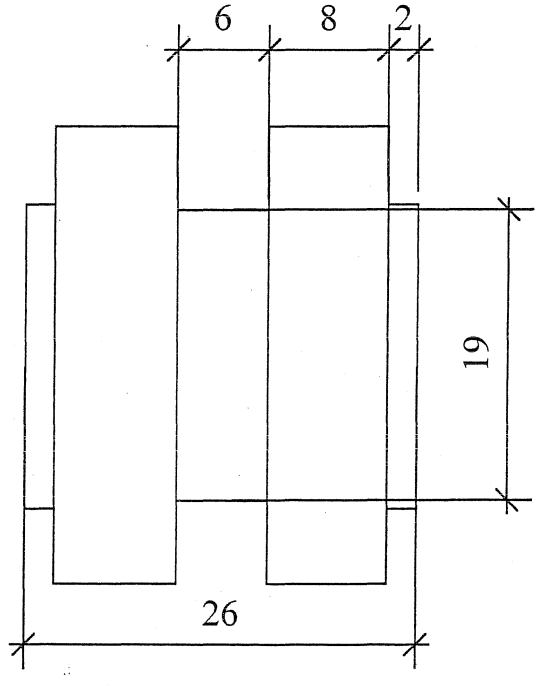
Side view

Part: ballast release roll		Nr: 1.3.8
Scale: 2:1	View(s): all	
Material: POM		Date: 23.1.97

Side view

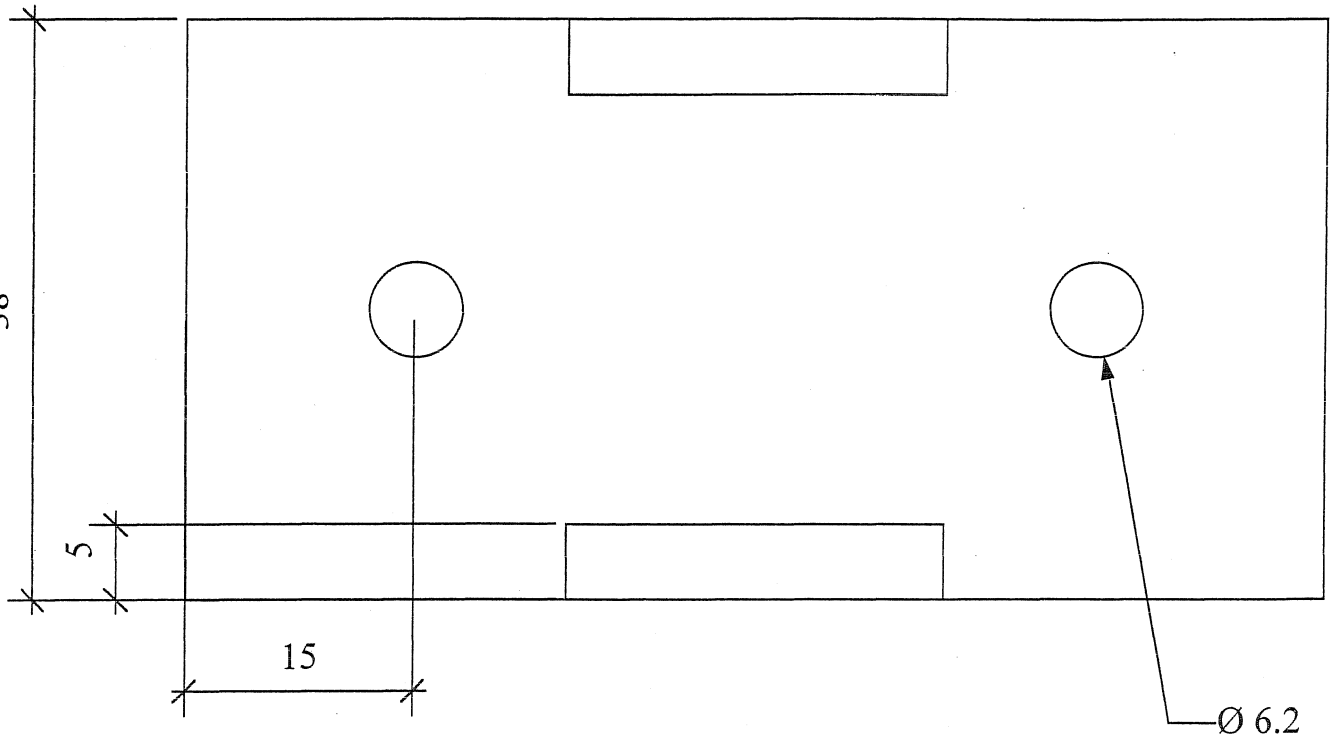


Top view

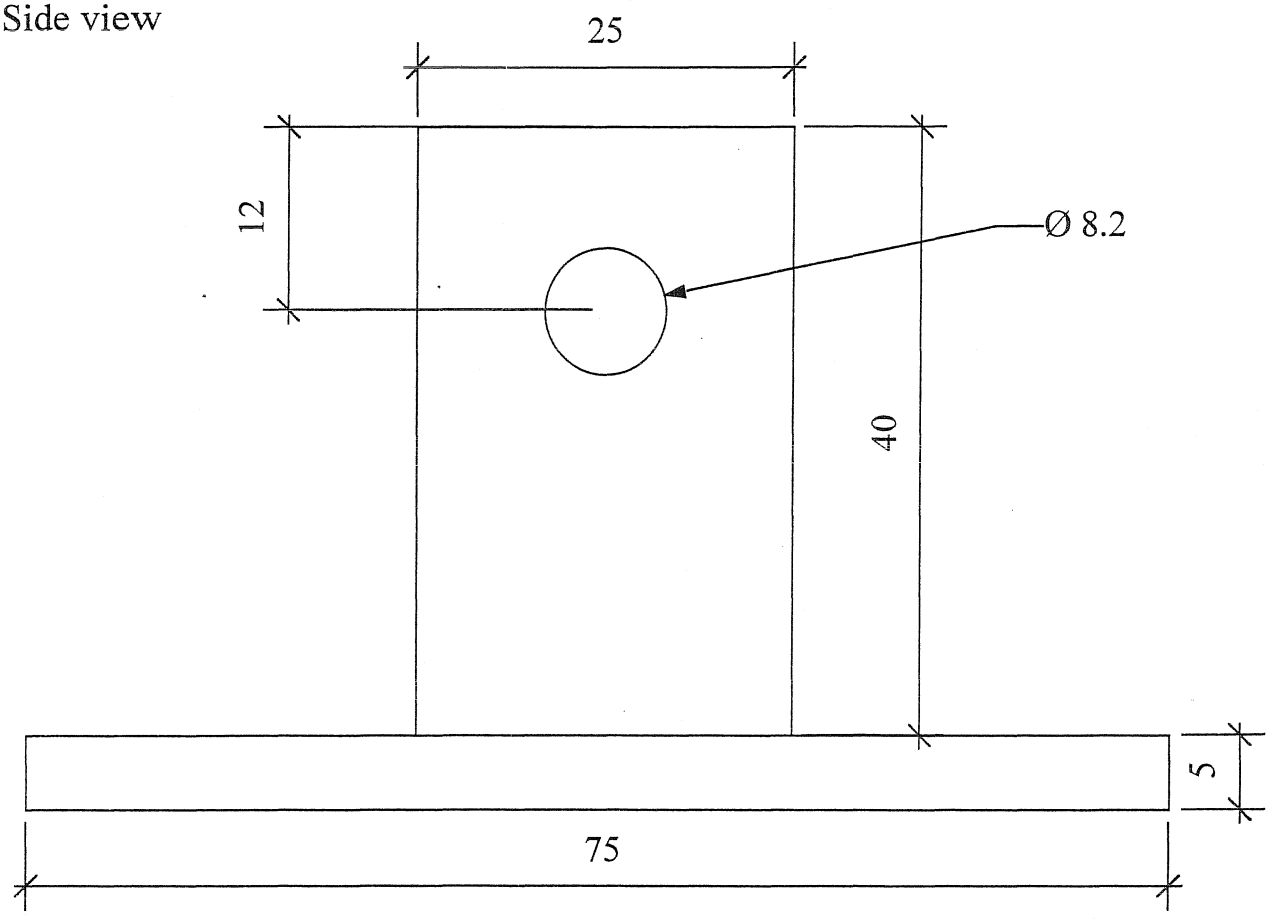


Part: ballast release roll holder		Nr: 1.3.9
Scale: 2:1	View(s): all	
Material: 316-6 steel		Date: 23.1.97

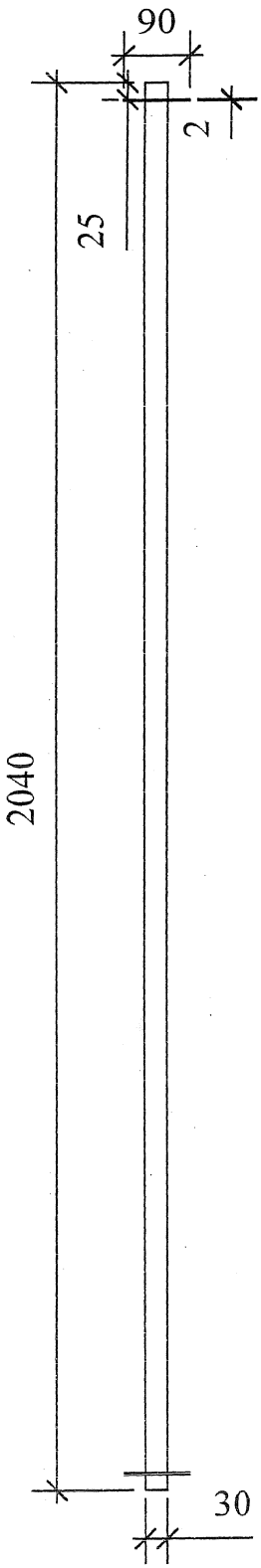
Top view

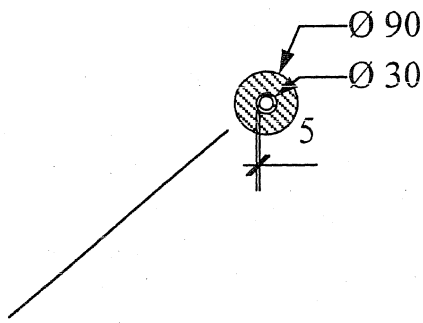


Side view



Part: Connecting steel bars		Nr: 2.1.1
Scale: 1:11	View(s): all	
Material: 316-6 Steel		Date: 27.11.96

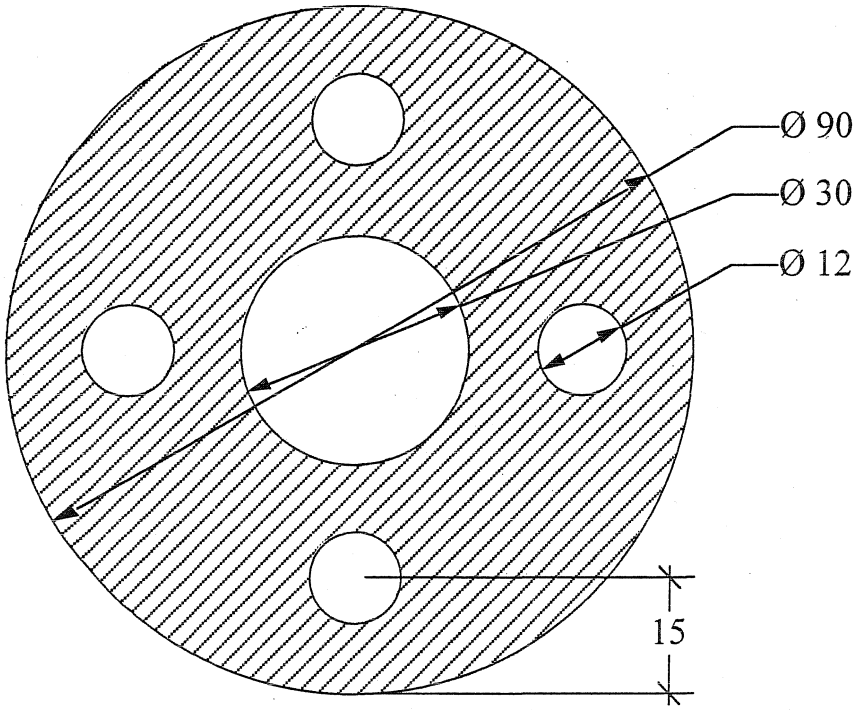




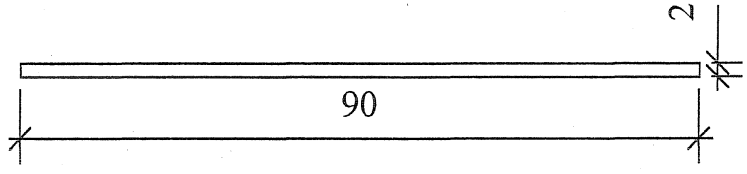
Attachment plates for connection to upper and lower level

Part: Top plates for conn. steel bars		Nr: 2.1.2
Scale: 1:1	View(s): all	
Material: 316-6 Steel		Date: 27.11.96

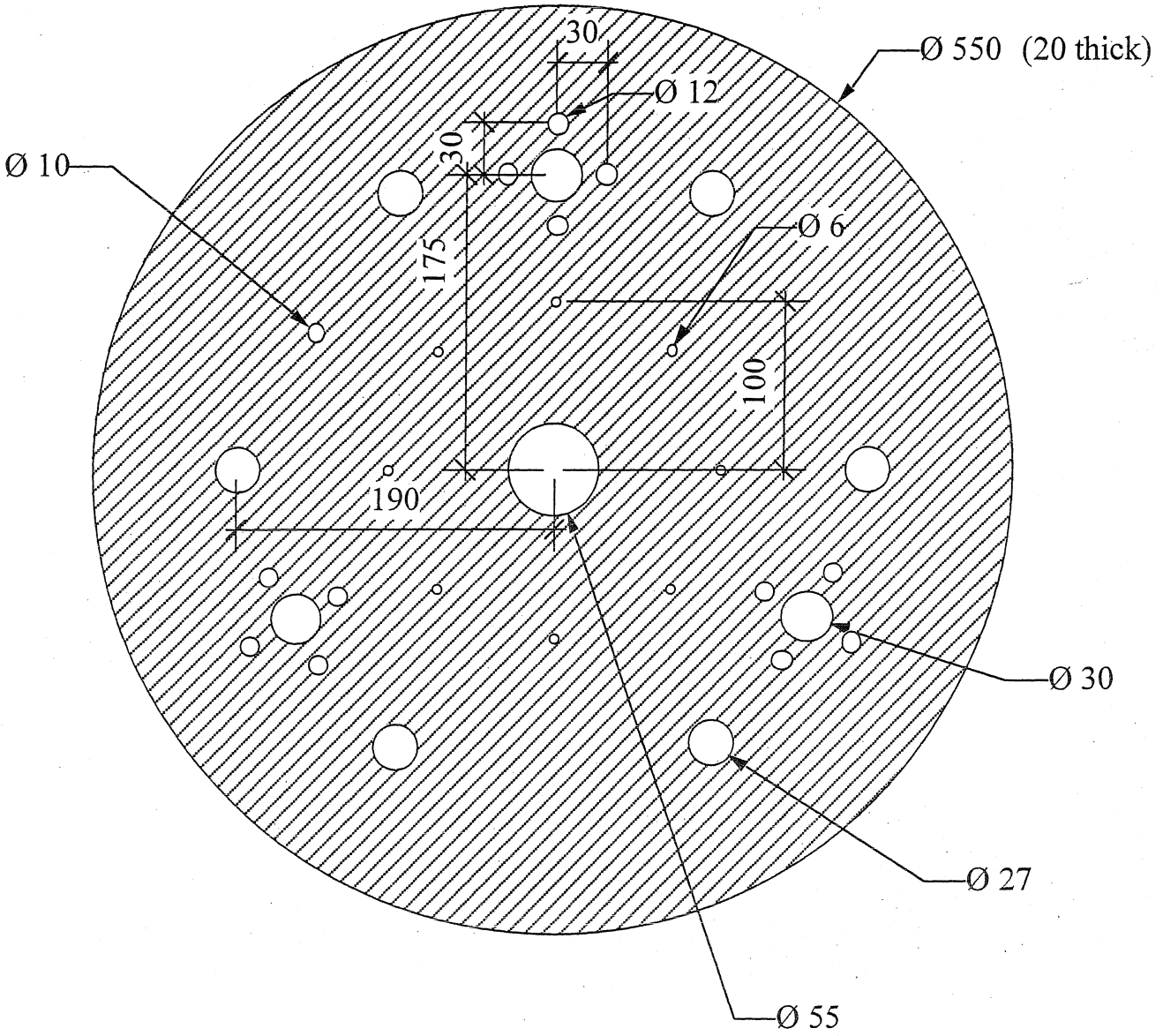
Top view



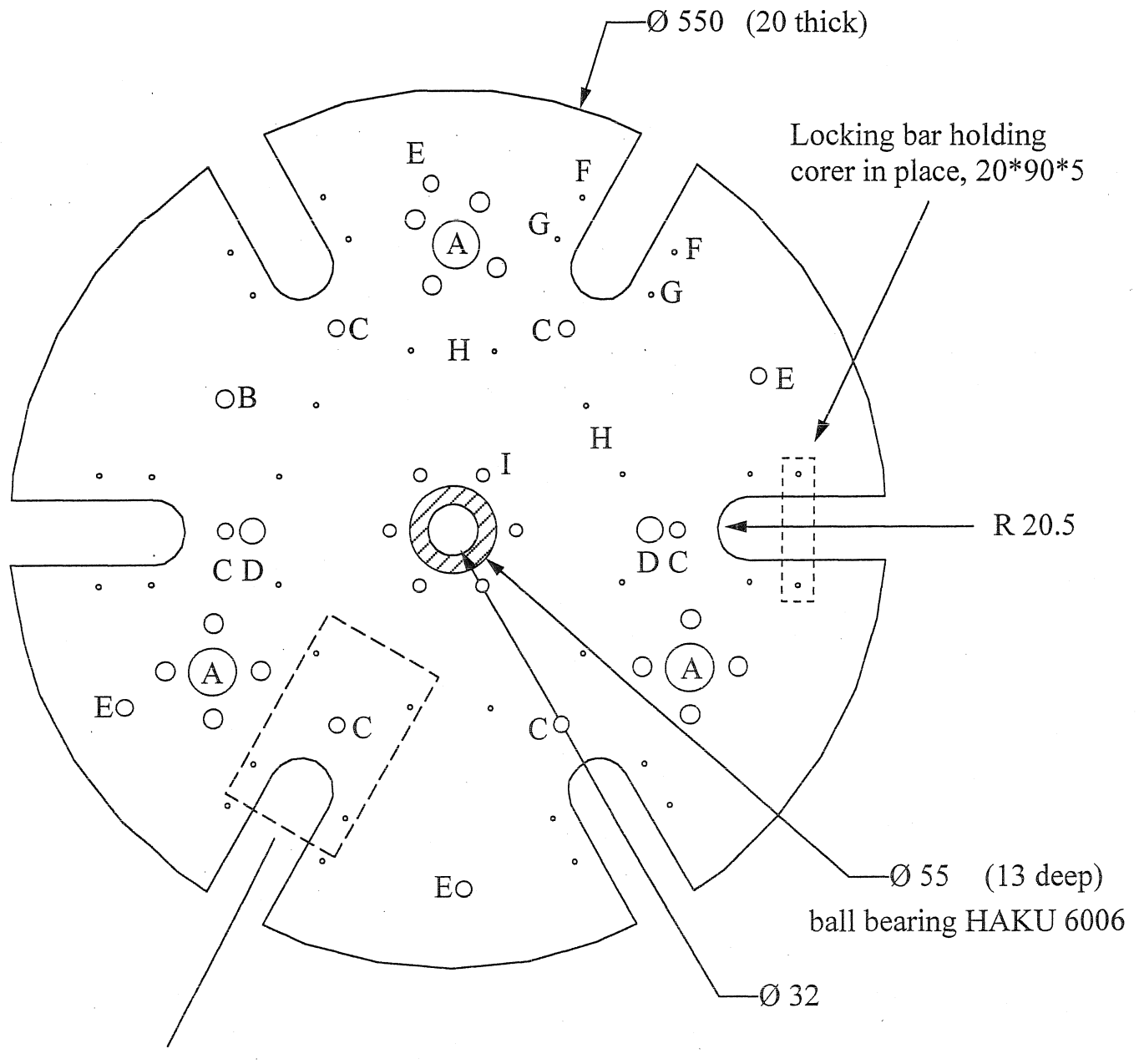
Side view



Part: Top level		Nr: 2.1.3
Scale: 1:4	View(s): top/bottom	
Material: POM		Date: 27.11.96



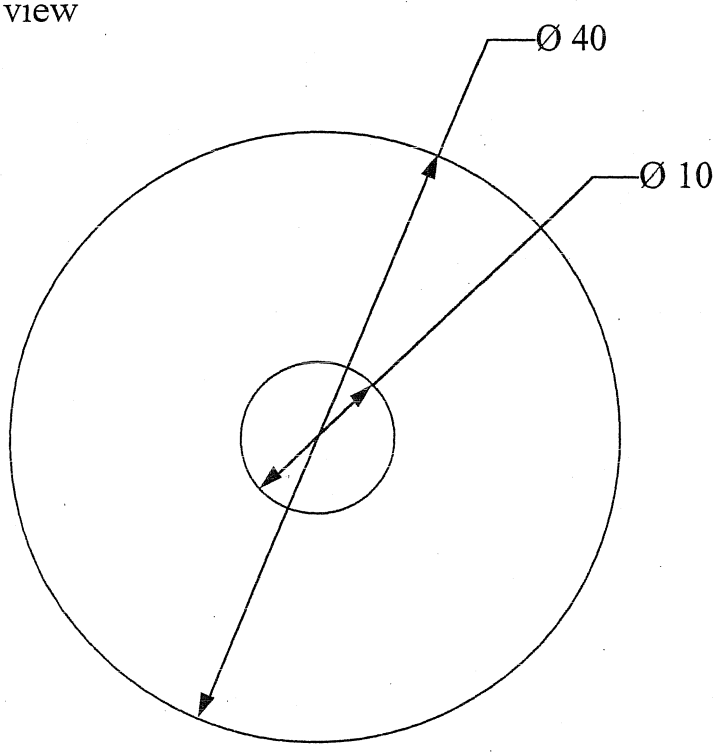
Part: level bottom		Nr: 2.1.4
Scale: 1:4	View(s): top	
Material: POM		Date: 23.1.97



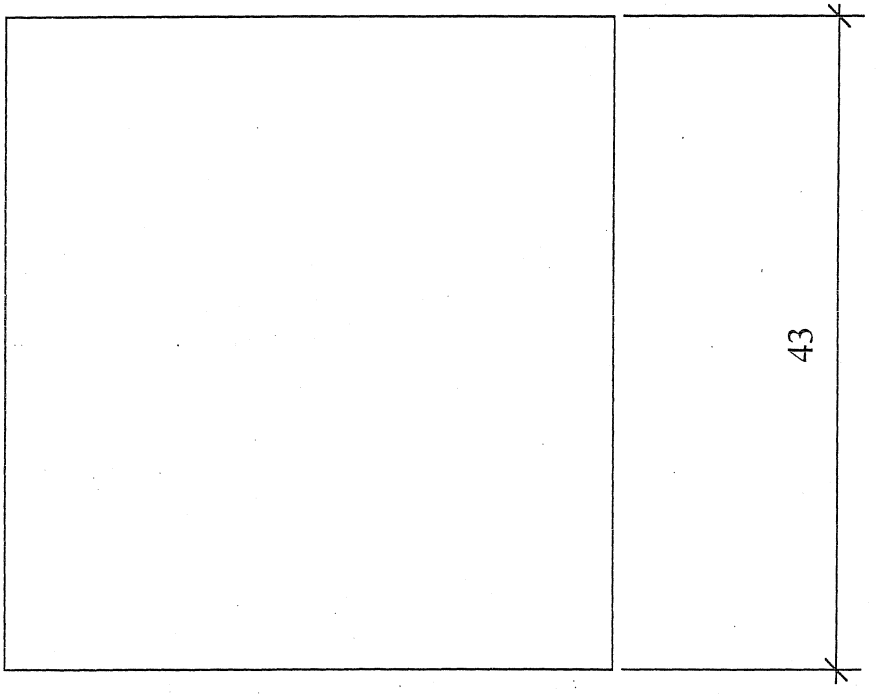
Hole no.	A	B	C	D	E	F	G	H	I
Distance from center	178	166	145	126	225	221	193	114	40
Diameter	30	11	M10	16	10	M3	M3	M3	8

Part: Spacer for central unit		Nr: 2.1.5
Scale: 2:1	View(s): all	
Material: POM		Date: 27.11.96

Top view

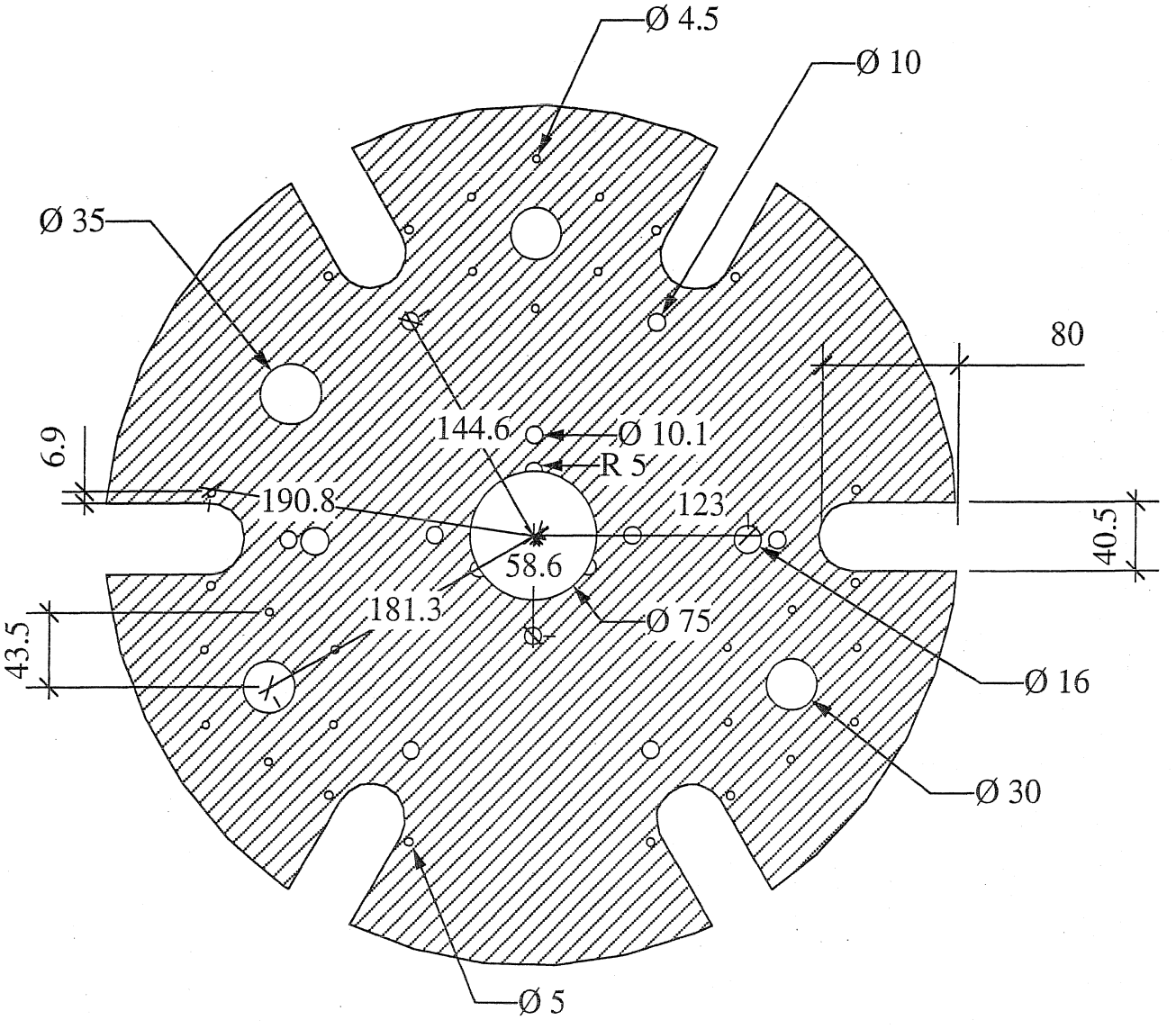


Side view

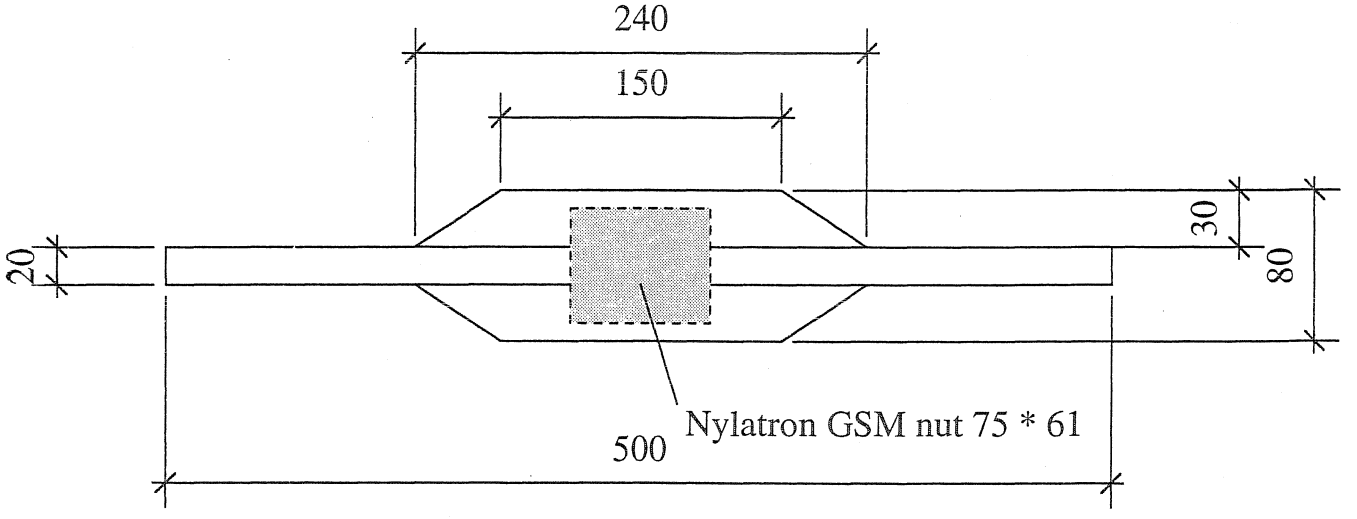


Part: Corer level		Nr: 2.2.1.1
Scale: 1:4	View(s): all	
Material: POM		Date: 21.1.97

Bottom view

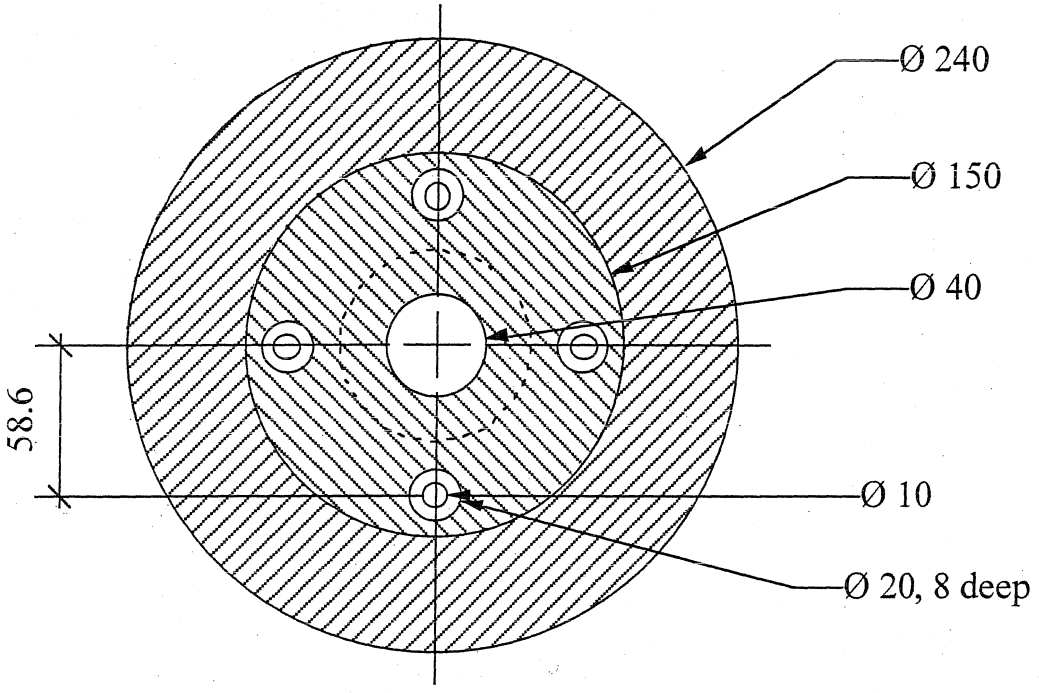


Center section

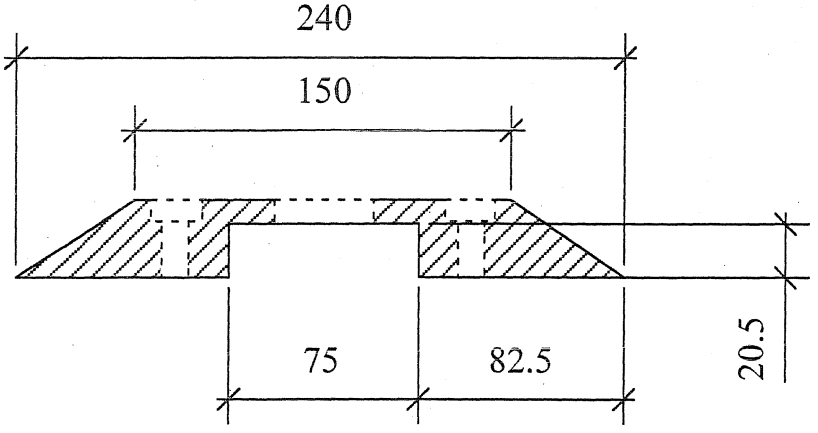


Part: cover plates on corer level		Nr: 2.2.1.2
Scale: 1:3	View(s): all	
Material: POM		Date: 30.1.97

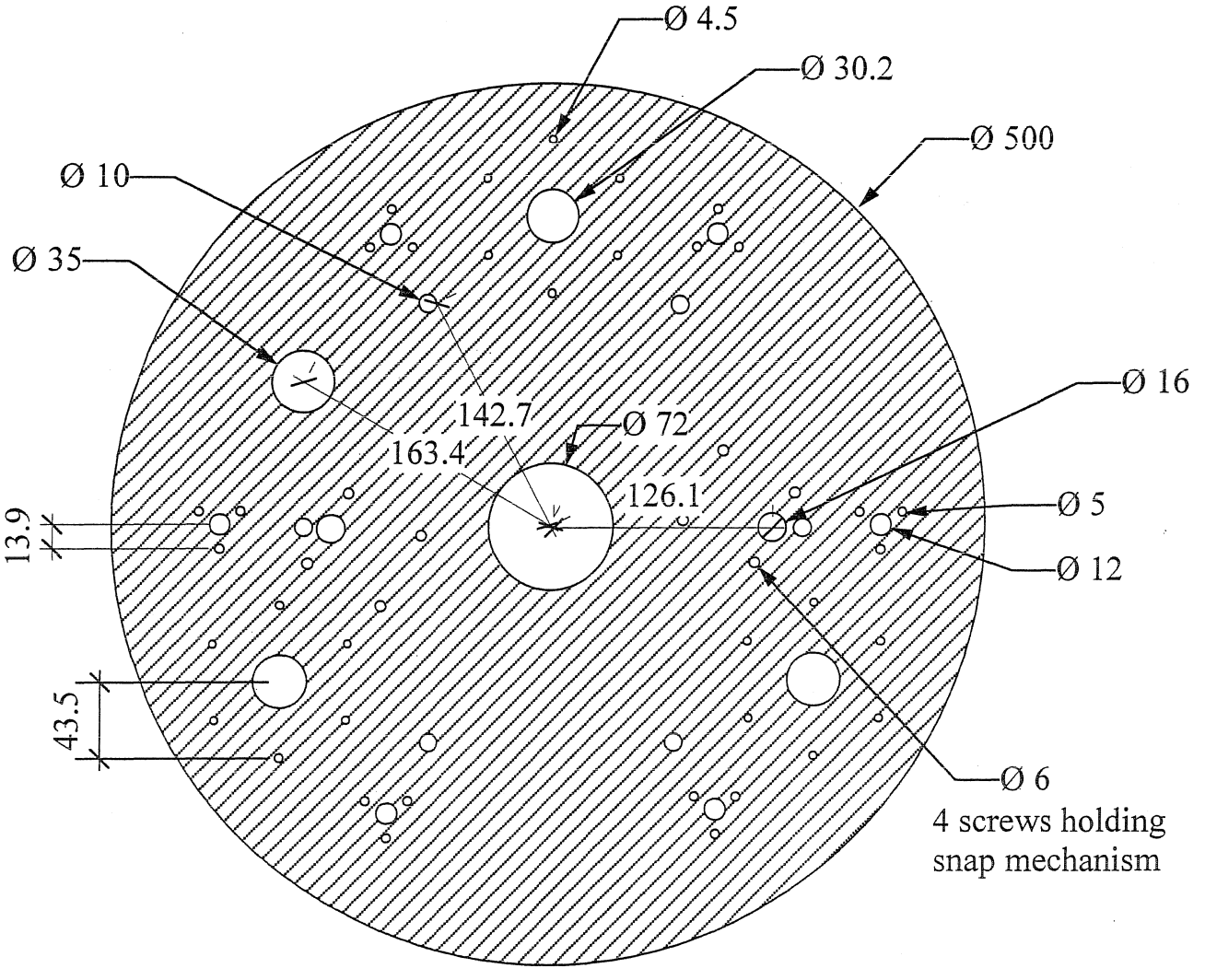
Top view

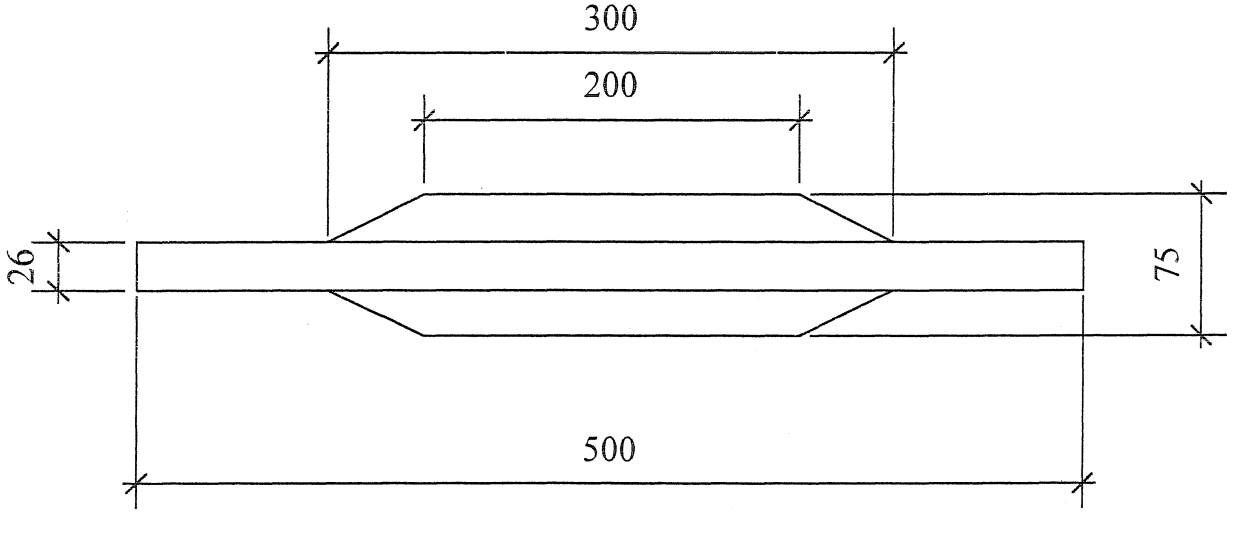


Center section



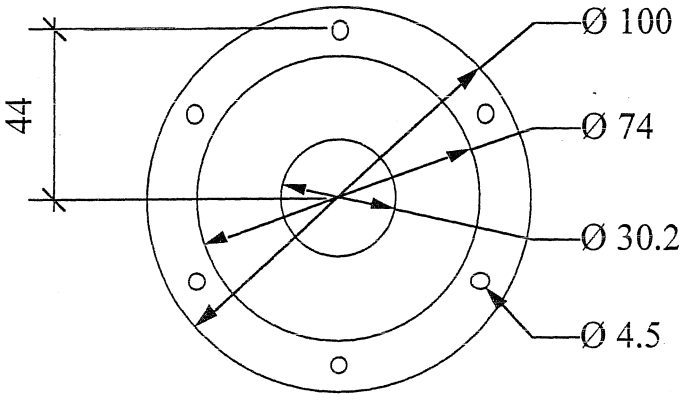
Part: Level piston		Nr: 2.2.2
Scale: 1:4	View(s): top/bottom	
Material: POM		Date: 27.11.96



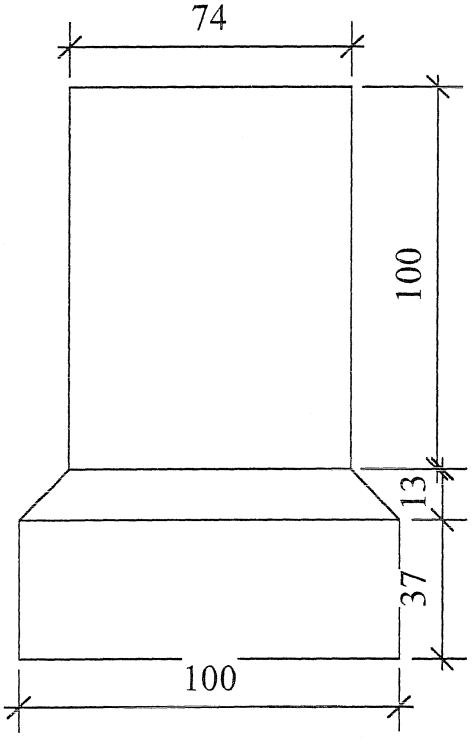


Part: Sliding tube for moving levels		Nr: 2.2.3
Scale: 1:2	View(s): all	
Material: POM		Date: 20.1.97

Top view

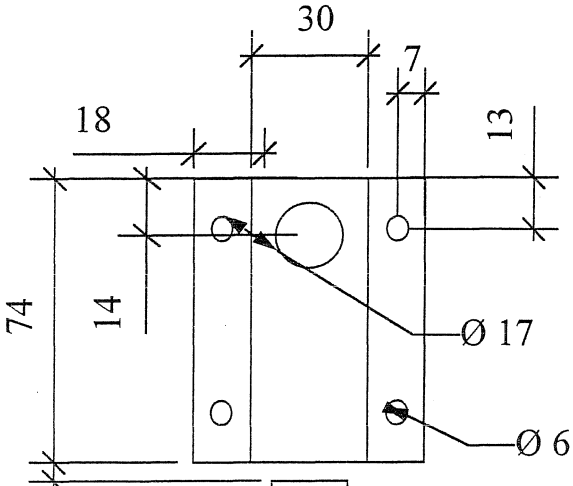


Side view

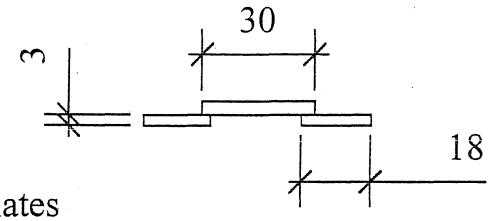


Part:Locking mechanism for upper level		Nr: 2.2.4
Scale: 1:2	View(s): all	
Material: 316-6 Steel		Date: 20.1.97

Overview

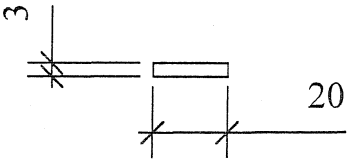


Side views

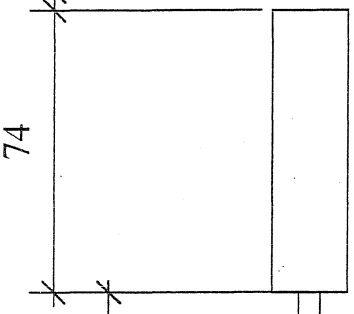


Steel plates

weld

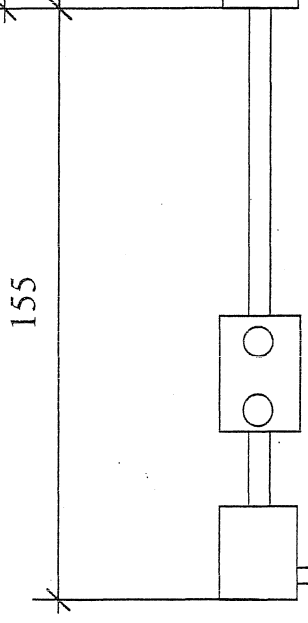


Steel plate

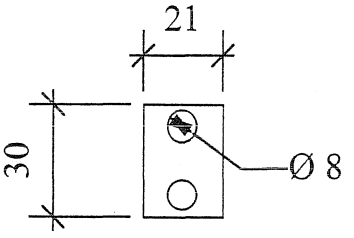


weld

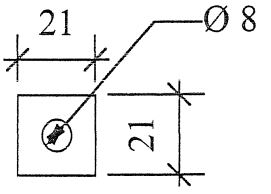
Steel bar (6 dia)
(spring on it)



Top view

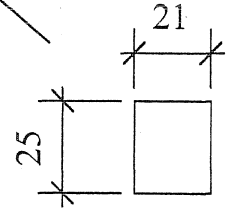


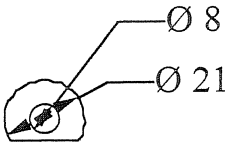
Rear view



POM blocks

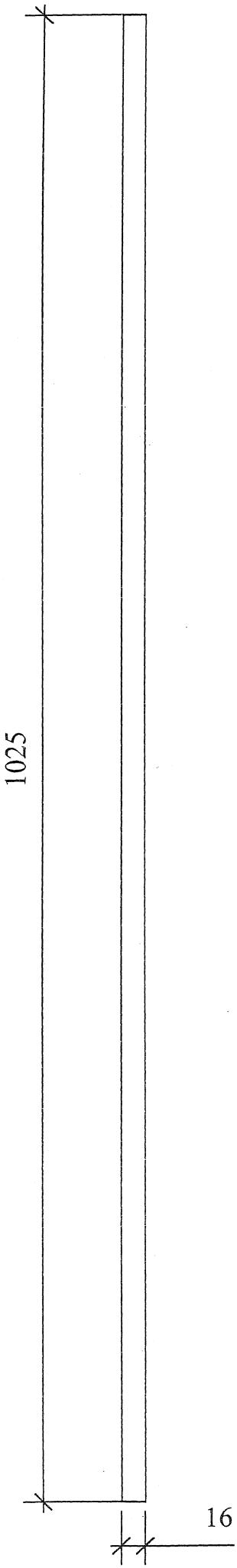
Screw



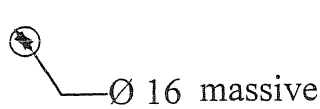


Part: Locking bars		Nr: 2.2.5
Scale: 1:4	View(s): all	
Material: 316-6 Steel		Date: 20.1.97

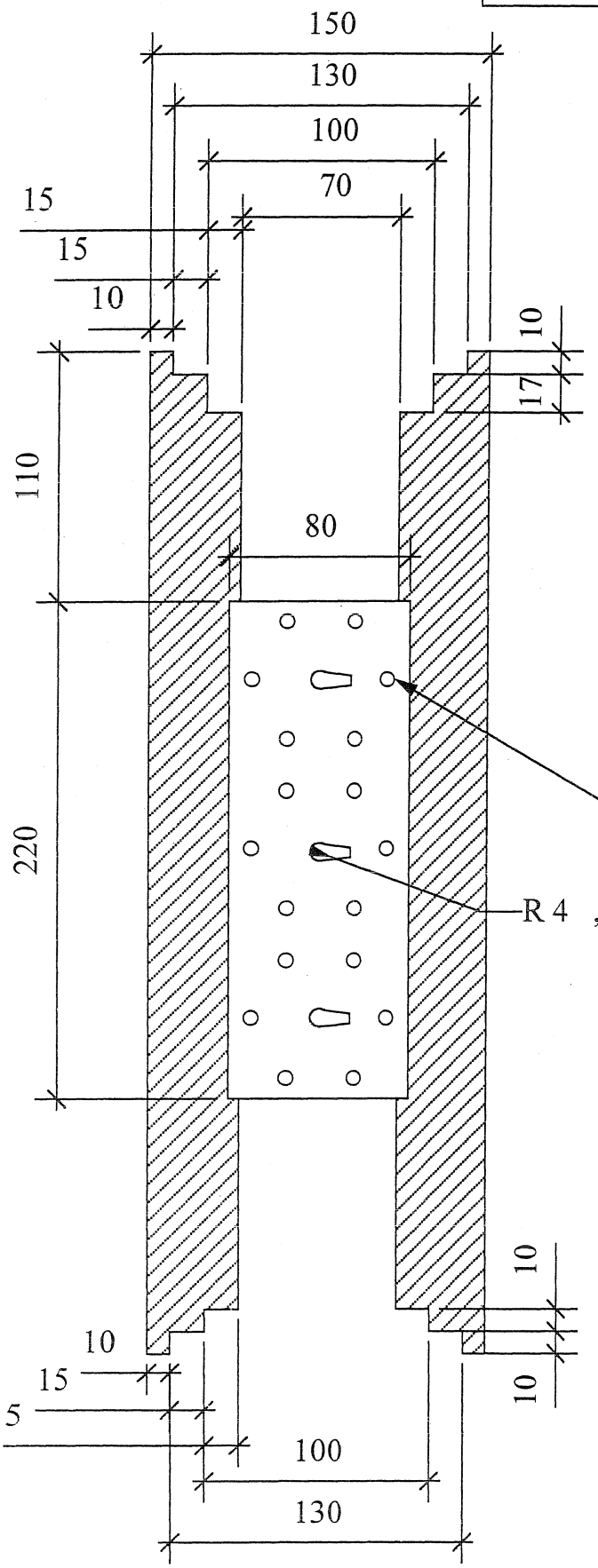
Side view



Top view



Part: big motorhouse		Nr: 2.3.1
Scale: 1:3	View(s): side	
Material:cast plexiglass (PMMA)	Date: 29.1.97	



Note: middle part of drawing shows flattened area on outside to which membranes are fixed. 12 deep from outer dia.

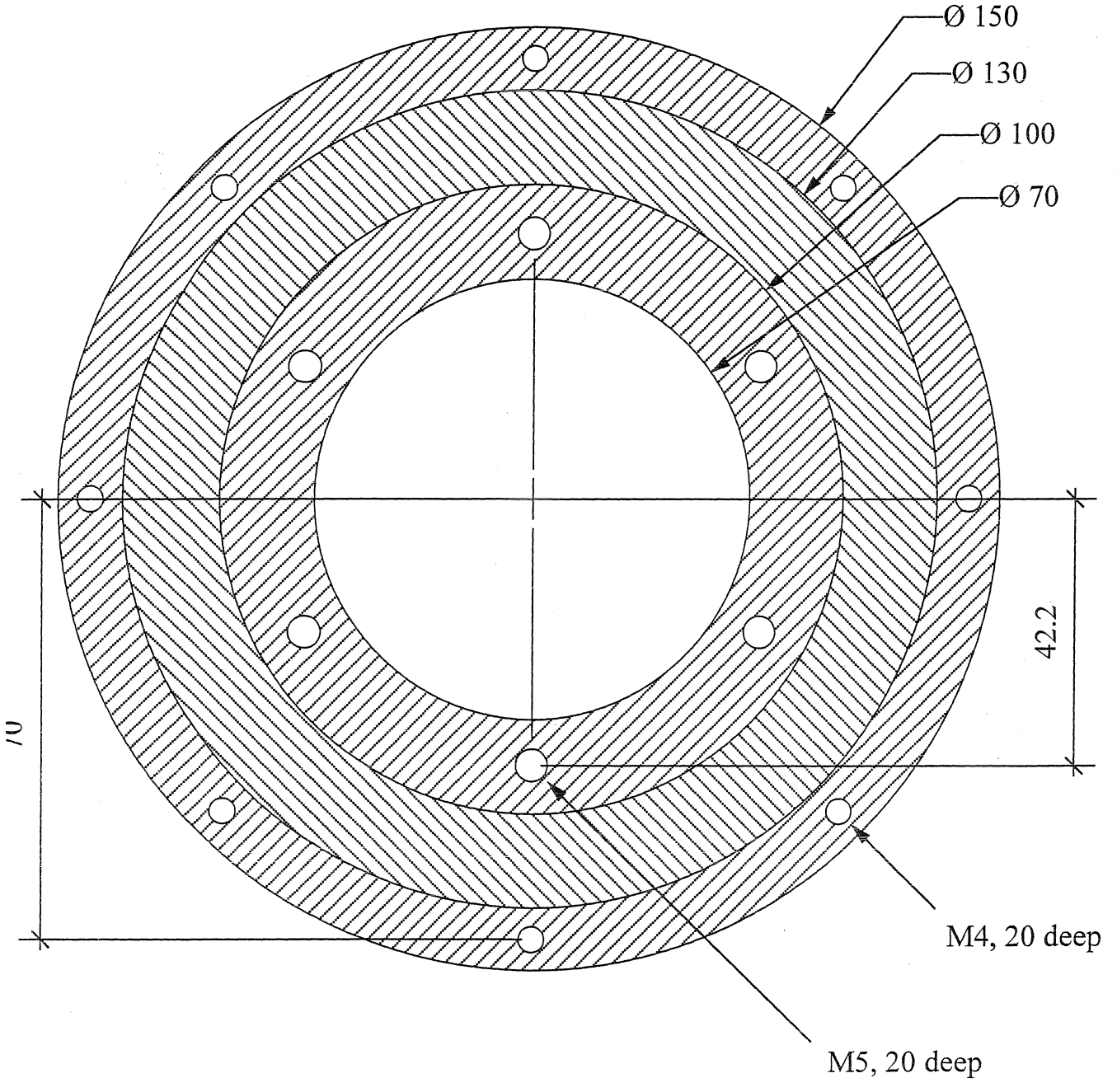
M6, 20 deep

R 4 , section through hole:

Part: big motorhouse		Nr: 2.3.2
Scale: 1:3	View(s): top/bottom	
Material:cast plexiglass (PMMA)		Date: 29.1.97

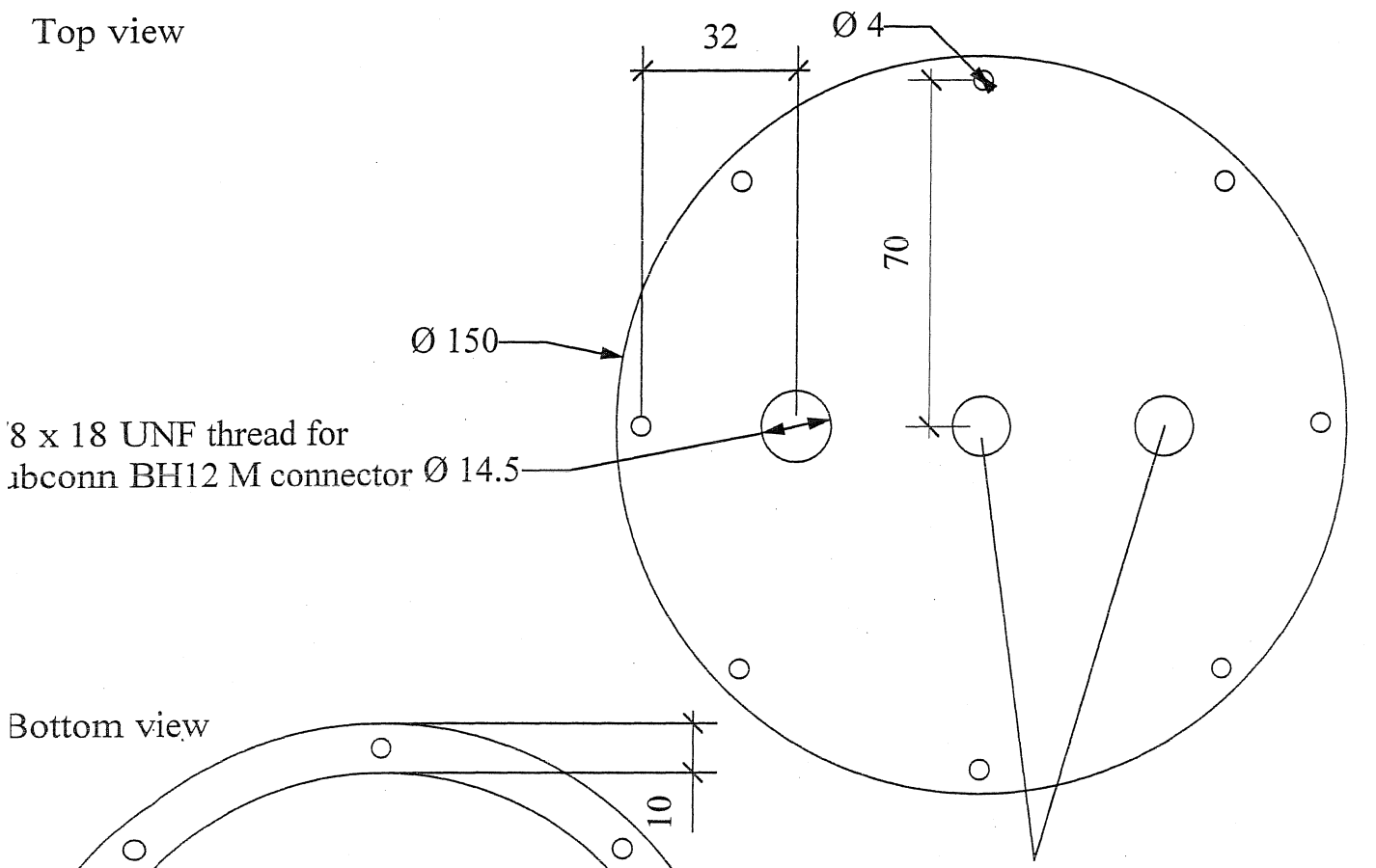
Note: connect M4 holes to outside at bottom

Note: connect M5 holes to inside at bottom

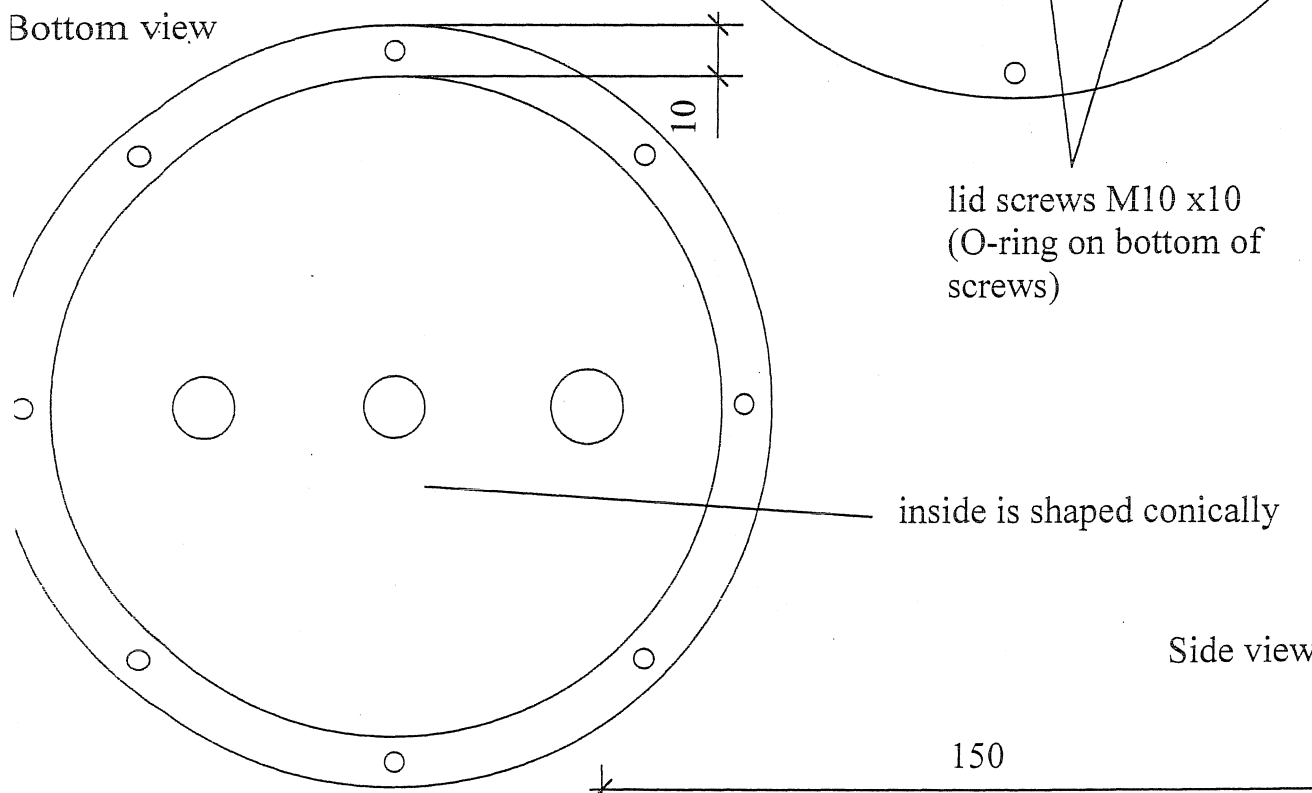


Part: top lid for big motorhouse		Nr: 2.3.3
Scale: 1:1.5	View(s): all	
Material: POM		Date: 20.1.97

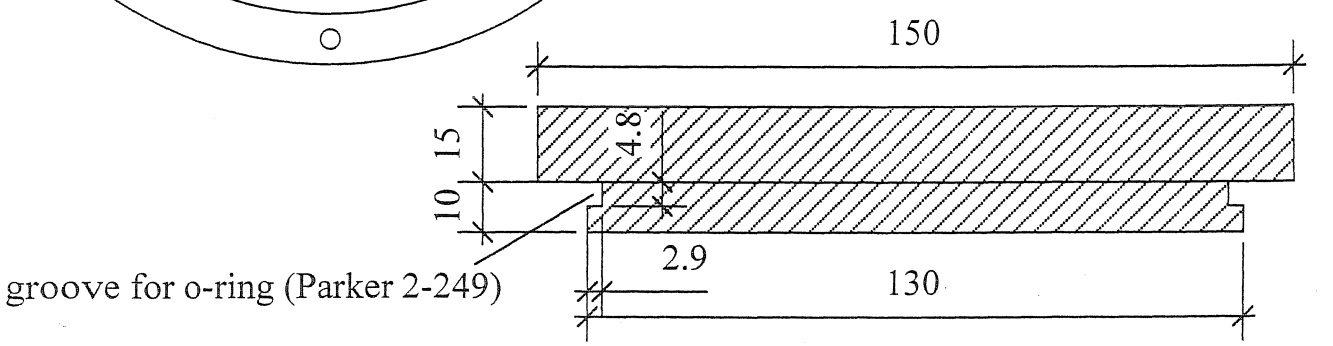
Top view



Bottom view

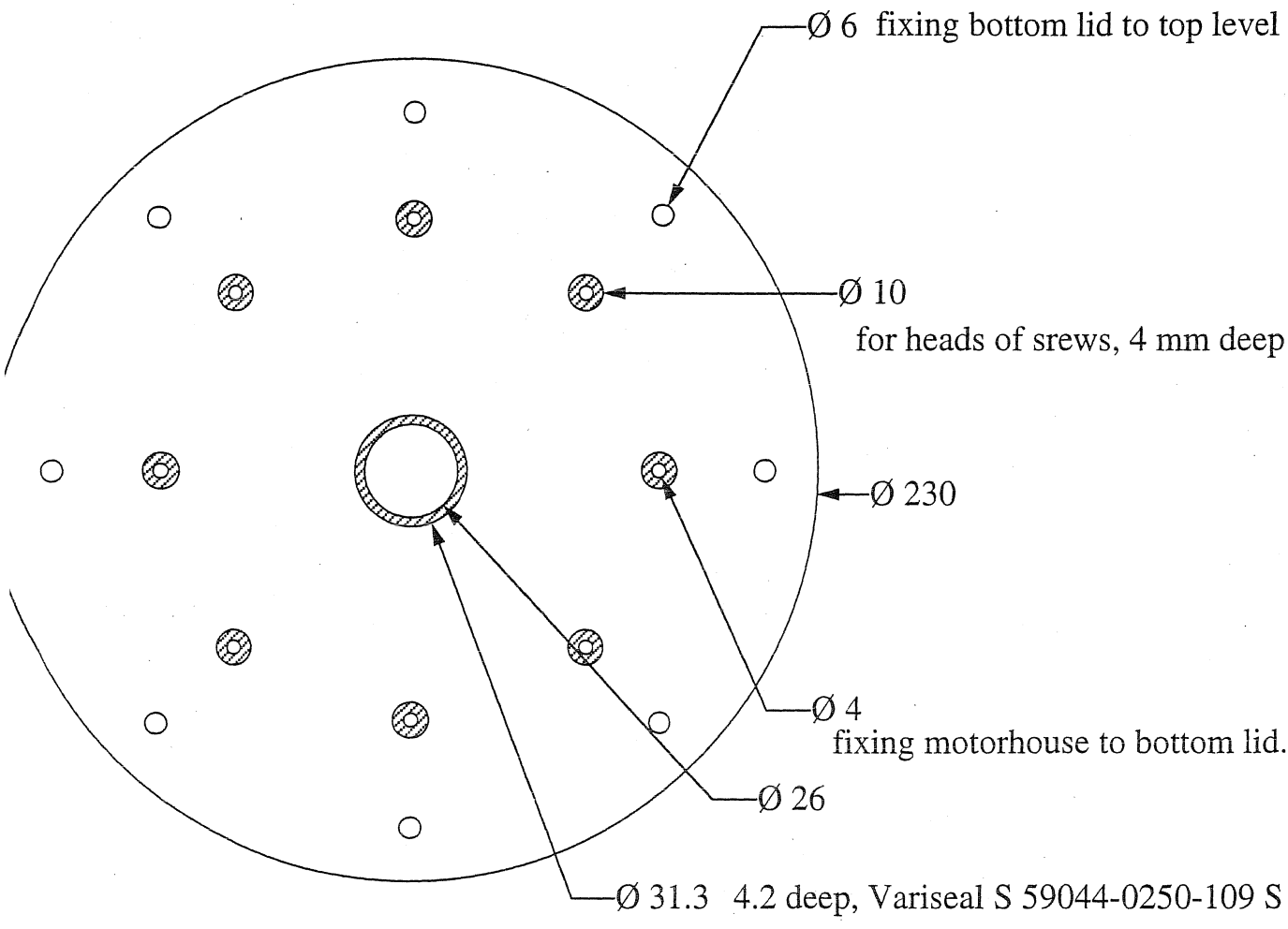


Side view

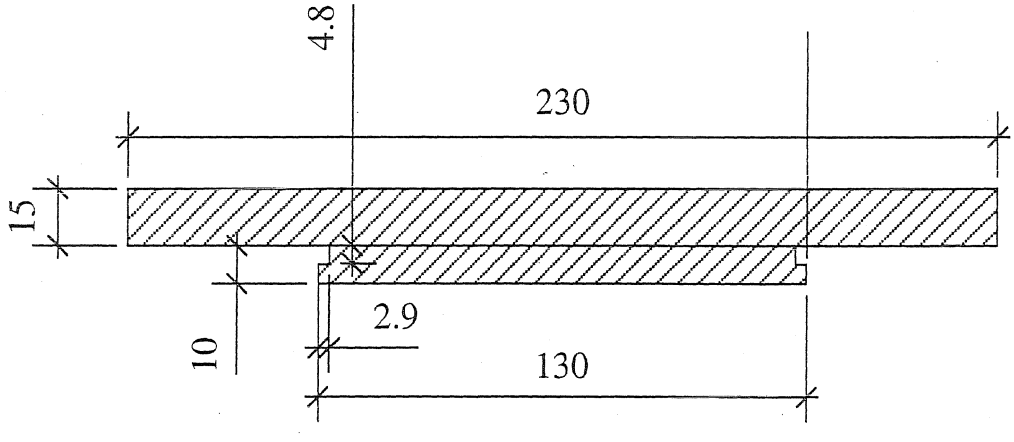


Part: bottom lid for big motorhouse		Nr: 2.3.4
Scale: 1:2	View(s): all	
Material: POM		Date: 22.1.97

Bottom view



de view

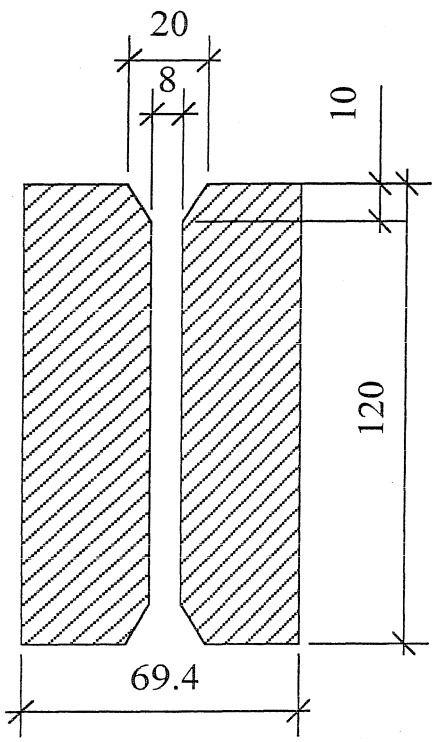


groove for o-ring (Parker 2-249)

Part: motorcovers		Nr: 2.3.5
Scale: 1:2	View(s): all	
Material:cast plexiglass (PMMA)	Date: 30.1.97	

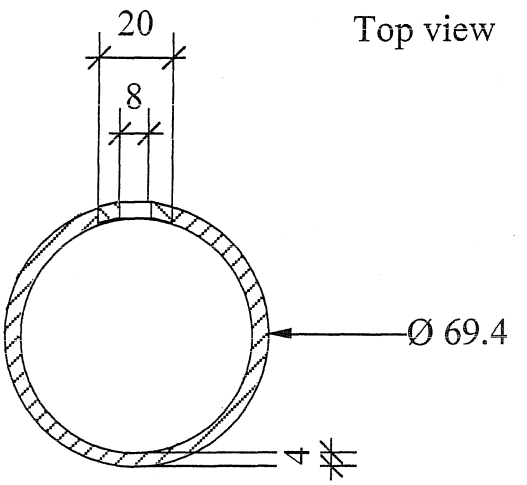
Cover for upper motor

Side view

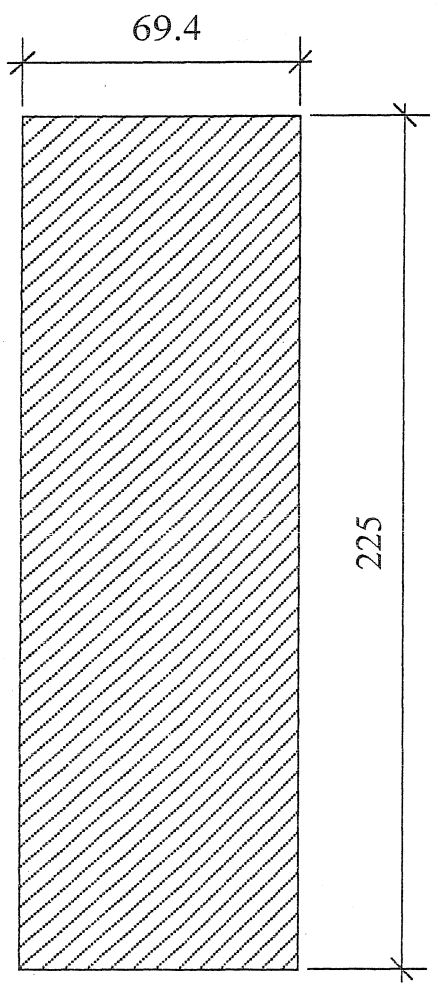


Note: slit takes up cables from motors to subconn connector

Top view

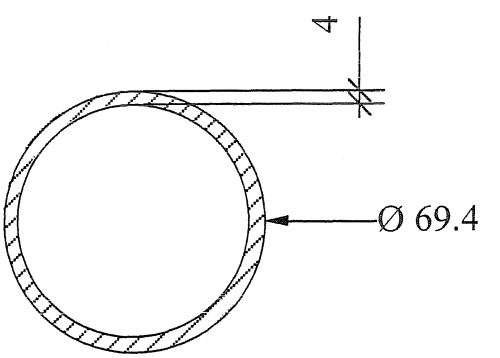


Cover for lower motor



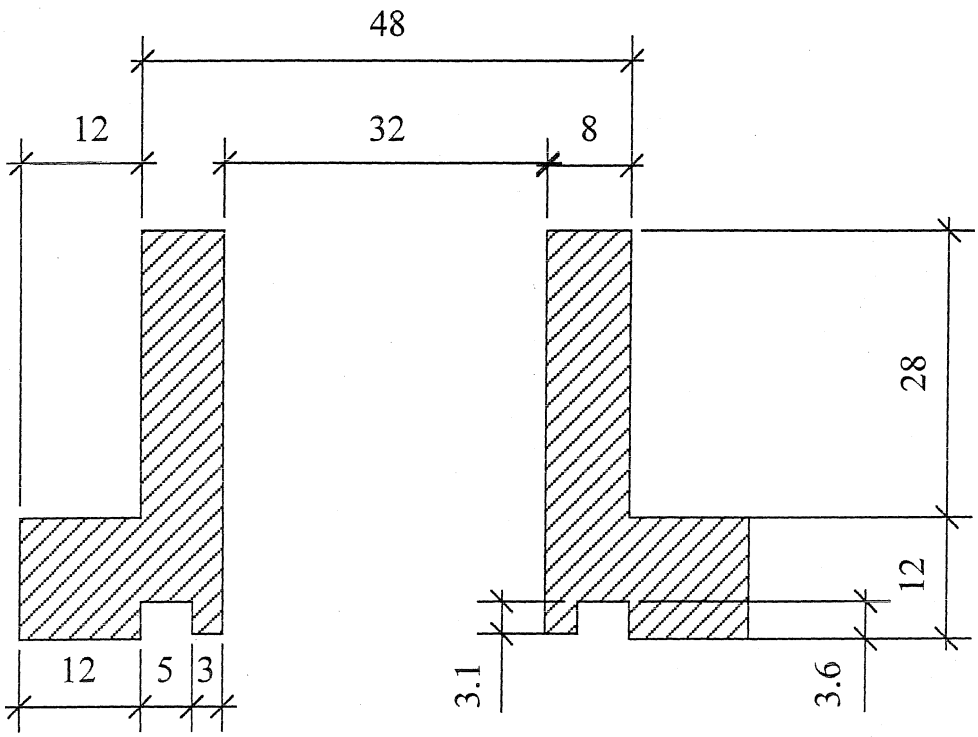
Side view

Top view

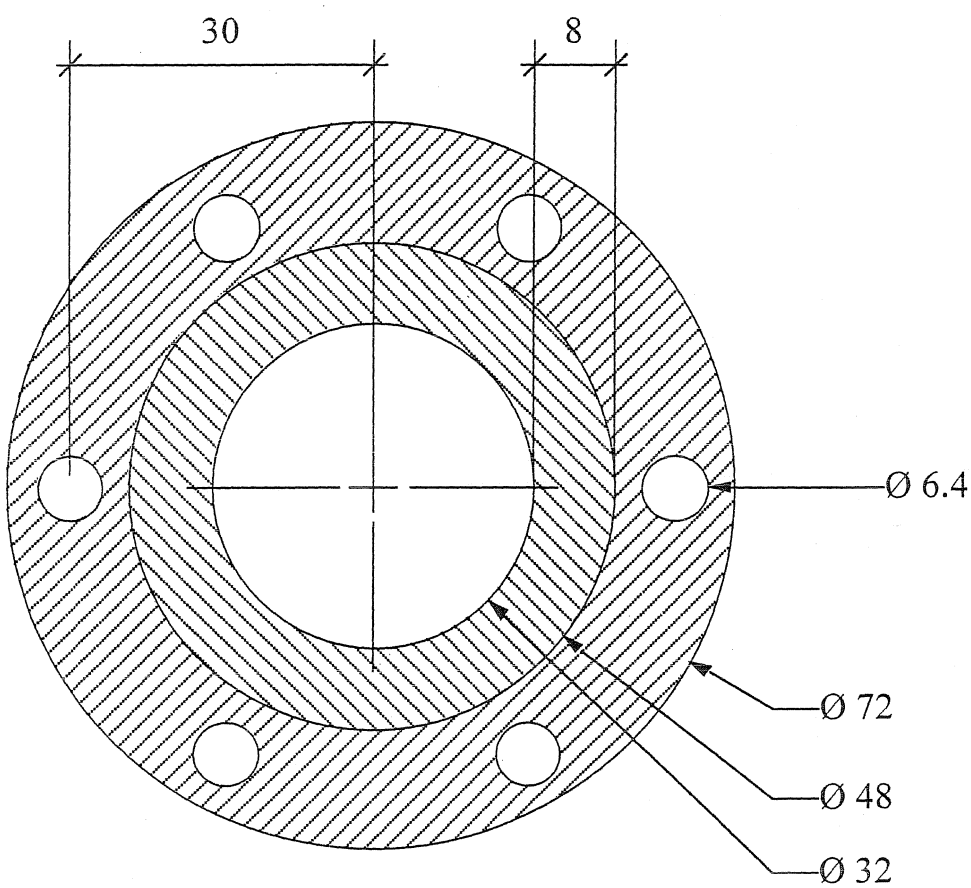


Part: membrane holder big motorhouse		Nr: 2.3.6
Scale: 1:0.75	View(s): all	
Material: POM		Date: 22.1.97

Center section

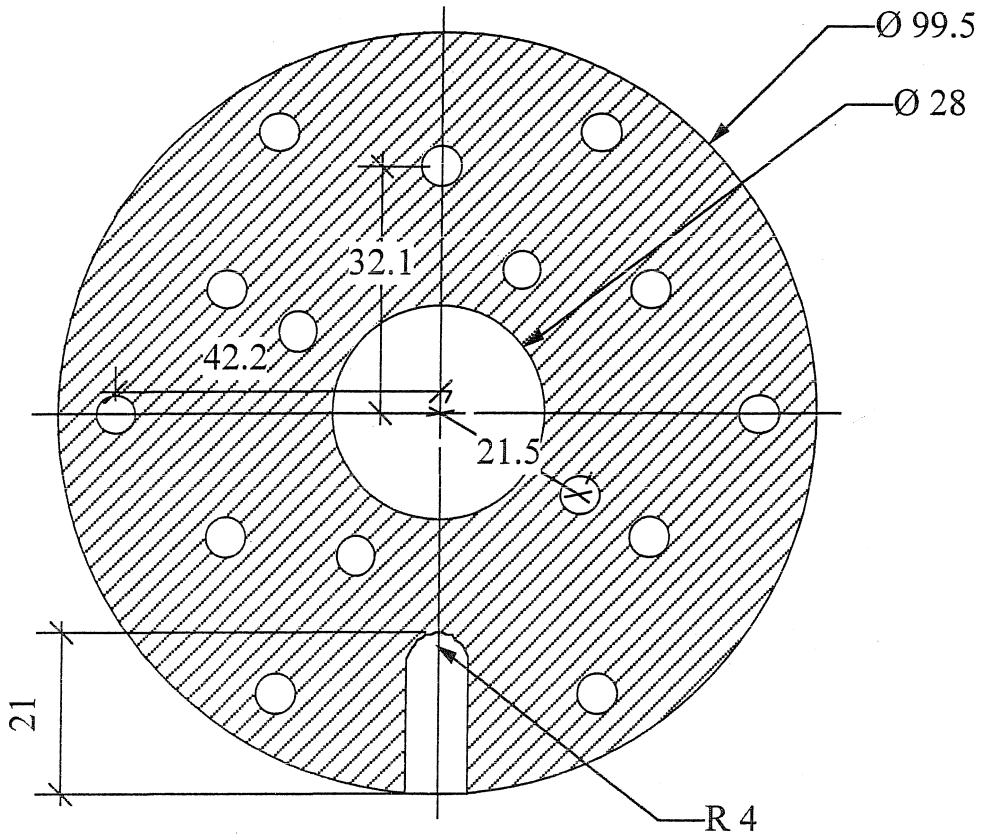


Top view

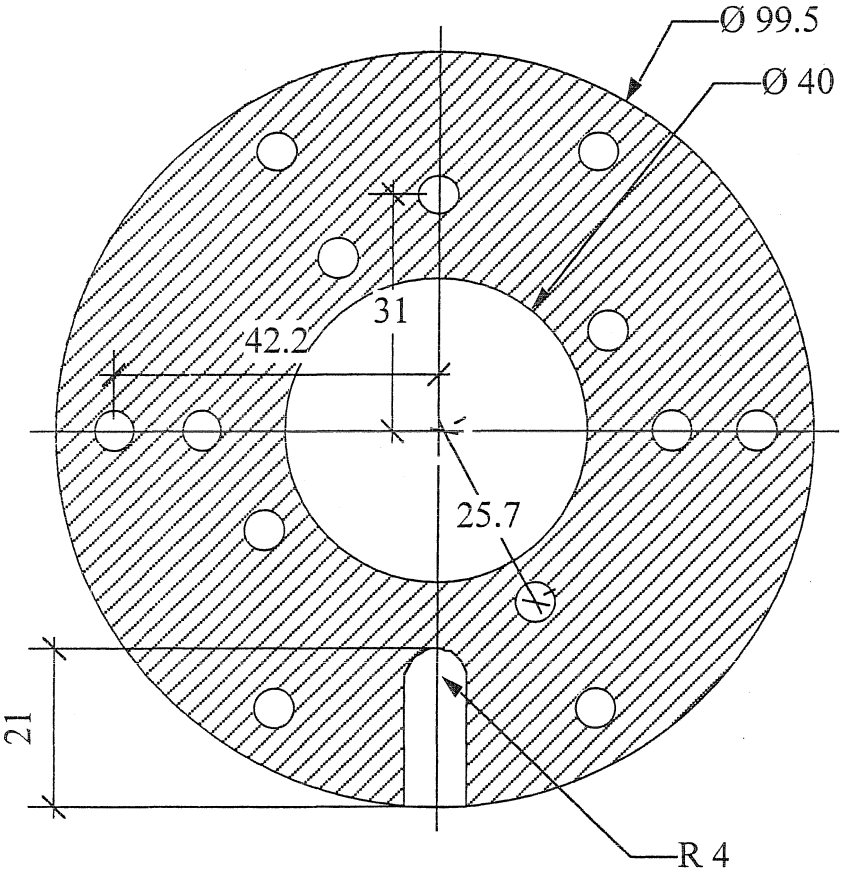


NOTE: all small holes 5.1 dia

Part: plates holding motors		Nr: 2.3.7
Scale: 1:1	View(s): top/bottom	
Material: 316-6 steel, 3.5 mm		Date: 29.1.97

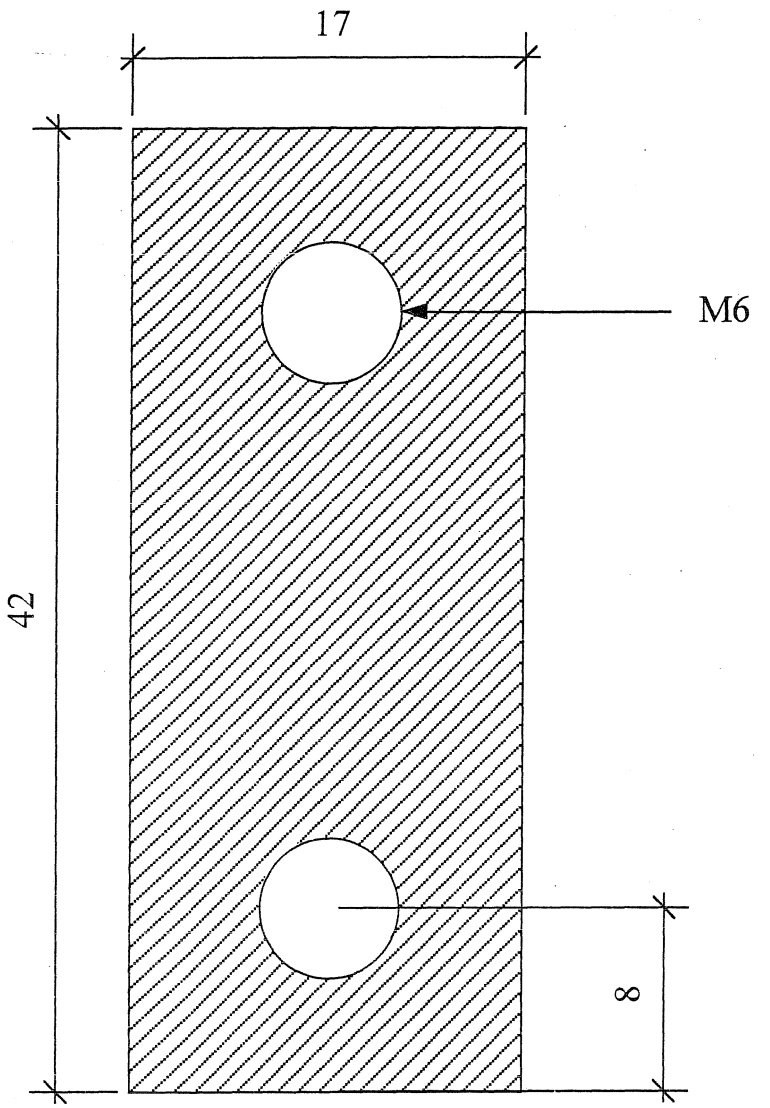


Top plate

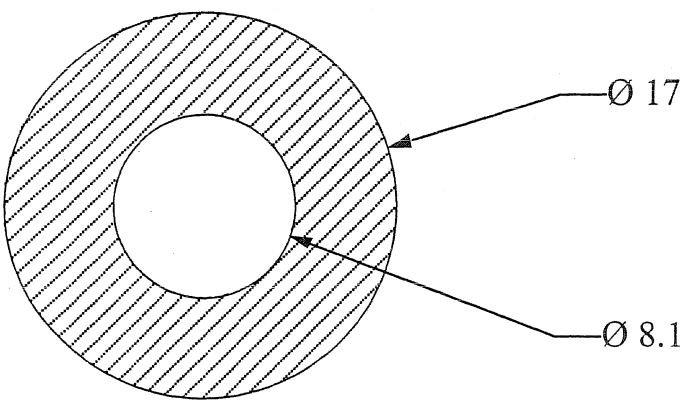


Bottom plate

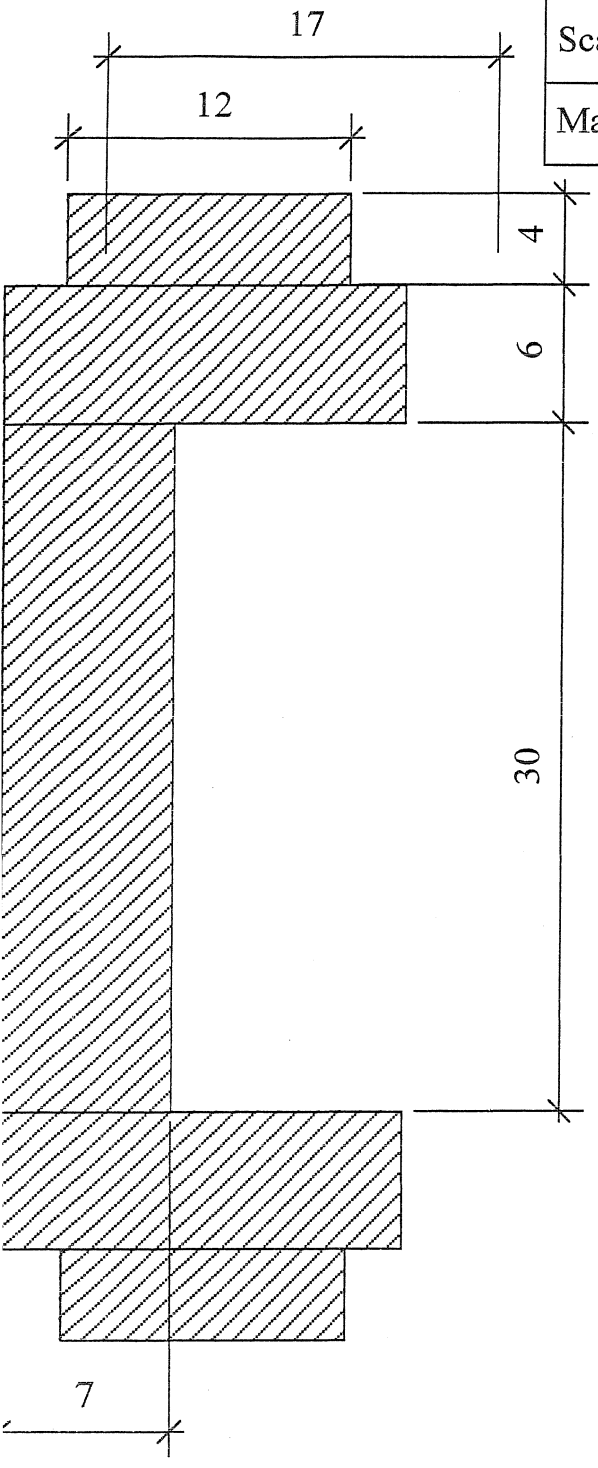
Part: axle to axle coupling		Nr: 2.3.8
Scale: 3:1	View(s): all	
Material: brass		Date: 29.1.97



Note: break edges

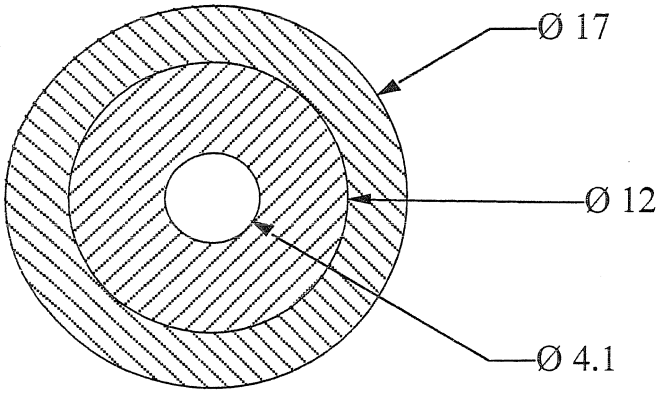


Part: connectors for motors		Nr: 2.3.9
Scale: 3:1	View(s): all	
Material: brass		Date: 29.1.97



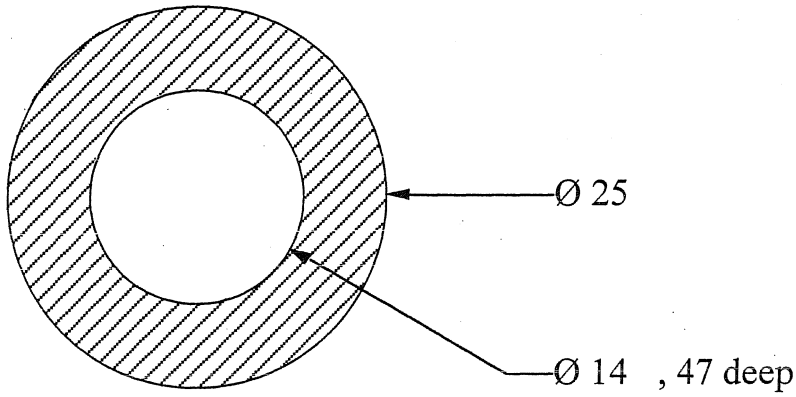
Side view

Top view

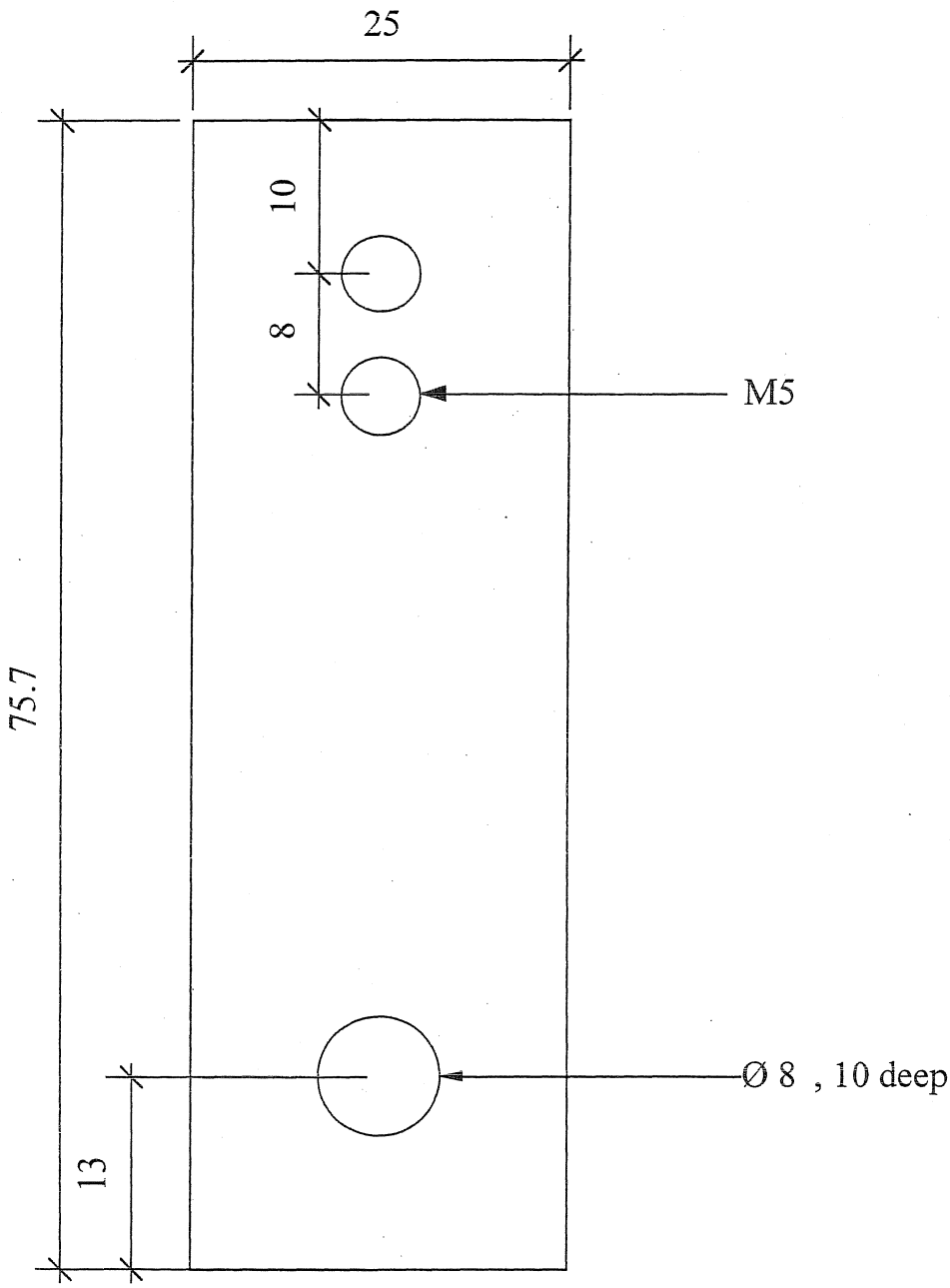


Part: Coupling on motor axle		Nr: 2.3.10
Scale: 2:1	View(s): all	
Material: 316-6 steel		Date: 29.1.97

Top view

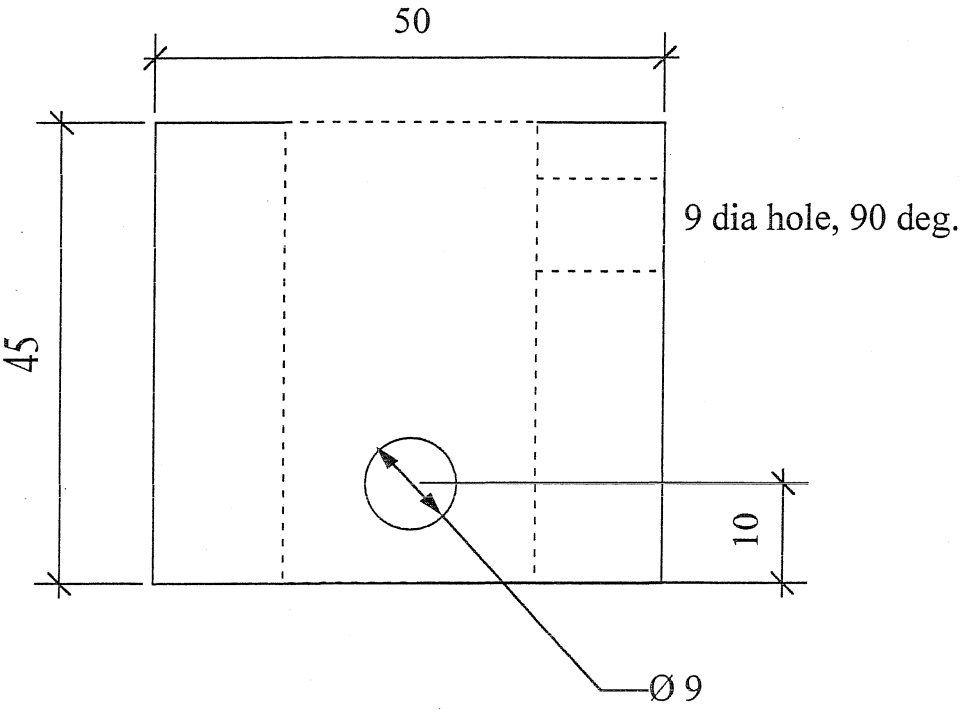


Side view

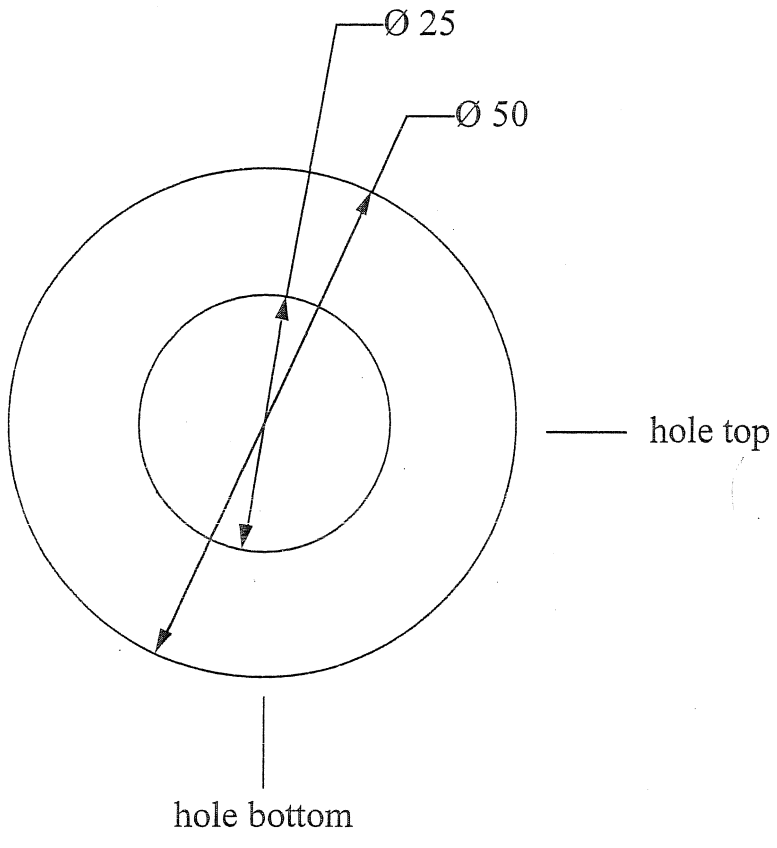


Part: Coupling motorhouse-spindlebar		Nr: 2.3.11
Scale: 1:0.75	View(s): all	
Material: 316-6 steel		Date: 20.1.97

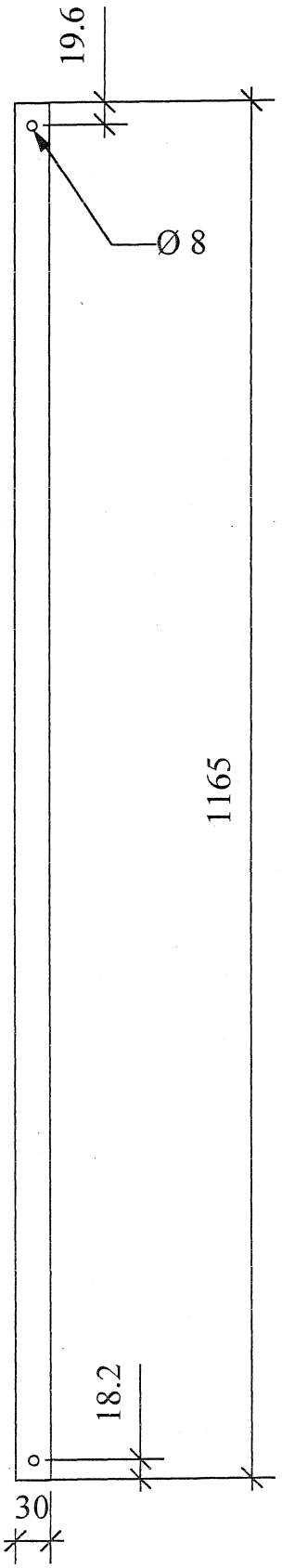
Side view



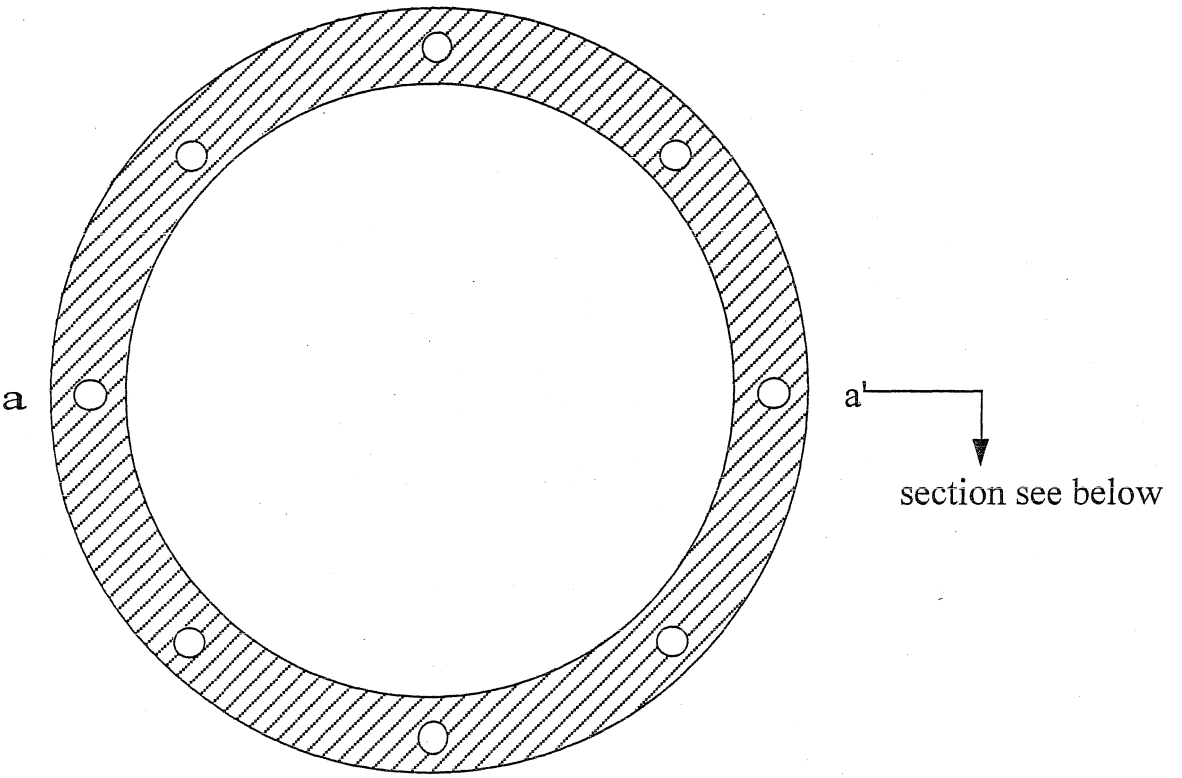
Top view

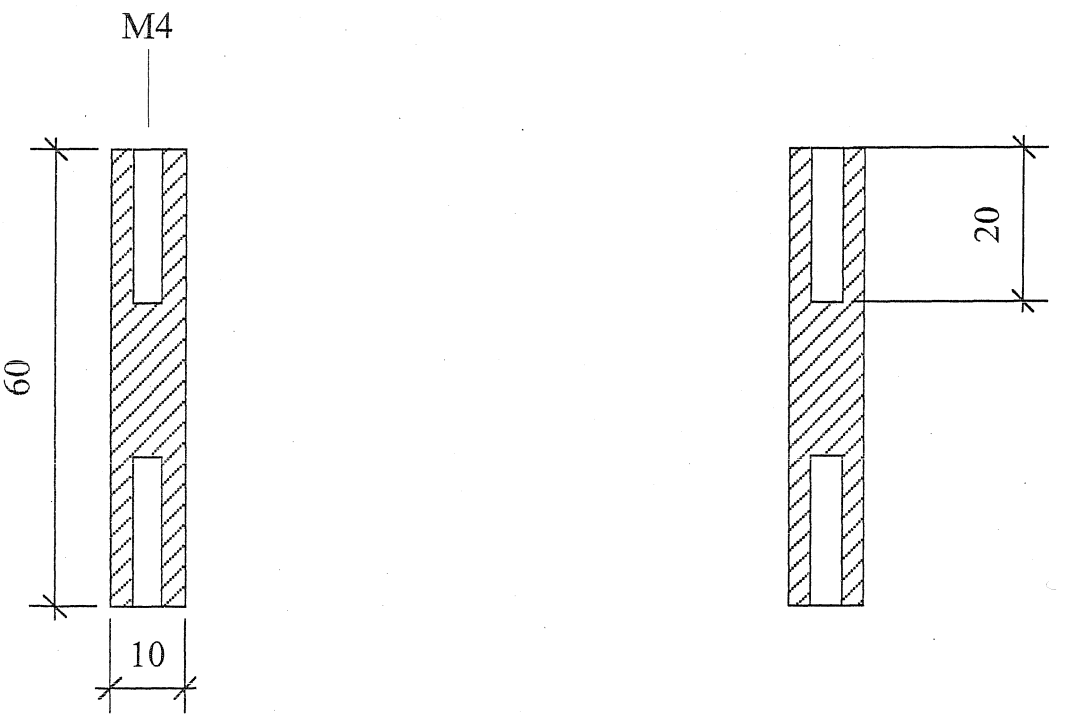


Part: Connecting tube to spindlebar		Nr: 2.3.12
Scale: 1:6	View(s): side	
Material: 316-6 steel, 30 * 3		Date: 23.1.97



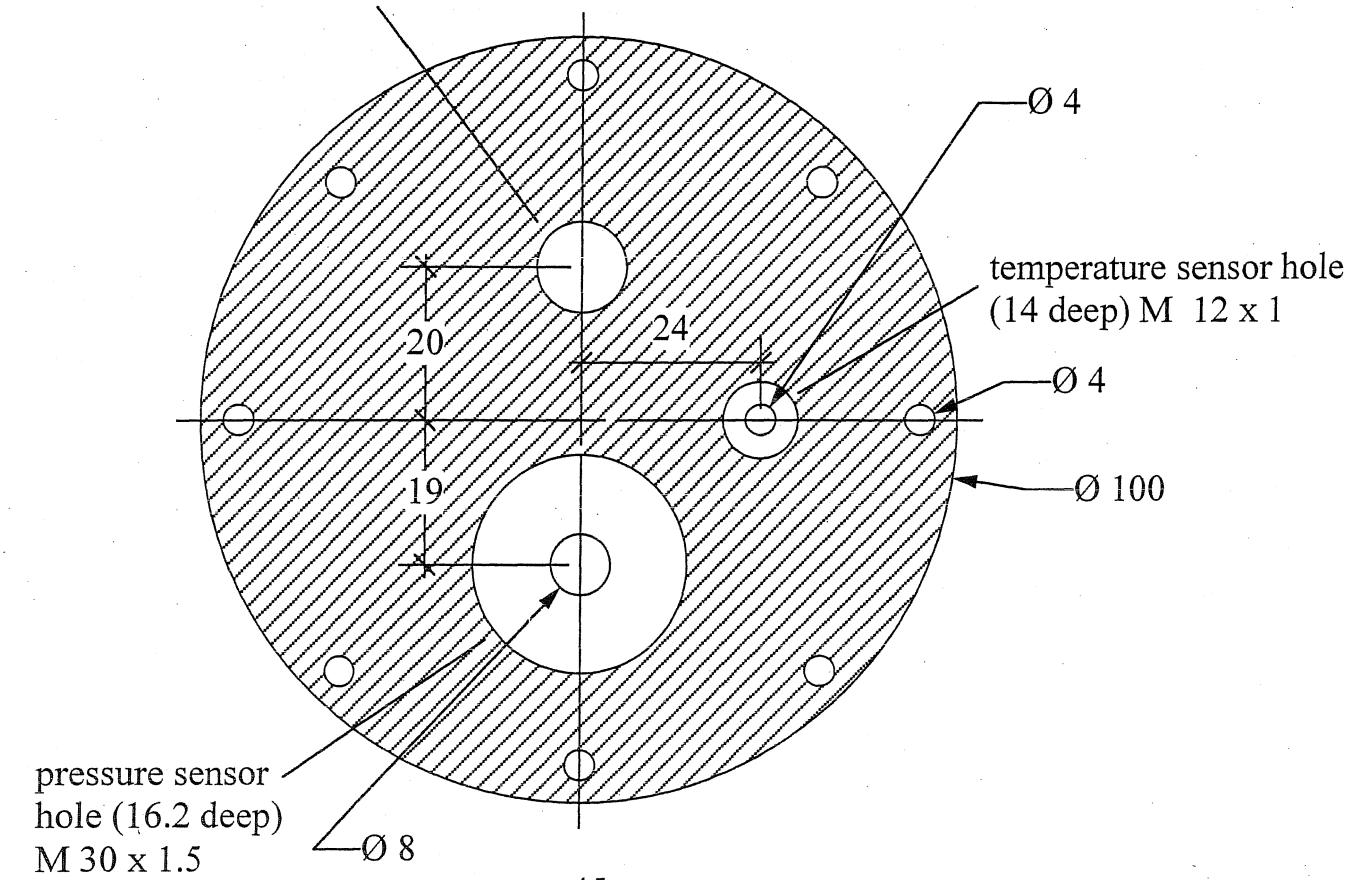
Part: Body of sensorhouse		Nr: 2.4.1
Scale: 1:1	View(s): all	
Material: cast plexiglass		Date: 20.1.97



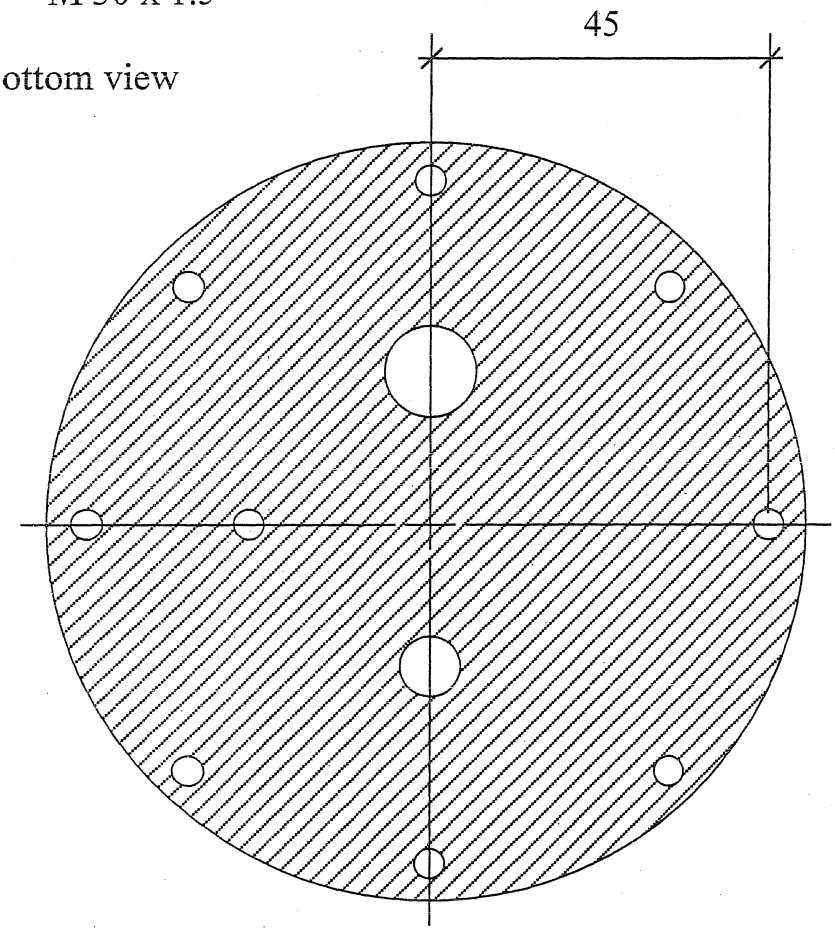


Part: top lid of sensorhouse		Nr: 2.4.2
Scale: 1:1	View(s): top/bottom	
Material: POM		Date: 20.1.97

Top view



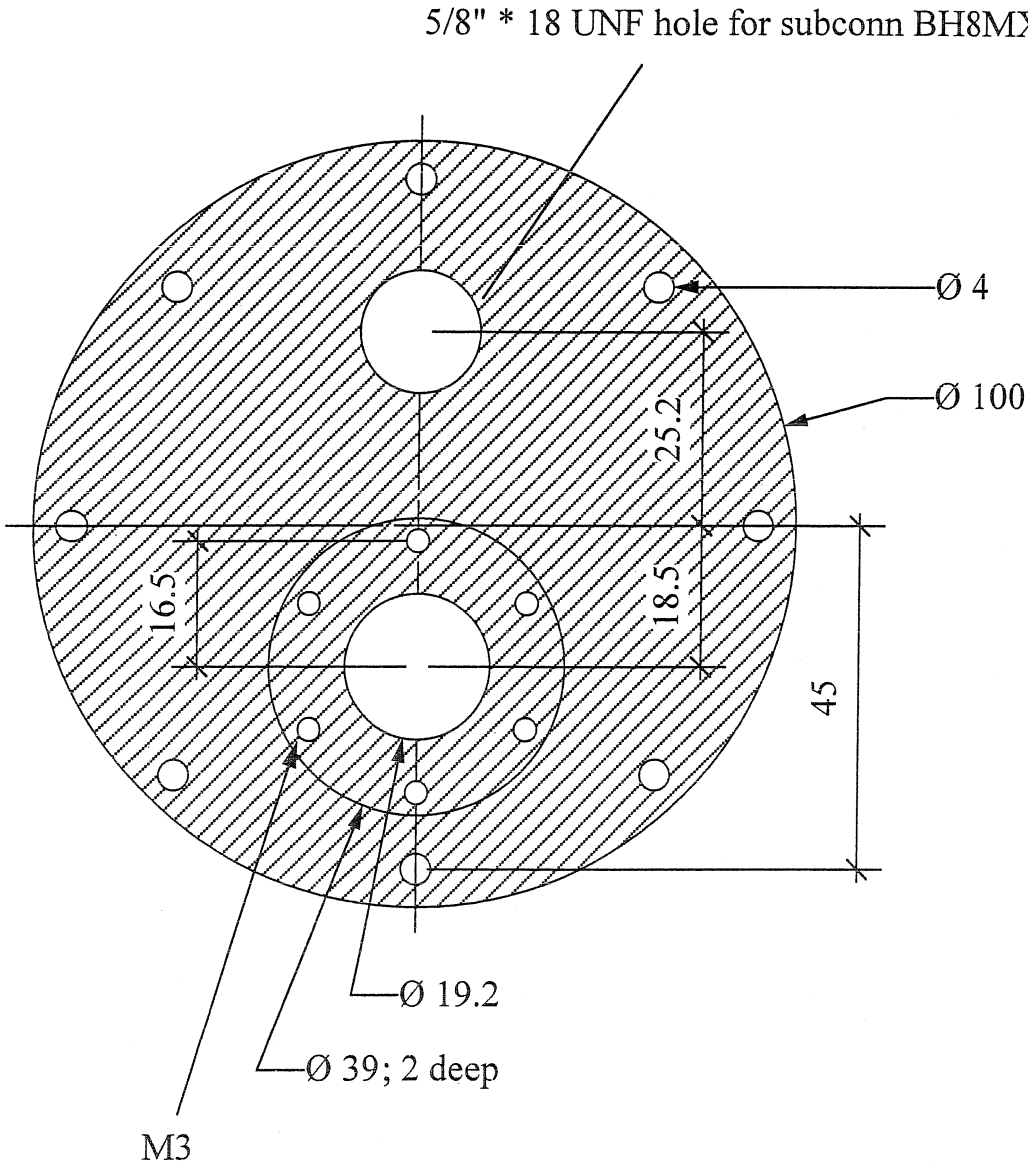
Bottom view



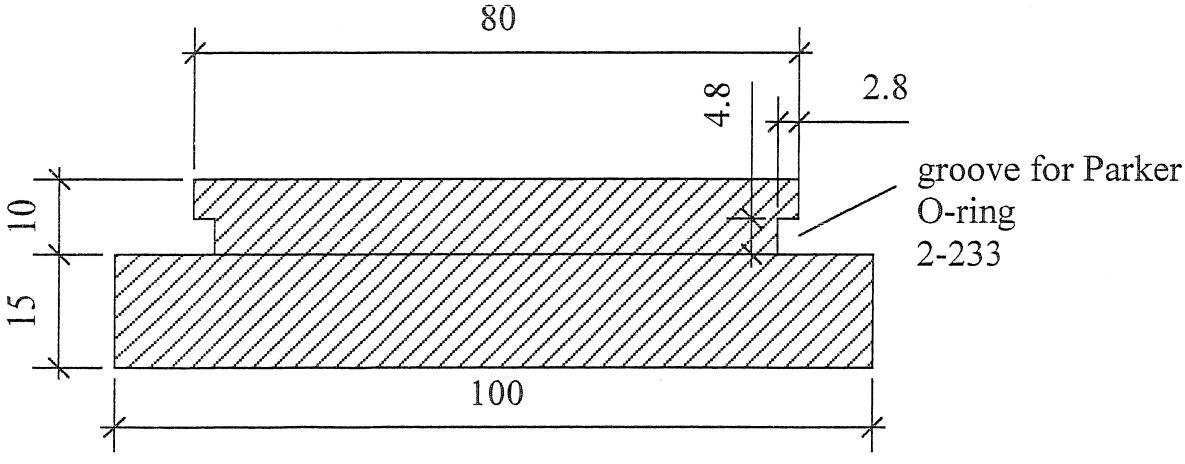
Note : Side view see bottom lid

Part: bottom lid of sensorhouse		Nr: 2.4.3
Scale: 1:1	View(s): all	
Material: POM		Date: 20.1.97

Top view

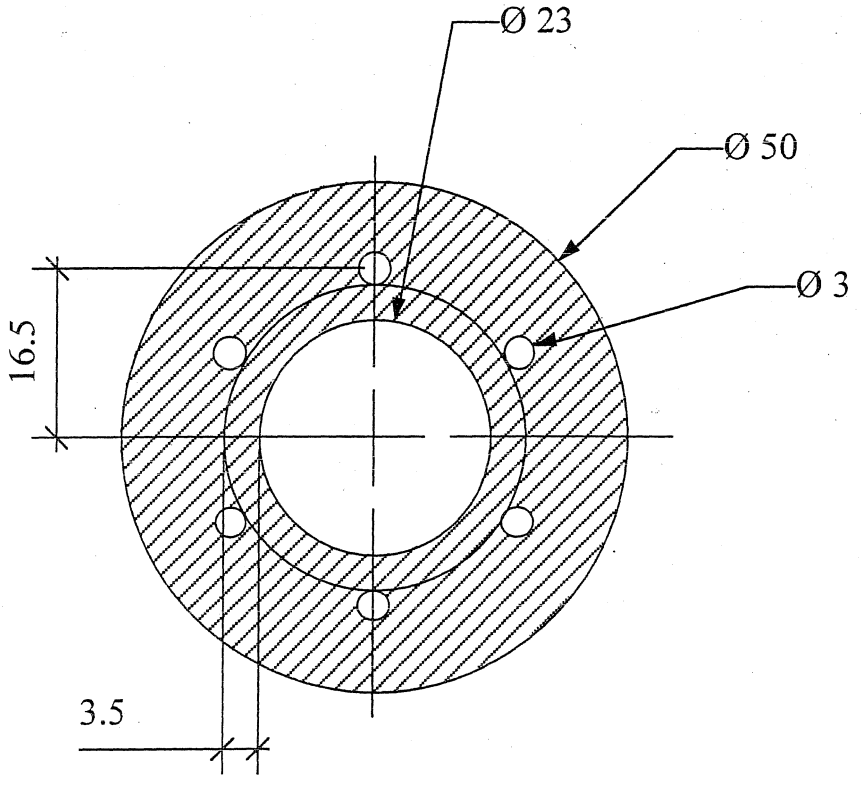


Side view

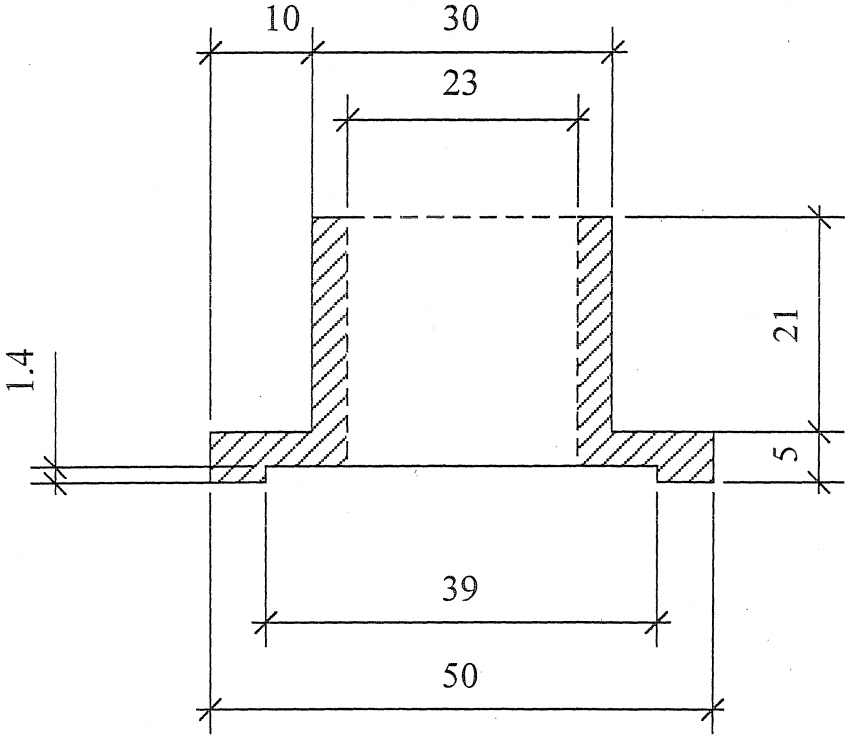


Part: Membrane holder sensorhouse		Nr: 2.4.4
Scale: 1:0,75	View(s): all	
Material: POM		Date: 22.1.97

Top view



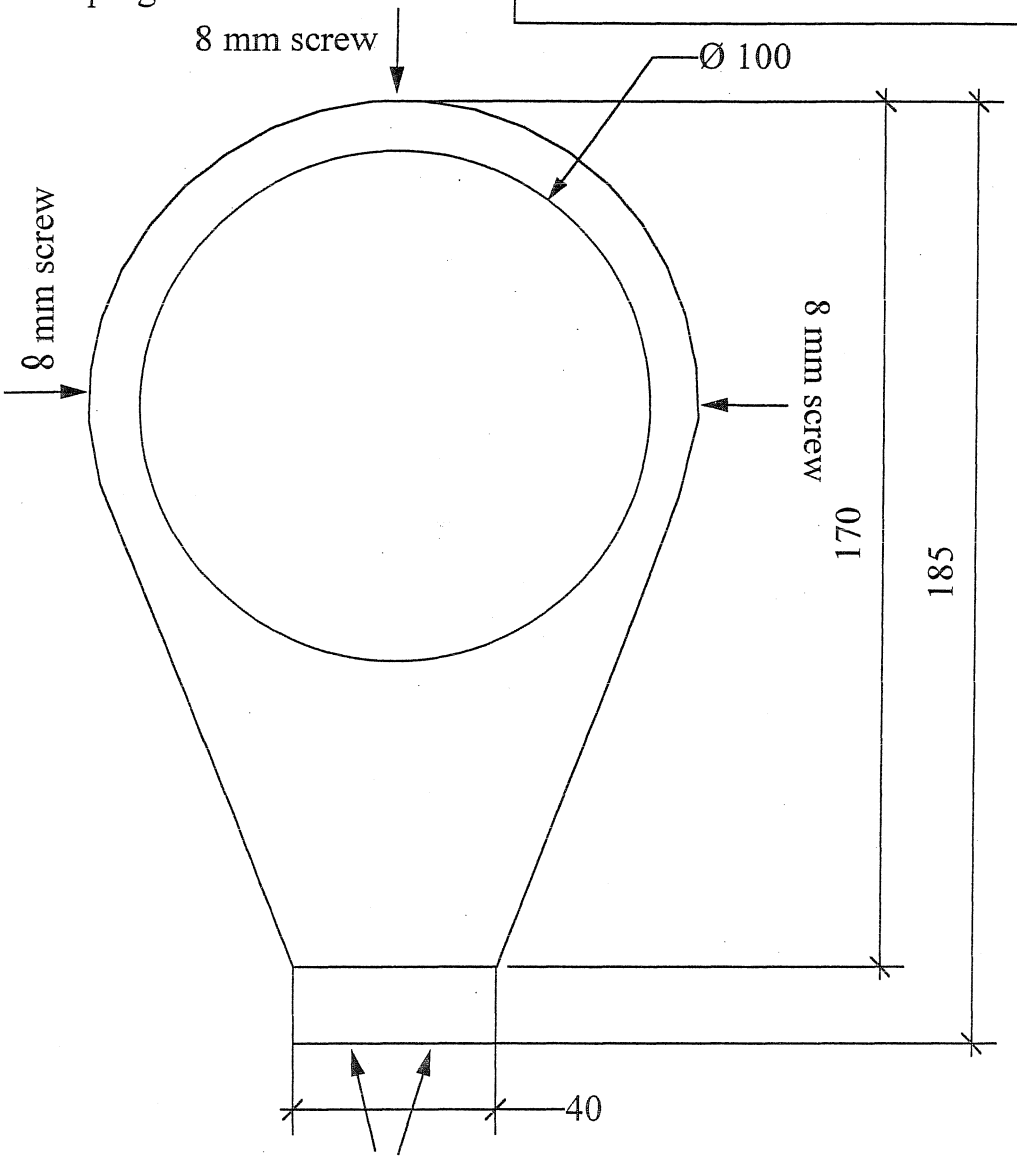
Side view



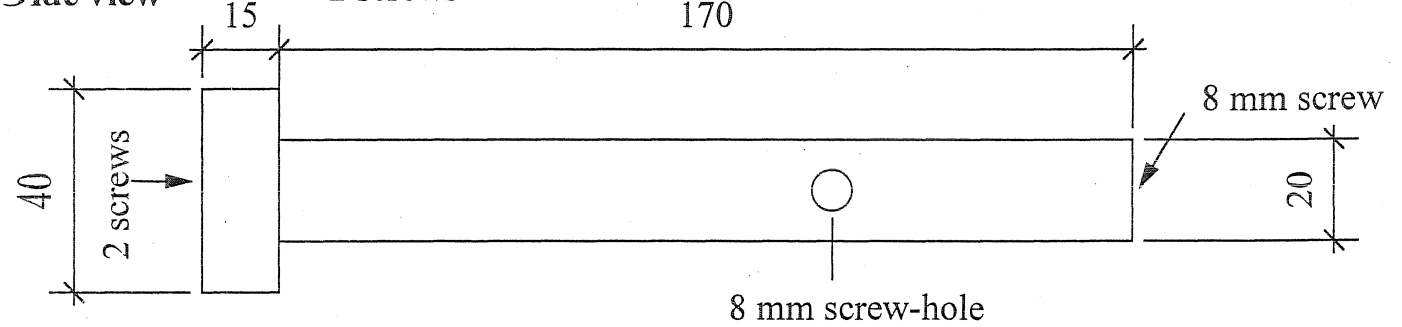
Part: Clamp holding sensorhouse		Nr: 2.4.5
Scale: 1:1.5	View(s): all	
Material: POM		Date: 20.1.97

Top view

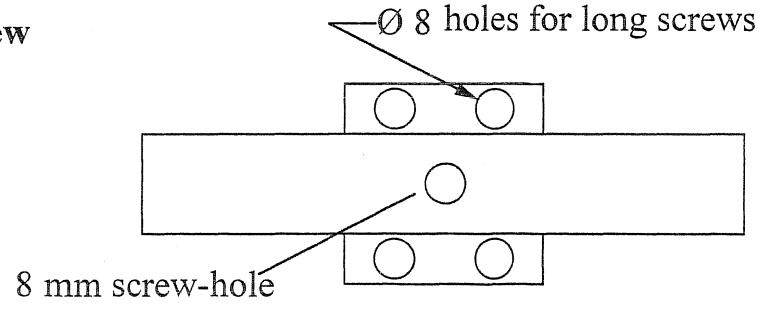
Note: the 3 screws hold the sensorhouse by clamping

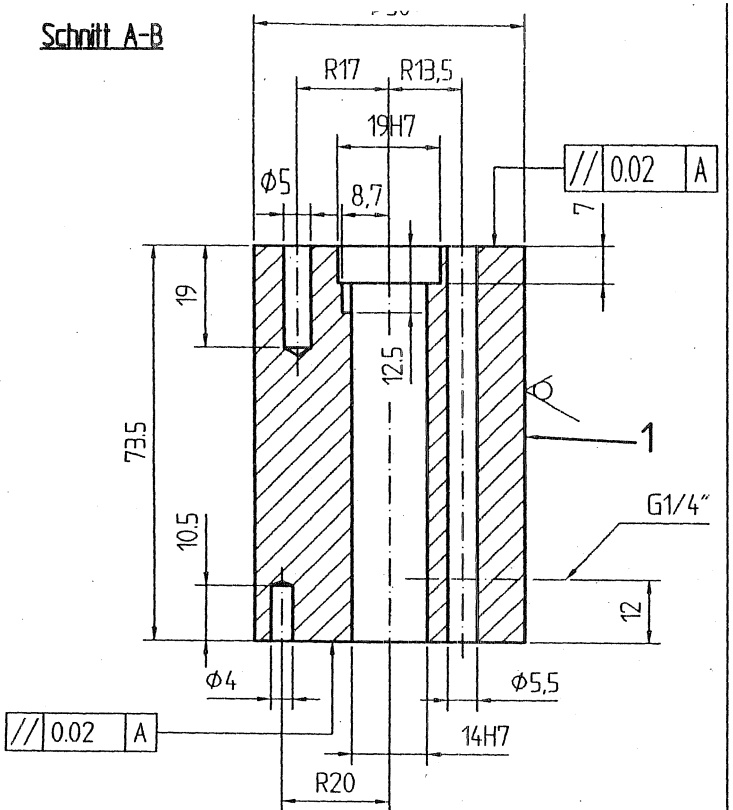


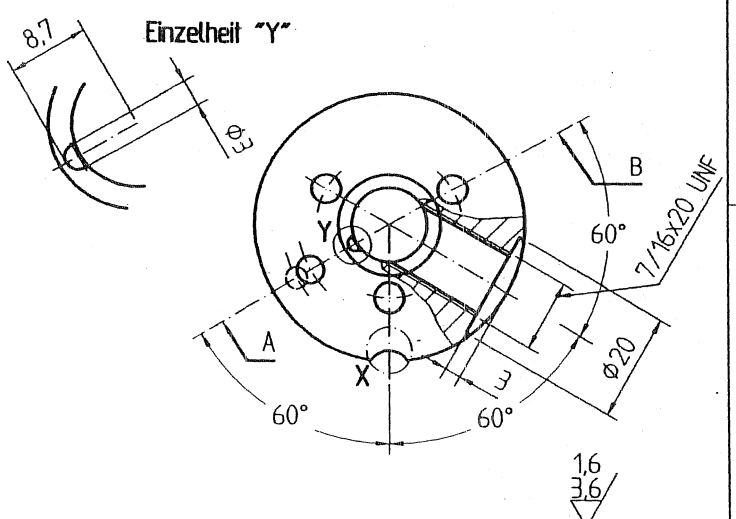
Side view

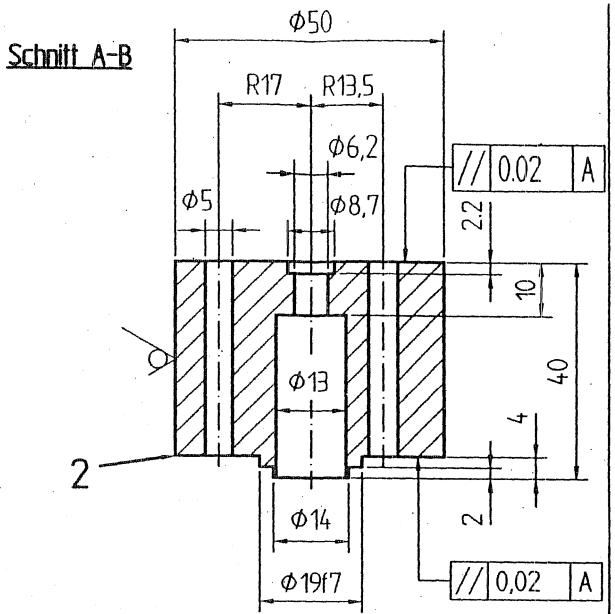


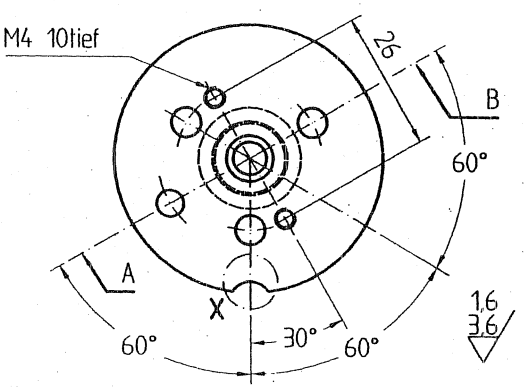
Front view

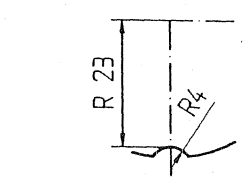




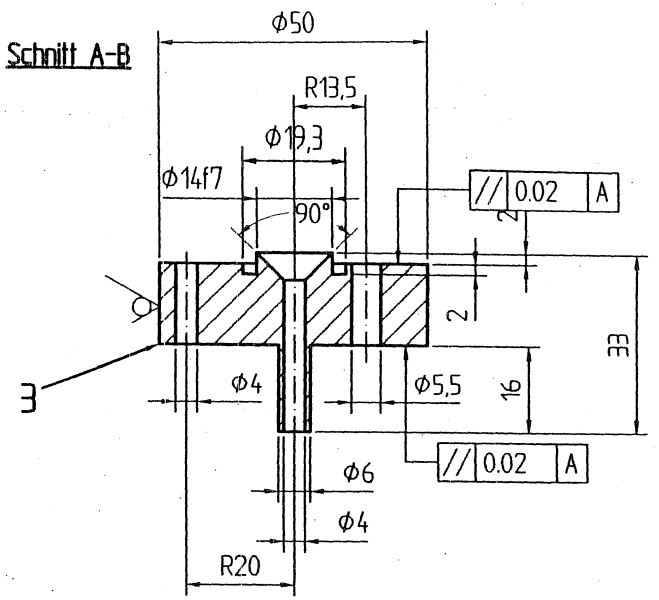


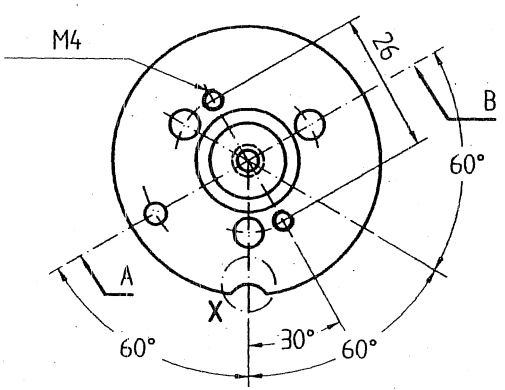






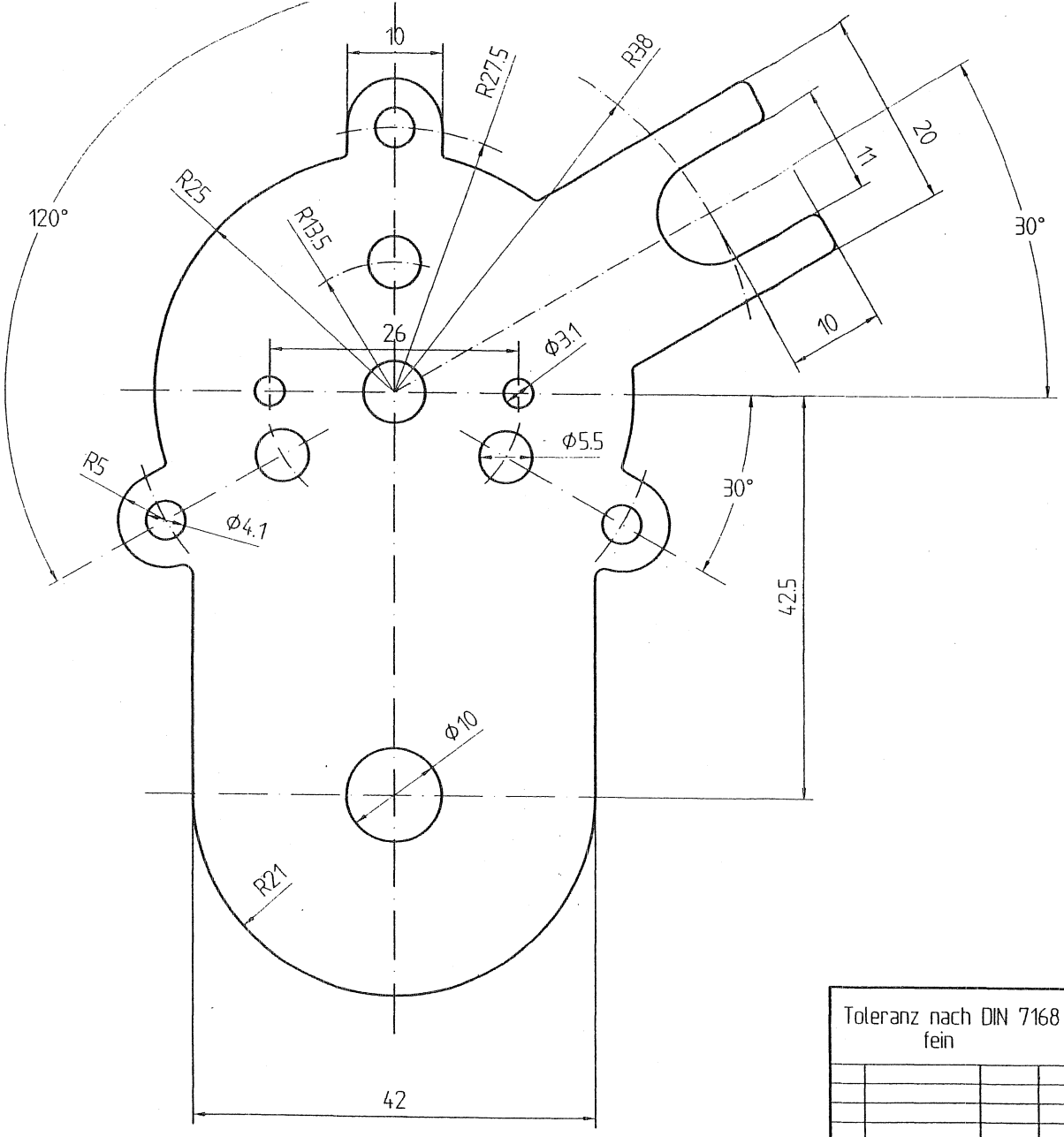
Einzelheit "X"



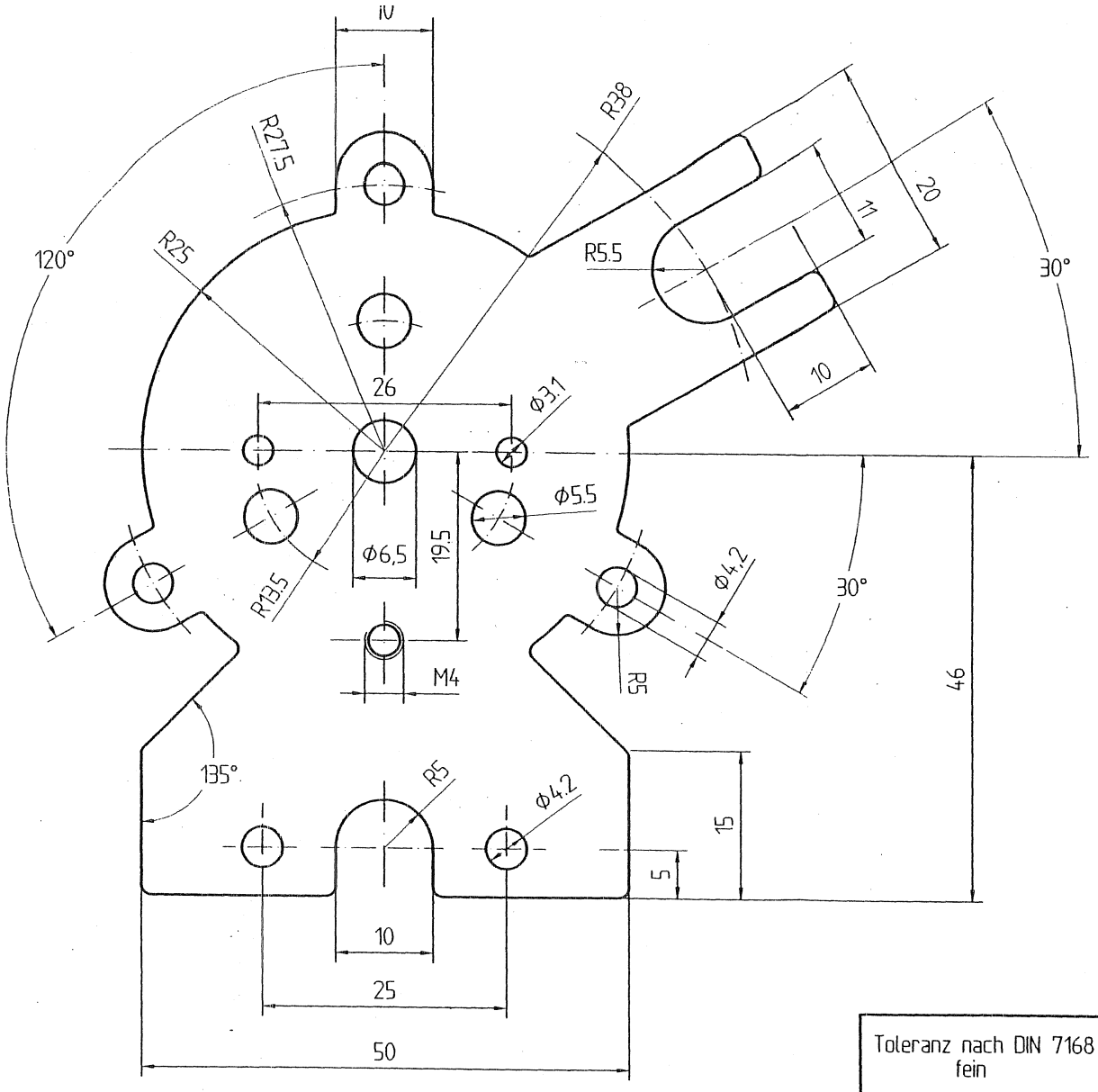


1,6
3,6

Toleranz nach DIN 7168 fein					Oberfläche	Maßstab 1 : 1	Position / Menge
						PMMA	
					Datum	Name	
				Bearb.	15.12.96	W.Pickl	Part: small motorhouse + sections
				Gepr.			
				Norm			
				MPI	Max-Plank-Institut für Marine Mikrobiologie		Nr.: 2.5.1
Zust.	Änderung	Datum	Name	EDV Nr.	max250		Blatt Bl

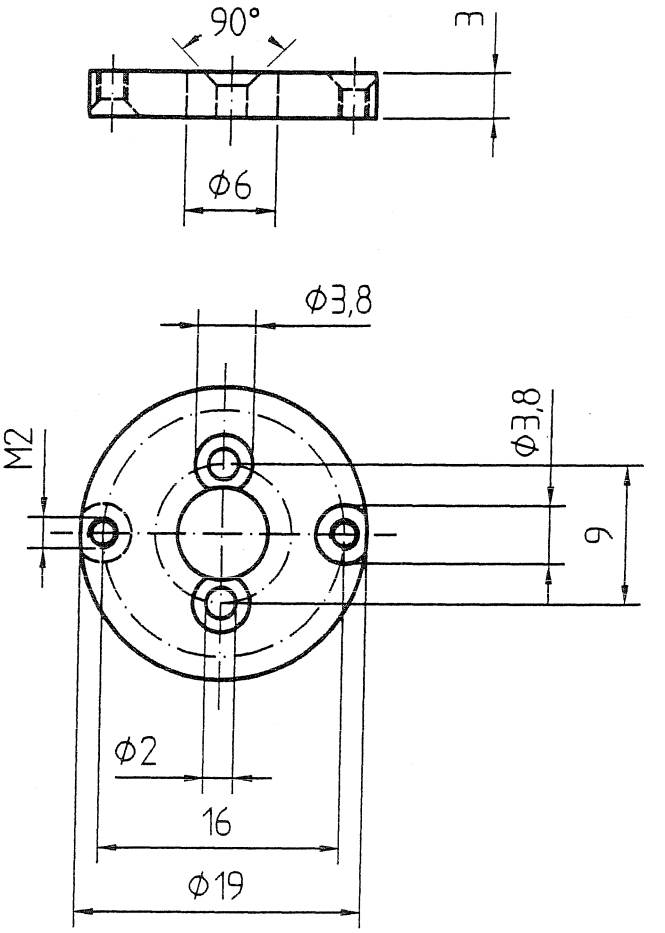


Toleranz nach DIN 7168 fein						Oberfläche	Maßstab 2 : 1
							Position / Menge
							V2A
					Datum	Name	
				Bearb.	11.12.96	W.Pickl	Part: lid plate, top
				Gepr.			
				Norm			
				MPI	Max-Plank-Institut für Marine Mikrobiologie		Nr.: 2.5.2
Zust.	Änderung	Datum	Name	EDV Nr.	max264		Blatt



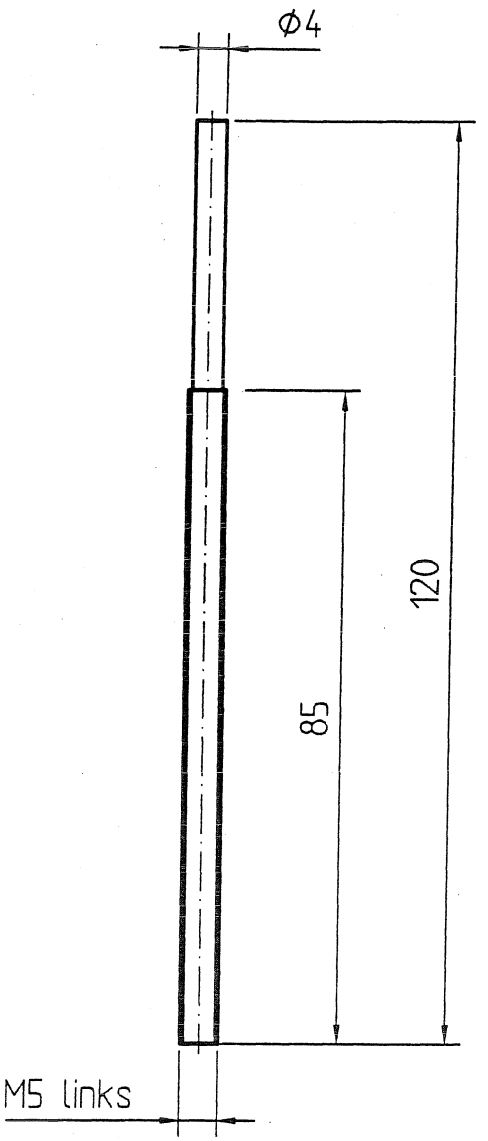
Toleranz nach DIN 7168 fein					Oberfläche	Maßstab 2 : 1	Position / Menge
						V2A	
					Datum	Name	
				Bearb.	19.12.96	W.Pickl	Part: lid plate, bottom
				Gepr.			
				Norm			
				MPI	Max-Plank-Institut für Marine Mikrobiologie		Nr.: 2.5.3
Zust.	Änderung	Datum	Name	EDV Nr.	max265		Blatt / Bl

8 7 6 5



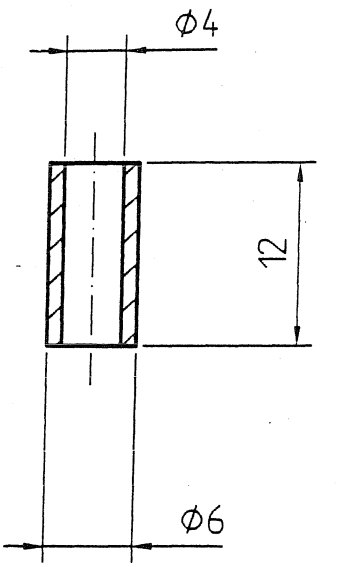
Toleranz nach DIN 7168 fein					Oberfläche	Maßstab 2 :1		Position	Menge
						Ms			
					Datum	Name	Part: motor fixing		
				Bearb.	02.01.97	W.Pickl			
				Gepr.					
				Norm					
				MPI	Max-Plank-Institut für Marine Mikrobiologie		Nr.: 2.5.4		Blatt
									Bl
Zust.	Änderung	Datum	Name	EDV Nr.	max256				

Gewindestange



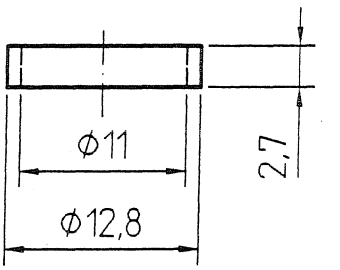
Werkstoff: 1.4571
Maßstab: 1 : 1

Hülse



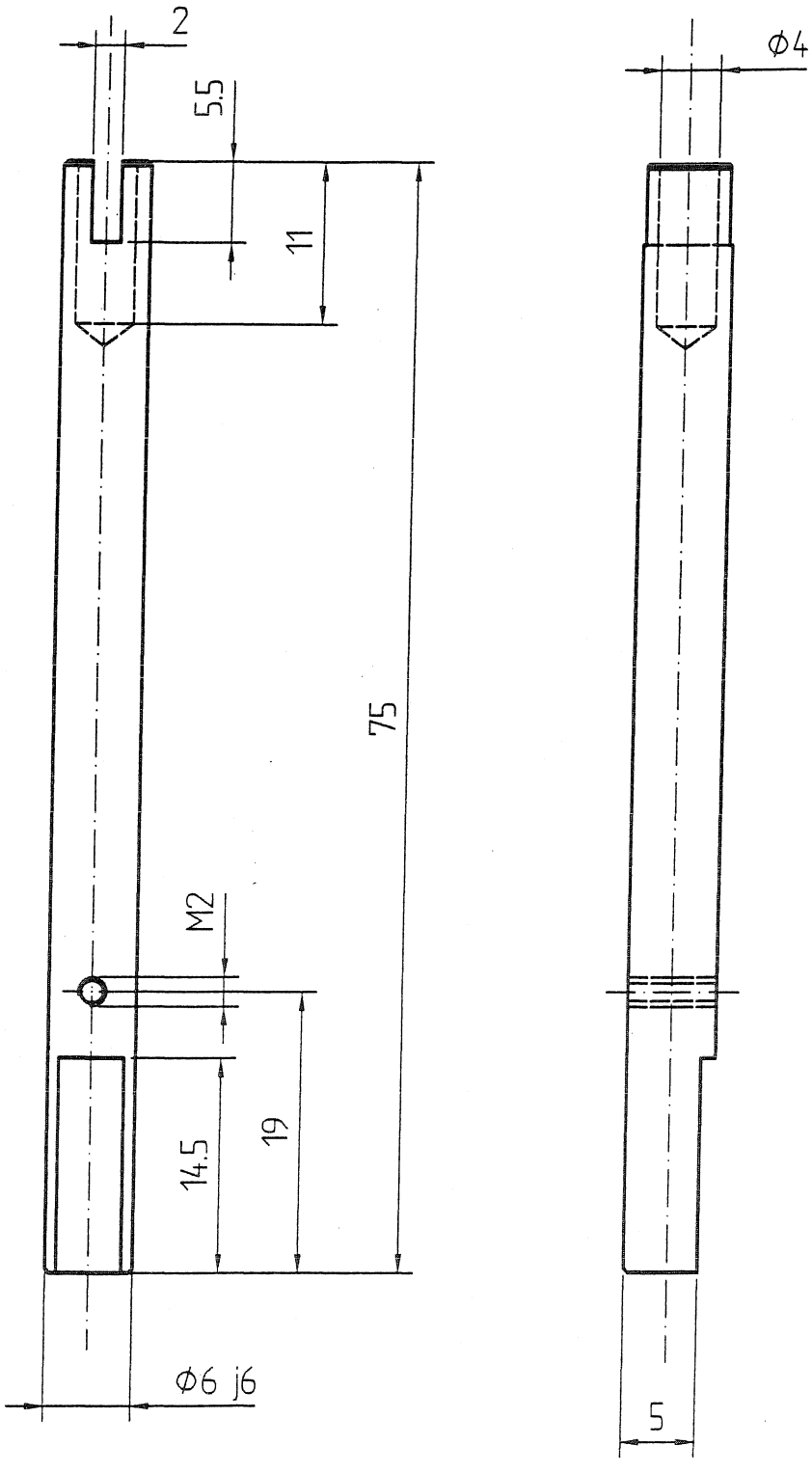
Werkstoff: 1.4571
Maßstab: 2 : 1

Ring



Werkstoff: Ms
Maßstab: 2 : 1

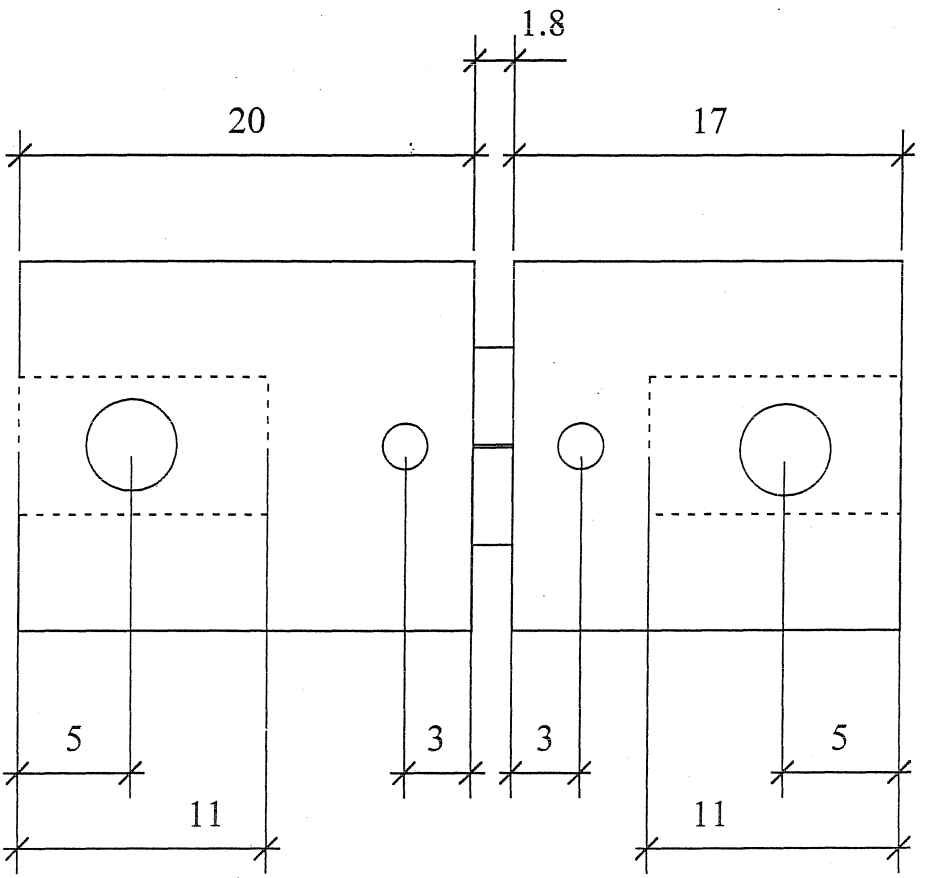
Toleranz nach DIN 7168 fein					Oberfläche	Maßstab	Position	Menge	
					Datum	Name			
				Bearb.	20.12.96	W.Pickl	Part: spindlebar		
				Gepr.					
				Norm					
				MPI	Max-Plank-Institut für Marine Mikrobiologie		Nr.: 2.5.5		Blatt
Zust.	Änderung	Datum	Name	EDV Nr.	max267				Bl.



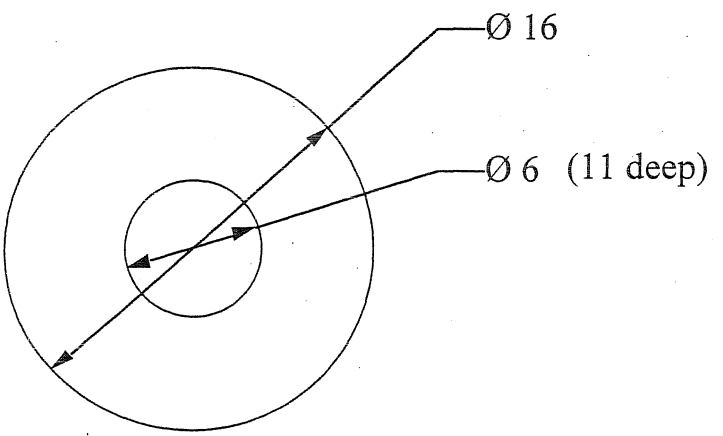
Toleranz nach DIN 7168 fein					Oberfläche	Maßstab 2 : 1		Position	Menge
						V2a			
					Datum	Name	Part: axle		
				Bearb.	13.01.97	W.Pickl			
				Gepr.					
				Norm					
				MPI	Max-Plank-Institut für Marine Mikrobiologie		Nr.: 2.5.6		Blatt
									Bl
Zust.	Änderung	Datum	Name	EDV Nr.	max268				

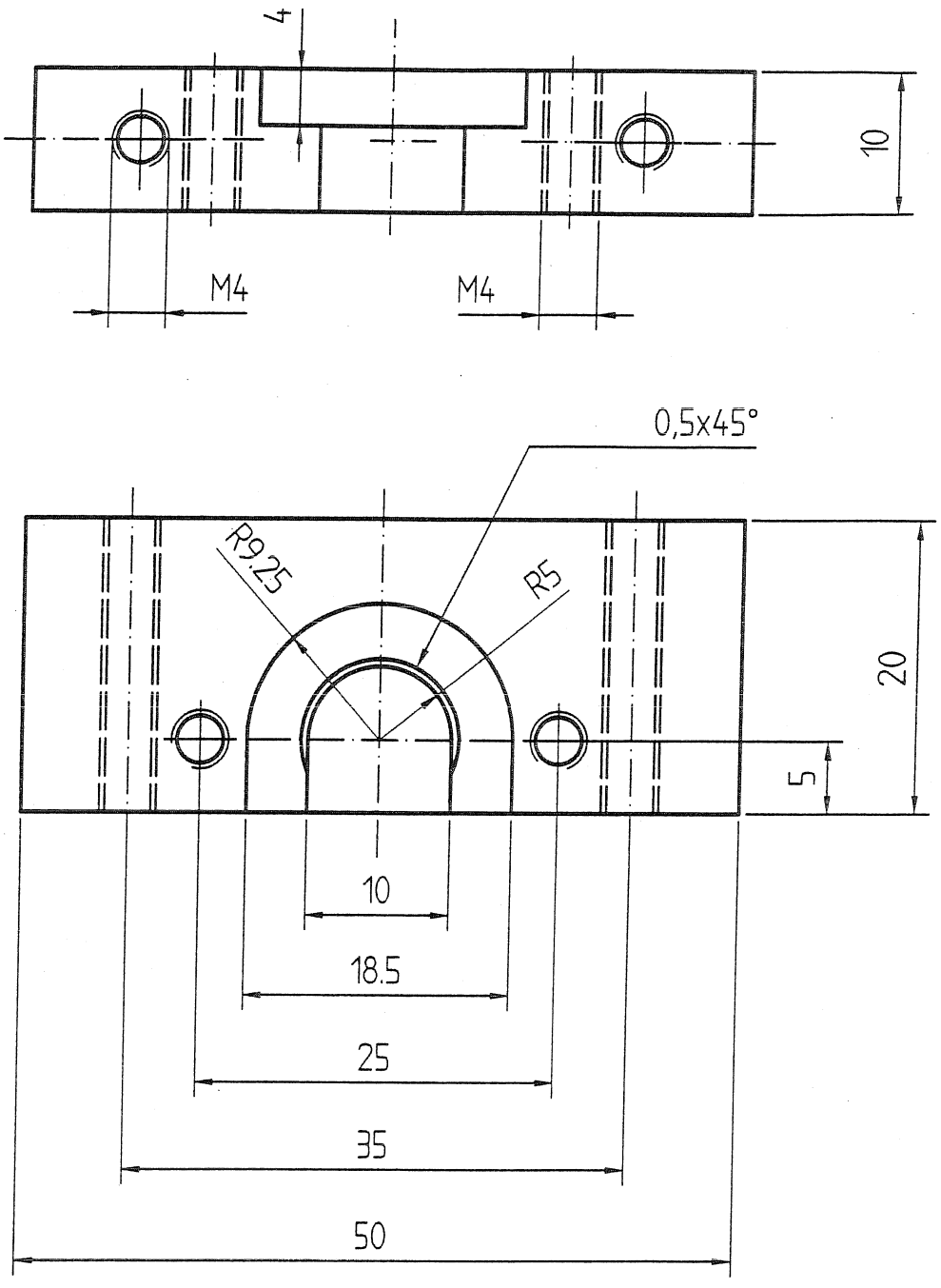
Part: coupling to spindlebar		Nr: 2.5.7
Scale: 1:0.33	View(s): all	
Material: 316-6 steel		Date: 20.1.97

Side view

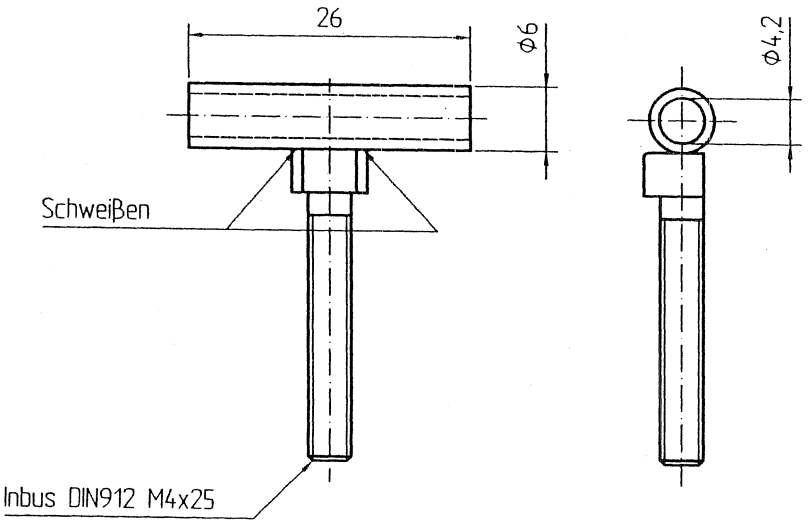


Top view

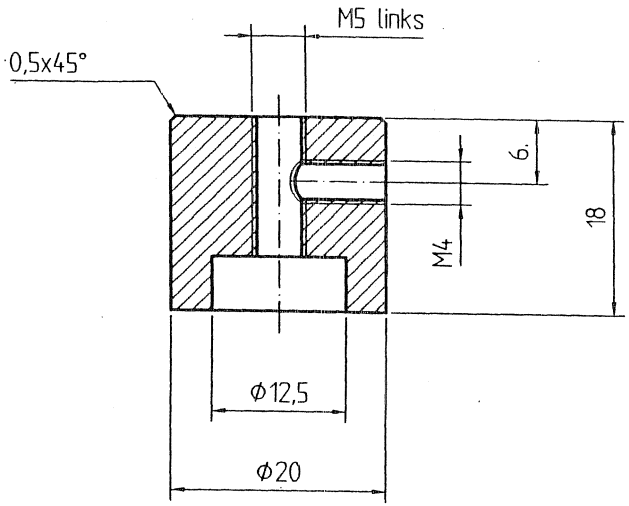




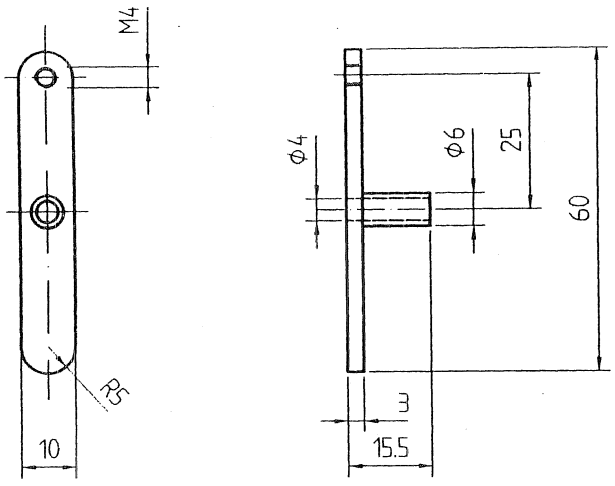
Toleranz nach DIN 7168 fein					Oberfläche	Maßstab 2 : 1	Position	Menge	
						PMMA			
					Datum	Name			
				Bearb.	18.12.96	W.Pickl	Part: syringe holder		
				Gepr.					
				Norm					
				MPI	Max-Plank-Institut für Marine Mikrobiologie		Nr.: 2.5.8		Blatt
									Bl.
Zust.	Änderung	Datum	Name	EDV Nr.	max263				



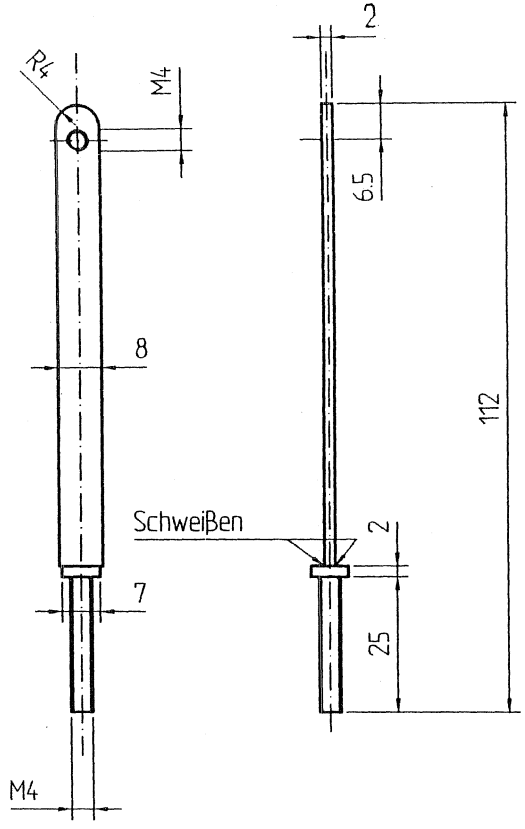
Toleranz nach DIN 7168 fein		Oberfläche -	Maßstab 2 : 1	Position	Menge
			V2A		
	Datum	Name			
Bearb.	20.12.96	W.Pickl	Part: syringe plunger		
Gepr.					
Norm					
MPI Max-Plank-Institut für Marine Mikrobiologie			Nr.: 2.5.9		Blatt



Toleranz nach DIN 7168 fein		Oberfläche	Maßstab 2 : 1	Position	Menge
			POM		
	Datum	Name			
Bearb.	06.01.97	W.Pickl			
Gepr.					
Norm					
MPI Max-Plank-Institut für Marine					Blatt



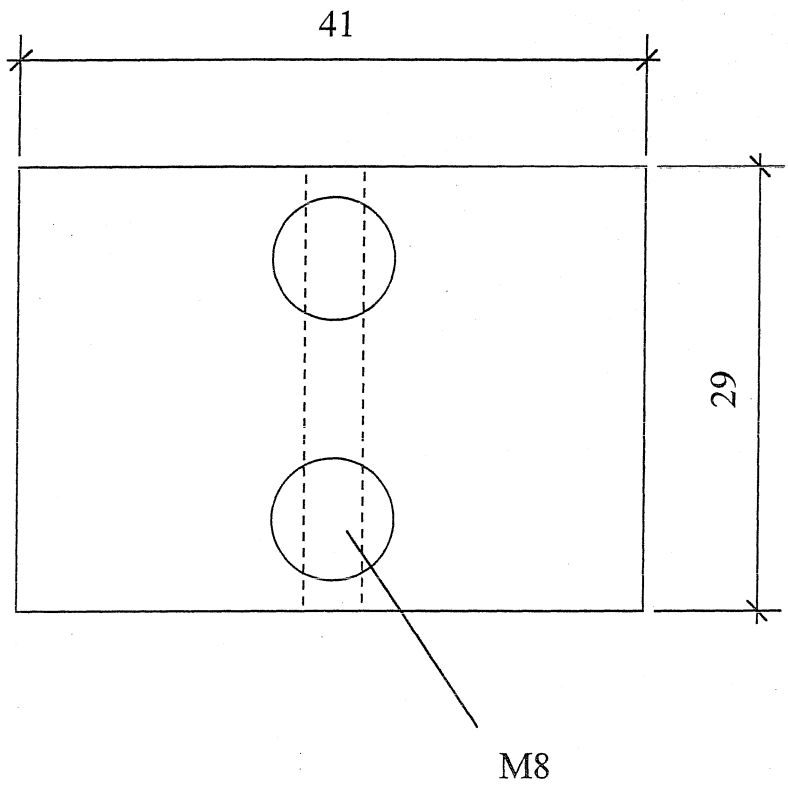
Toleranz nach DIN 7168 fein					Oberfläche	Maßstab 1: 1		Position	Menge		
						V2A					
					Datum	Name	Part: serving and spacer				
				Bearb.	07.01.97	W.Pickl					
				Gepr.							
				Norm							
				MPI Max-Plank-Institut für Marine Mikrobiologie			Nr.: 2.5.10			Blatt	
										Bl	
Zust.	Änderung	Datum	Name	EDV Nr. max261							



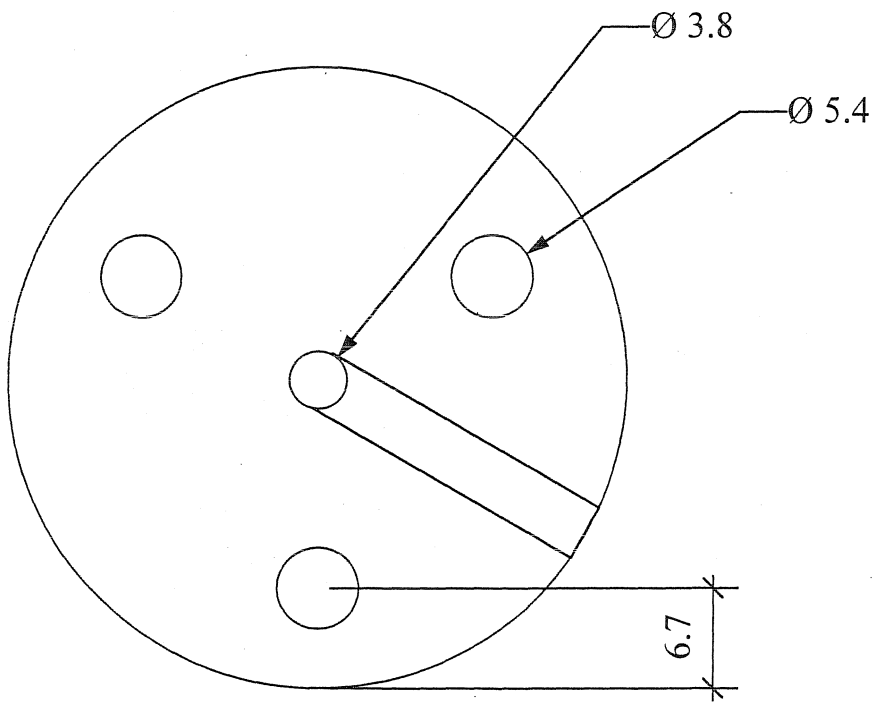
Toleranz nach DIN 7168 fein					Oberfläche	Maßstab 1 : 1		Position	Menge		
						V2A					
					Datum	Name					
				Bearb.	06.01.97	W.Pickl					
				Gepr.							
				Norm							
				MPI Max-Plank-Institut für Marine Mikrobiologie						Blatt	
										Bl	
Zust.	Änderung	Datum	Name	EDV Nr. max260							

Part: Needleholder		Nr: 2.5.11
Scale: 2:1	View(s): all	
Material: POM		Date: 23.1.97

Side view

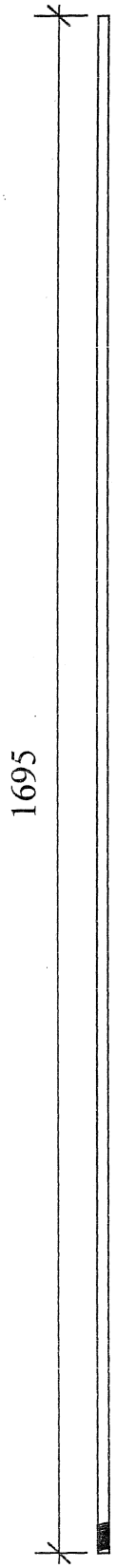


Top view

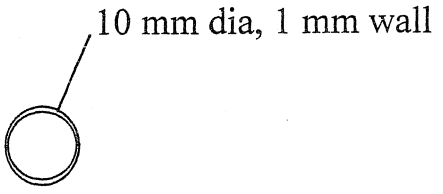


Part: guiding bars for motorhouses		Nr: 2.5.12
Scale: 1:8	View(s): all	
Material: 316-6 steel		Date: 20.1.97

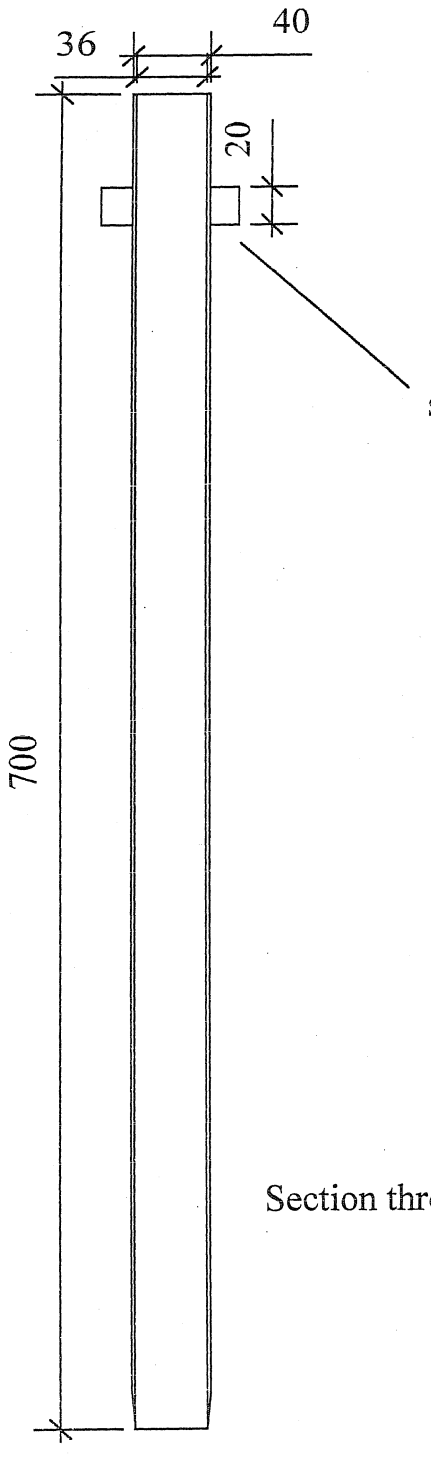
Side view



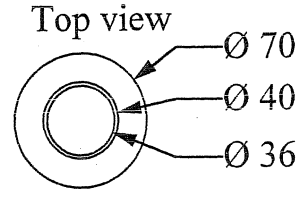
Top view, Scale 1:1



Part: coreliner		Nr: 2.6.1
Scale: 1:4	View(s): all	
Material: polycarbonate/PVC		Date: 20.1.97



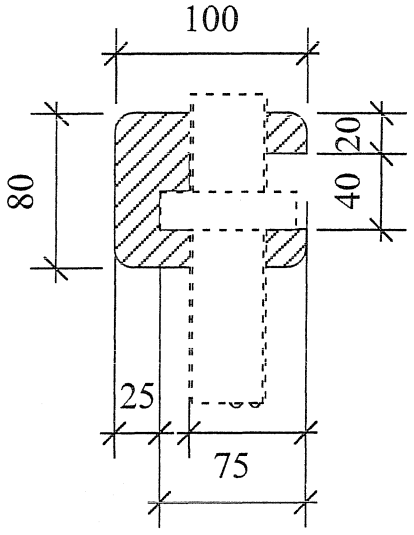
solid PVC ring glued to coreliner



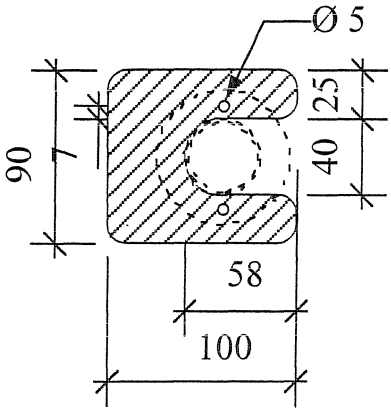
Section through corer (length 700 mm)

Part: clamp for coreliner		Nr: 2.6.2
Scale: 1:4	View(s): all	
Material: POM		Date: 20.1.97

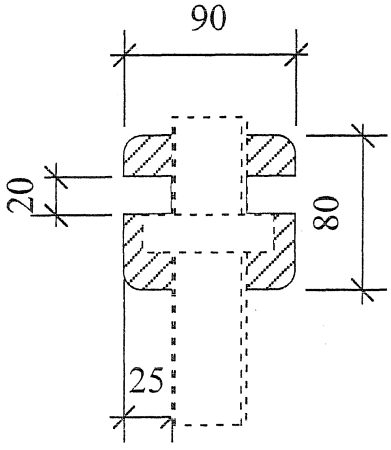
Side view



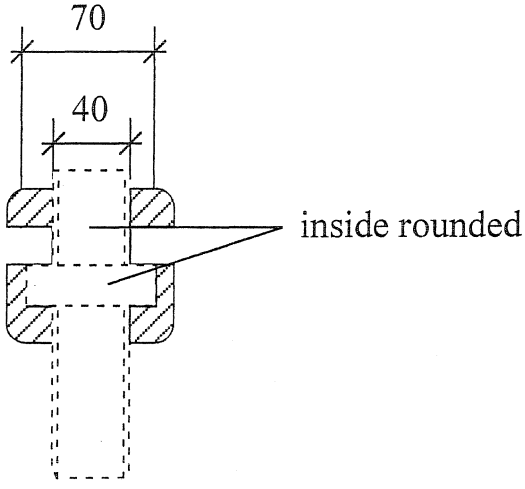
Top view



Rear view

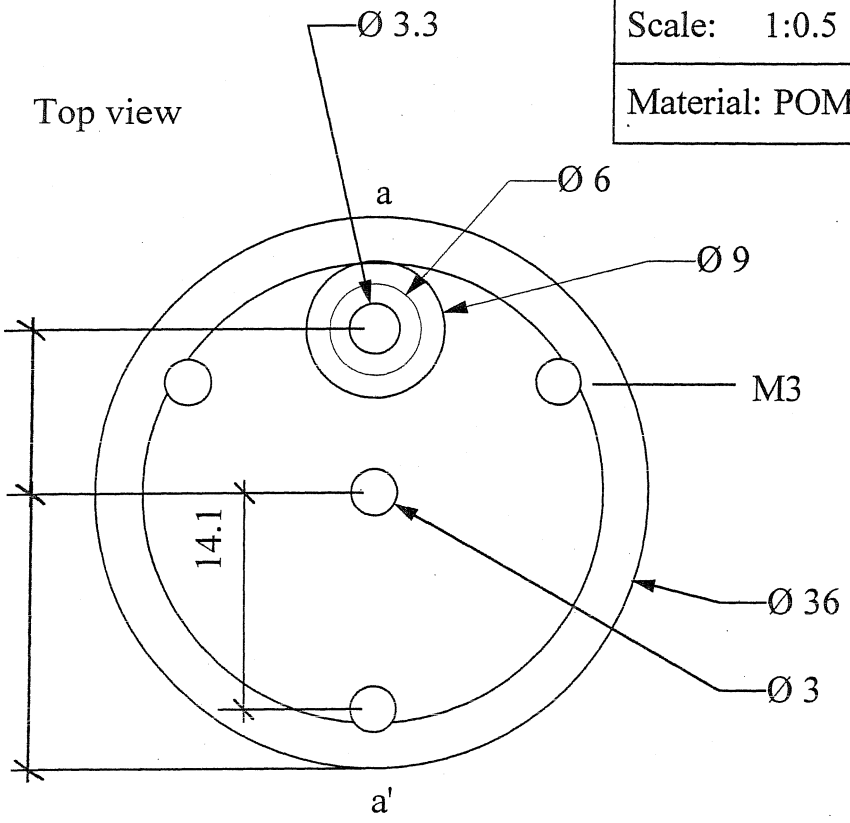


Front view

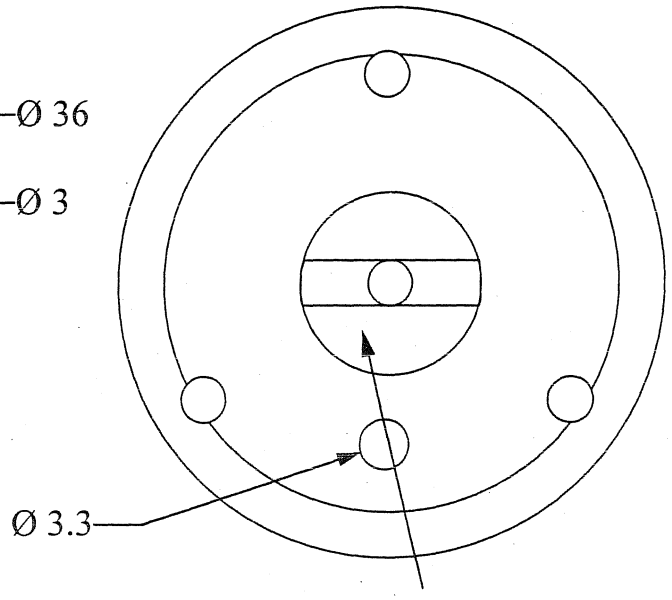


Part: piston		Nr: 2.6.3
Scale: 1:0.5	View(s): all	
Material: POM		Date: 20.1.97

Top view

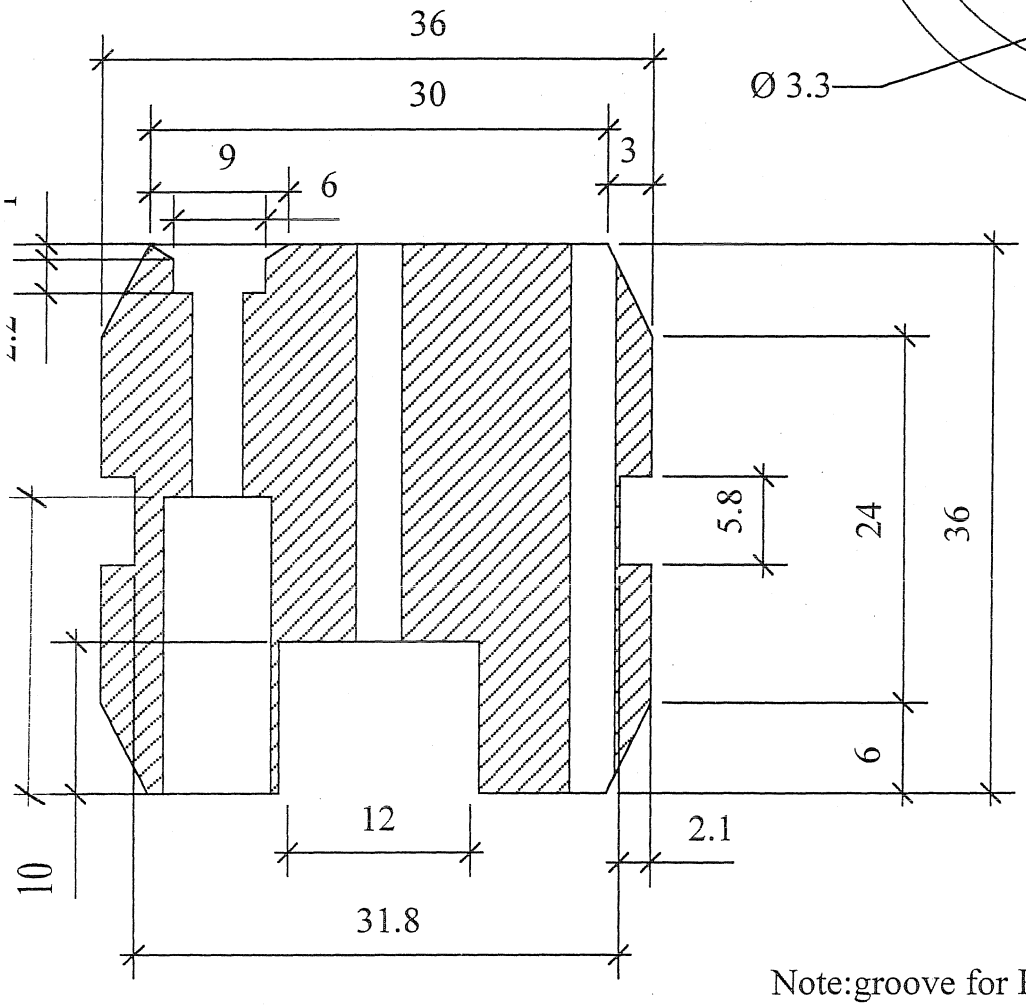


Bottom view



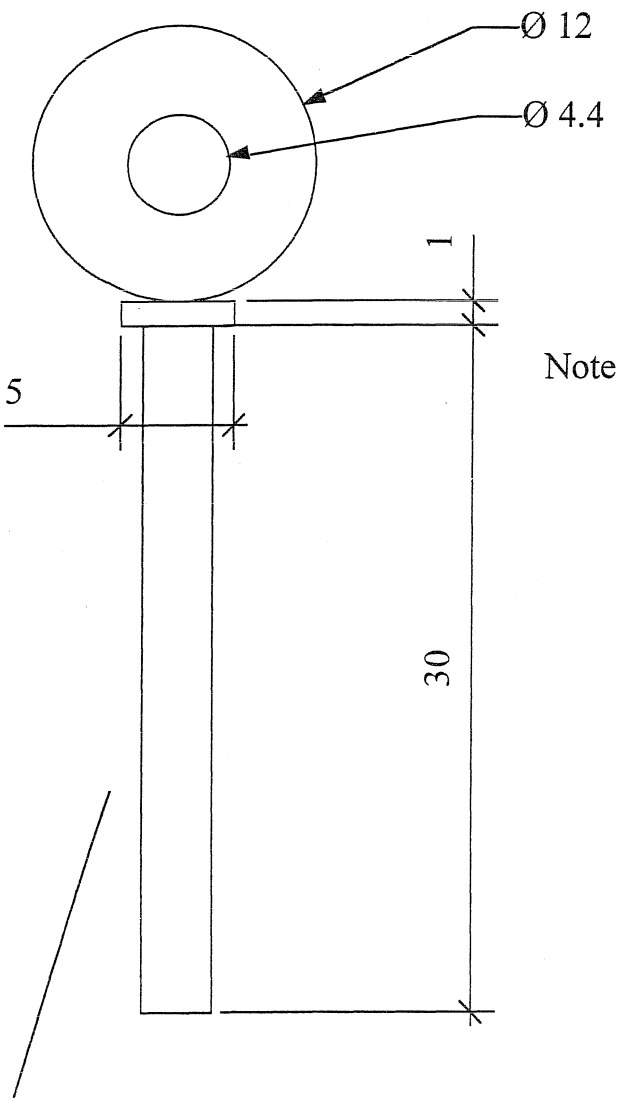
M12 sealing screw for lip ring 3 x 9,9 x 5 NBR 70

Center section a-a'



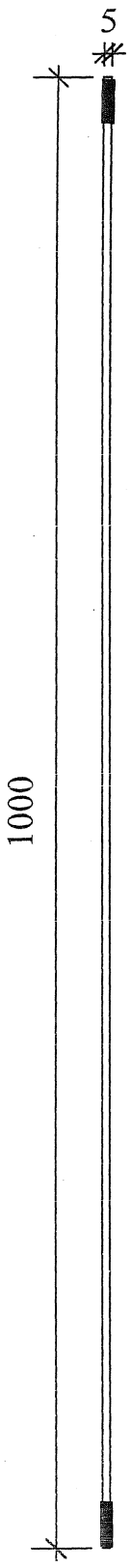
Note: groove for Parker O-ring 2-124

Part: piston valve		Nr: 2.6.4
Scale: 3:1	View(s): side (massive)	
Material: 316-6 steel		Date: 22.1.97



Note: O-ring underneath top plate

Note: M3 thread. Nut on end holds spring (316-6 steel)

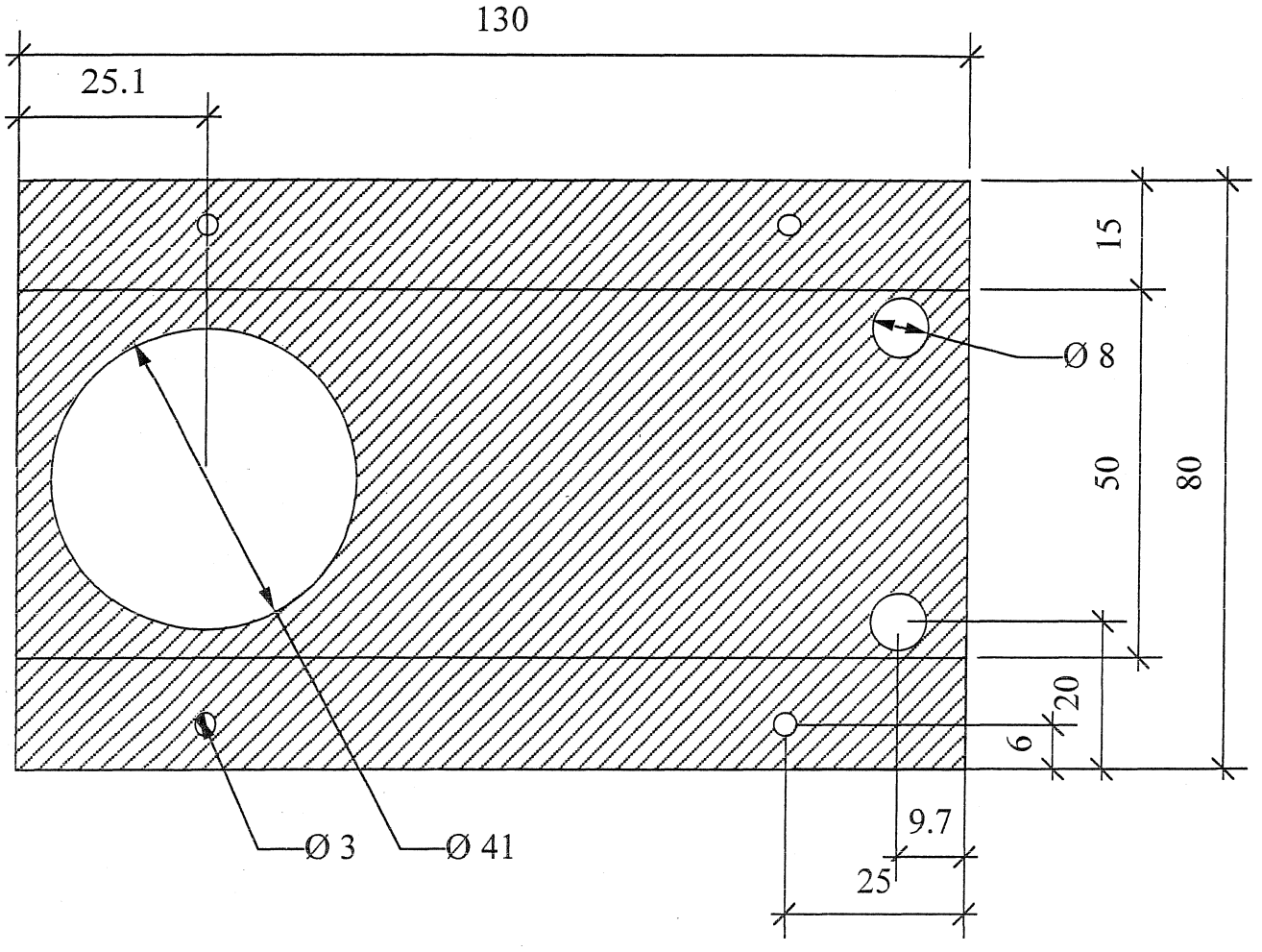


Part: holding bars for piston		Nr: 2.6.5
Scale: 1:5	View(s): side (massive)	
Material: 316-6 steel		Date: 20.1.97

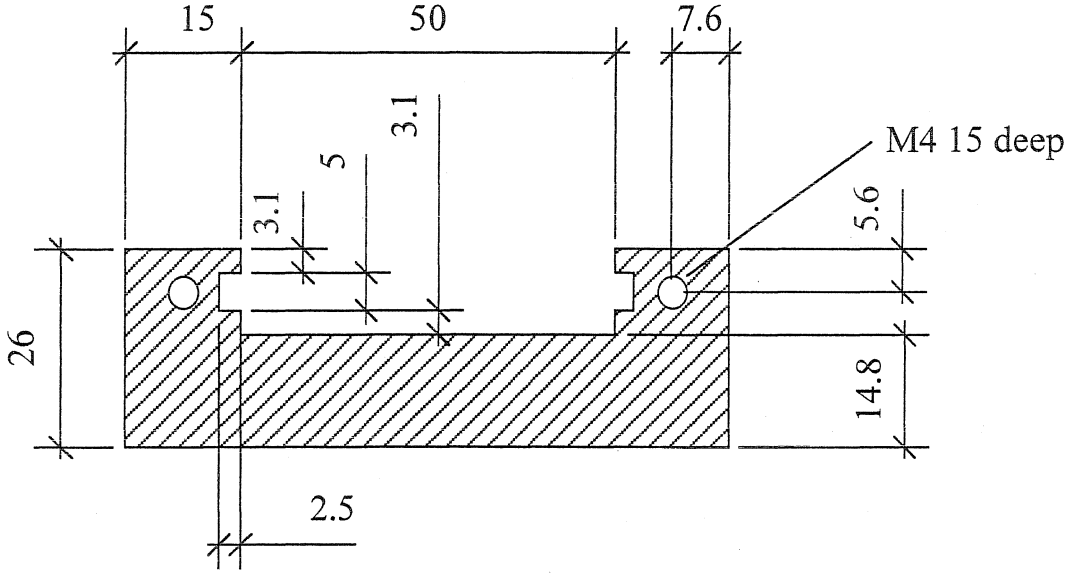
Note: top 30 mm M5 thread
bottom 14 mm M3 thread

Part: Corecatcher body		Nr: 2.7.1
Scale: 1:1	View(s): all	
Material: POM		Date: 21.1.97

Top view



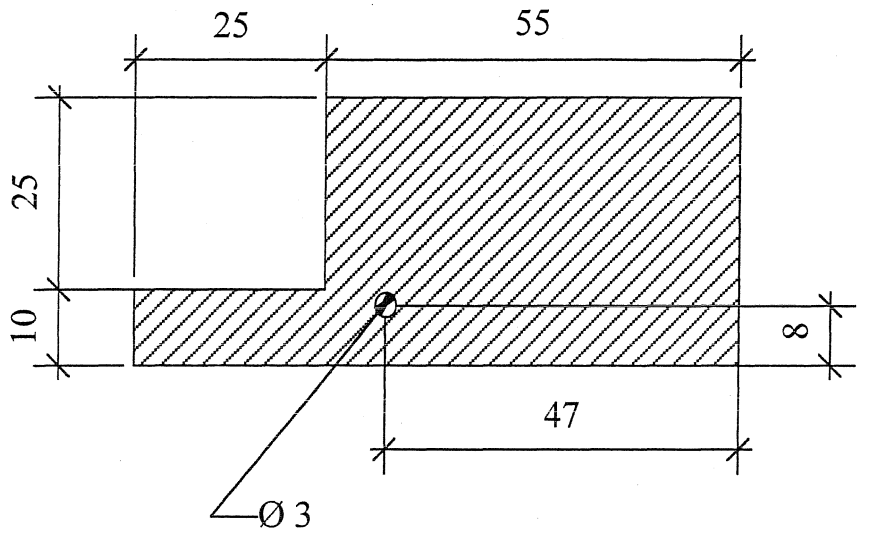
Front view



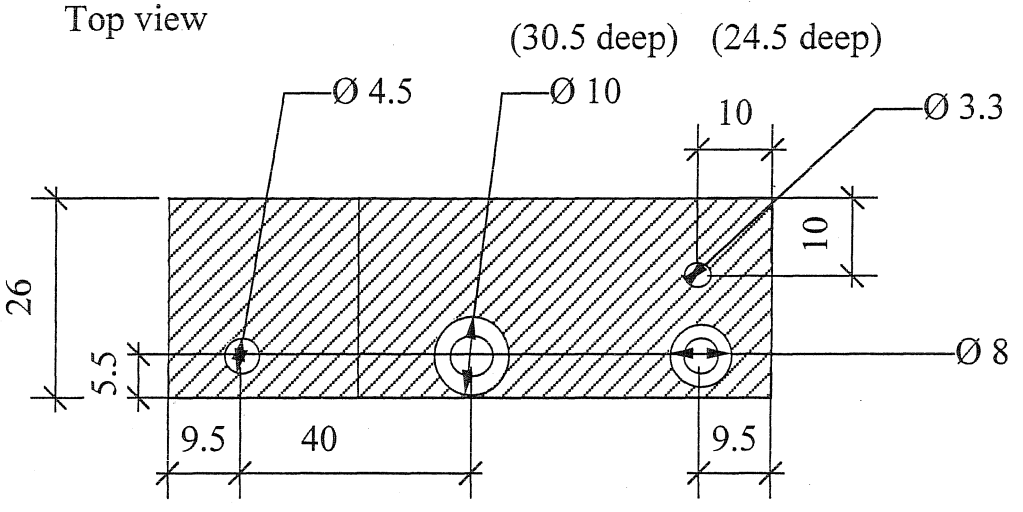
Note: groove takes up 316-6 steel bar, 130 x 5 mm

Part: Corecatcher head piece		Nr: 2.7.2
Scale: 1:1	View(s): all	
Material: POM		Date: 21.1.97

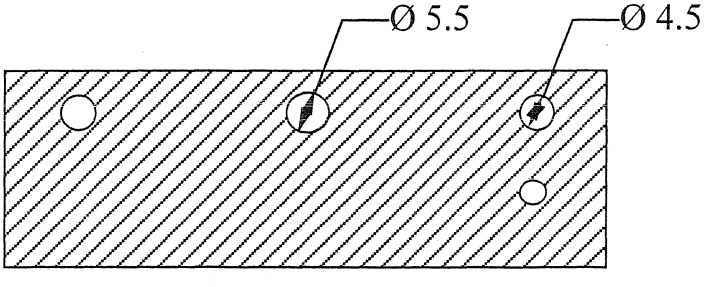
Side view



Top view

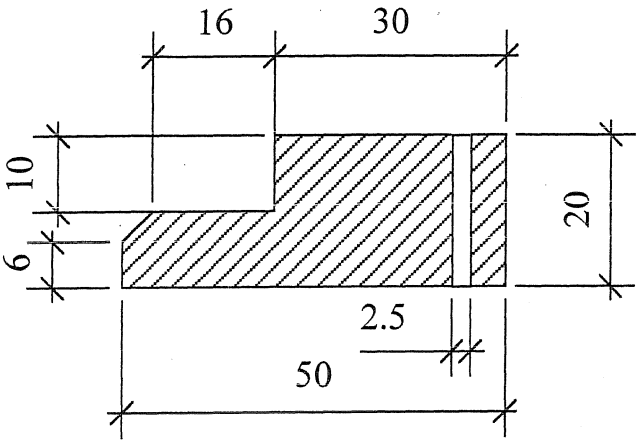


Bottom view

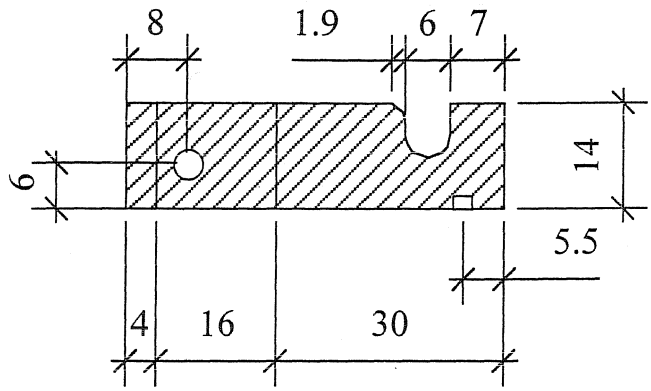


Part: Corecatcher top part and plate		Nr: 2.7.3
Scale: 1:1	View(s): all	
Material: POM		Date: 21.1.97

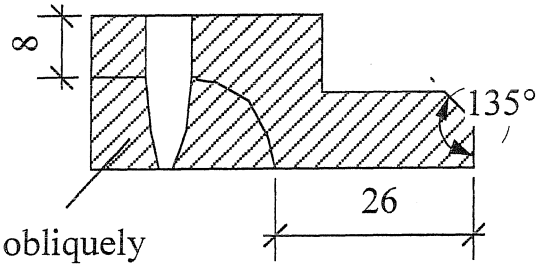
Front view



Top view

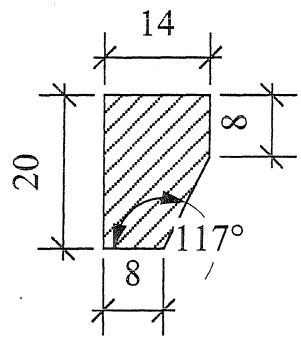


Rear view

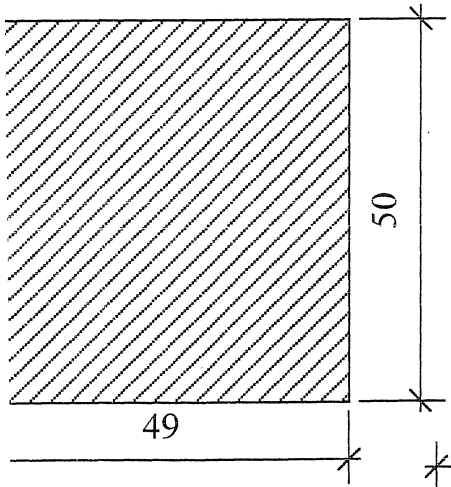


it obliquely

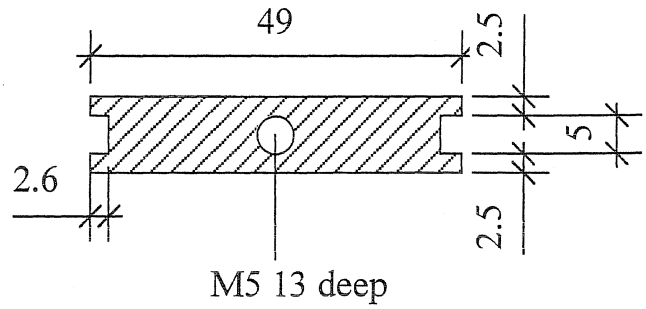
Back view



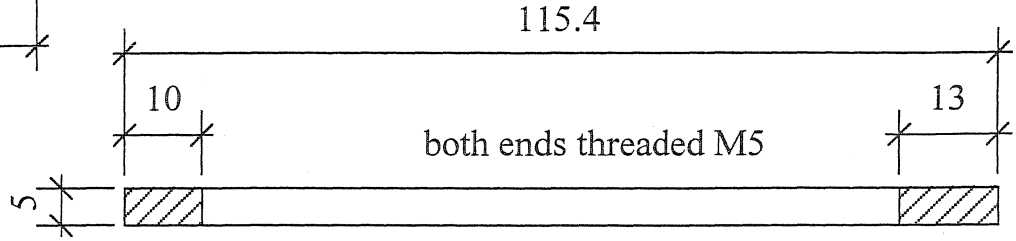
Plate, top view



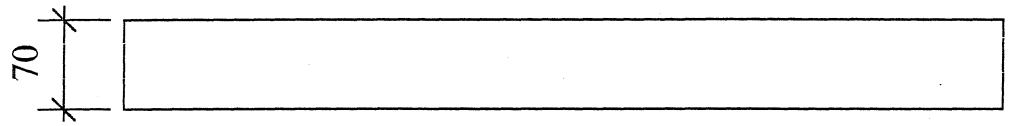
Back view

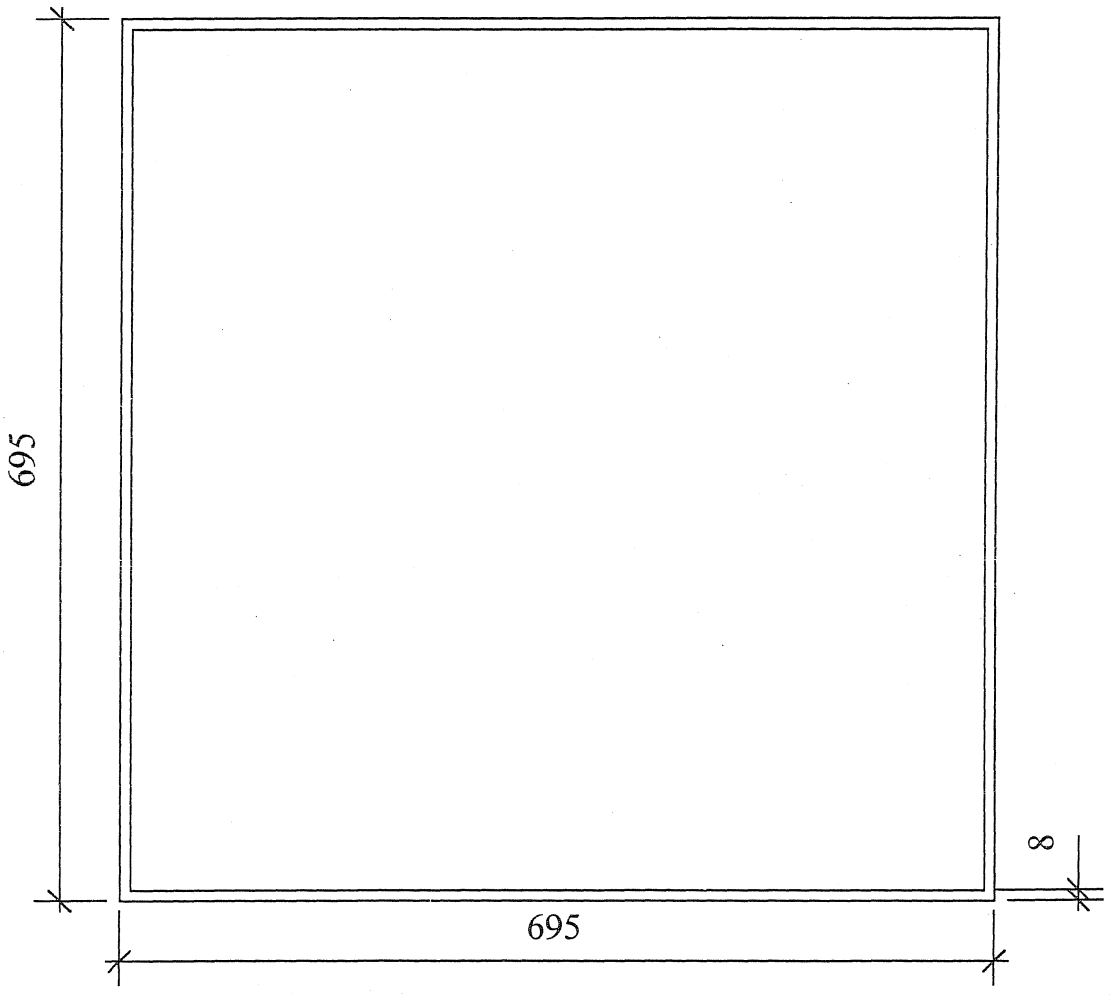


316-6 steel bar holding plate



Part: safety tub		Nr: 2.8.1
Scale: 1:6	View(s): all	
Material:Polypropylen		Date: 23.1.97

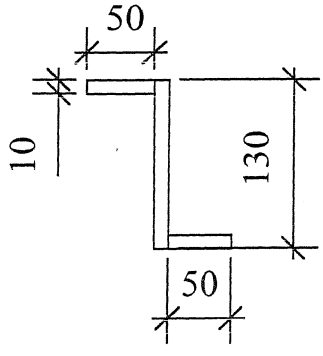




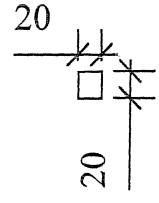
Part: safety tub holder		Nr: 2.8.2
Scale: 1:6	View(s): all	
Material:Polypropylen		Date: 23.1.97

Stabilizing bar

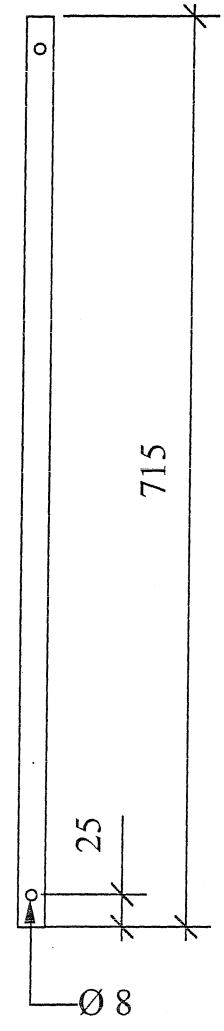
Rear view



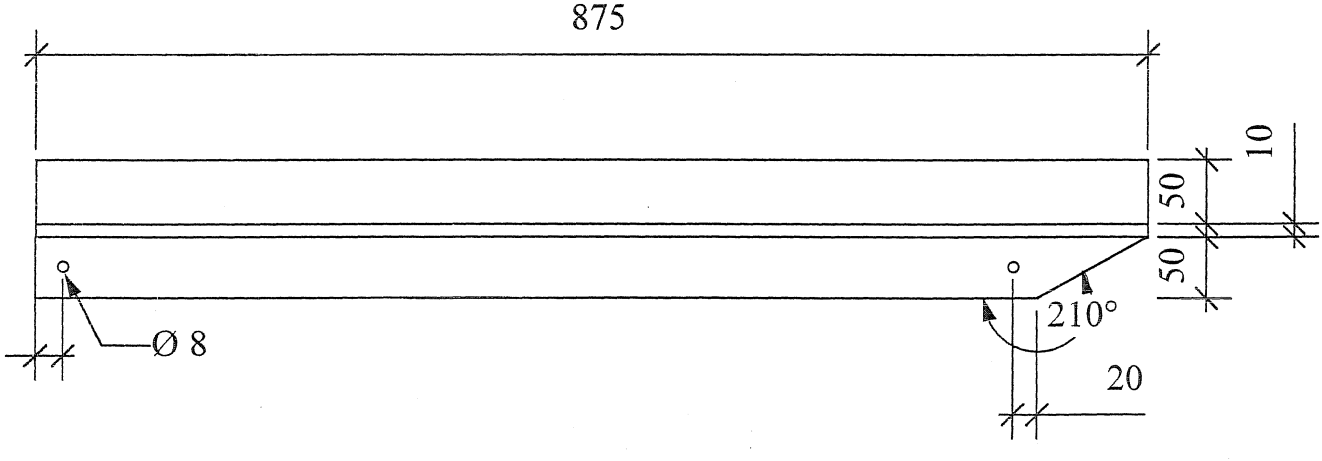
Front view



Side view

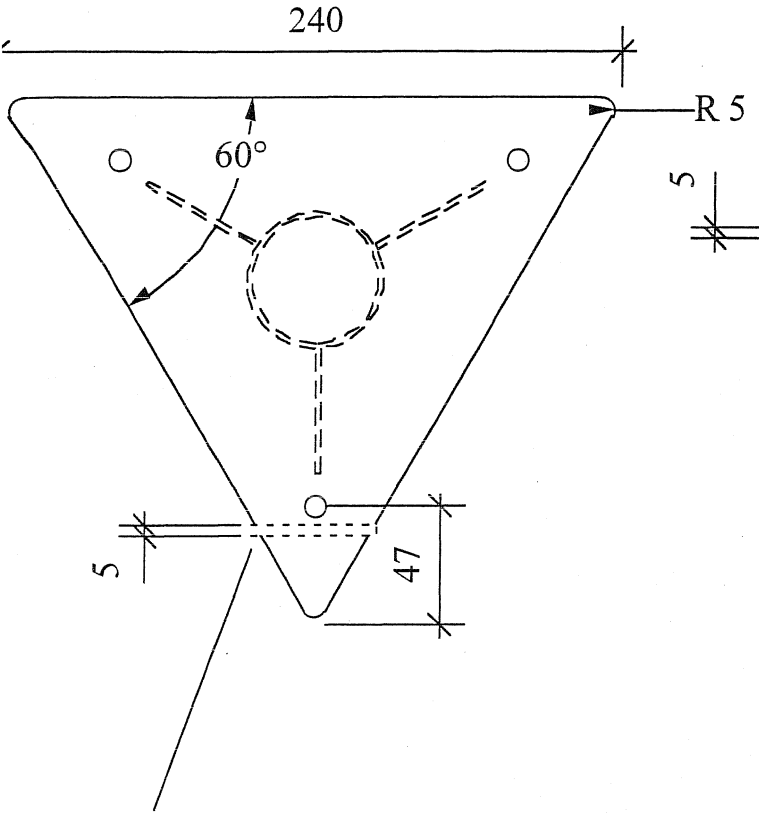


Top view

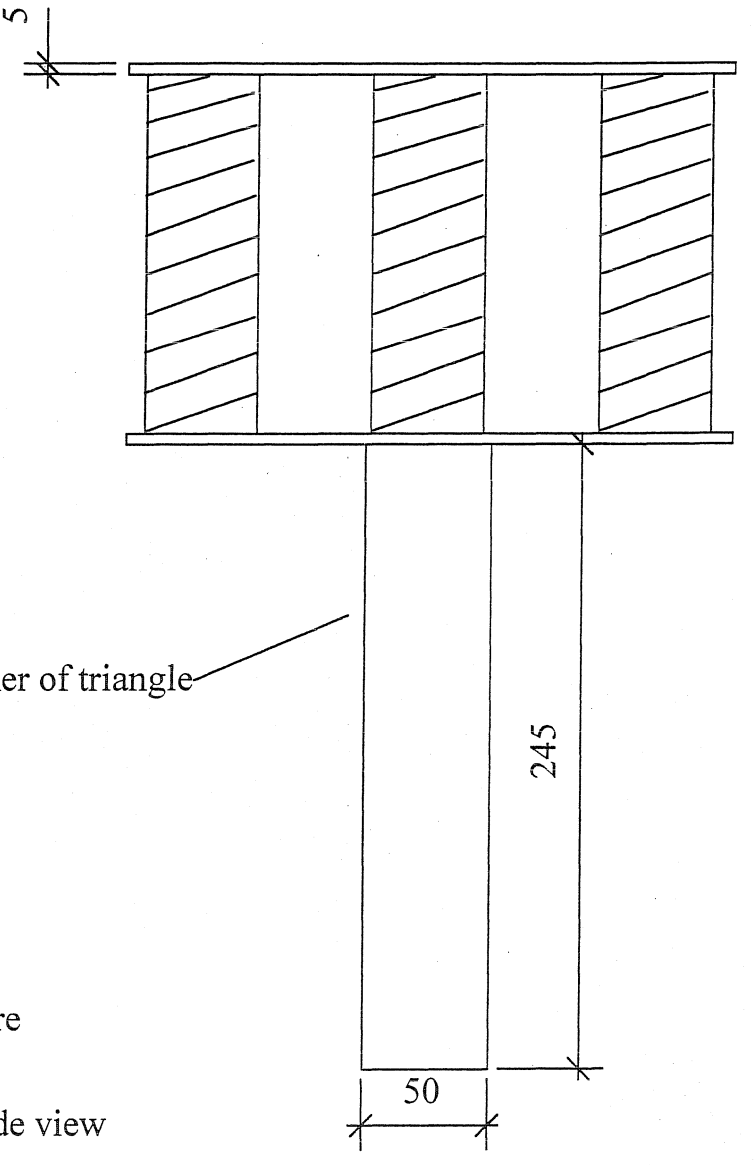


Part: antenna holder, flexible fixing		Nr: 2.8.3
Scale: 1:3	View(s): all	
Material: 316-6 Steel		Date: 24.1.97

Bottom/top plate, top view



Front view

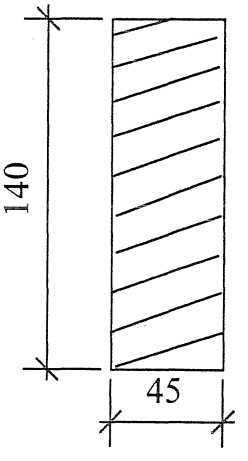


Note: weld supporting steel plate to corner of triangle

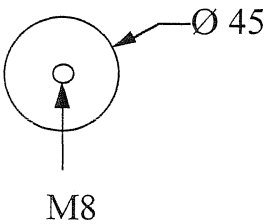
Spring

Note: spring made of 8 mm 316-6 steel wire

Side view

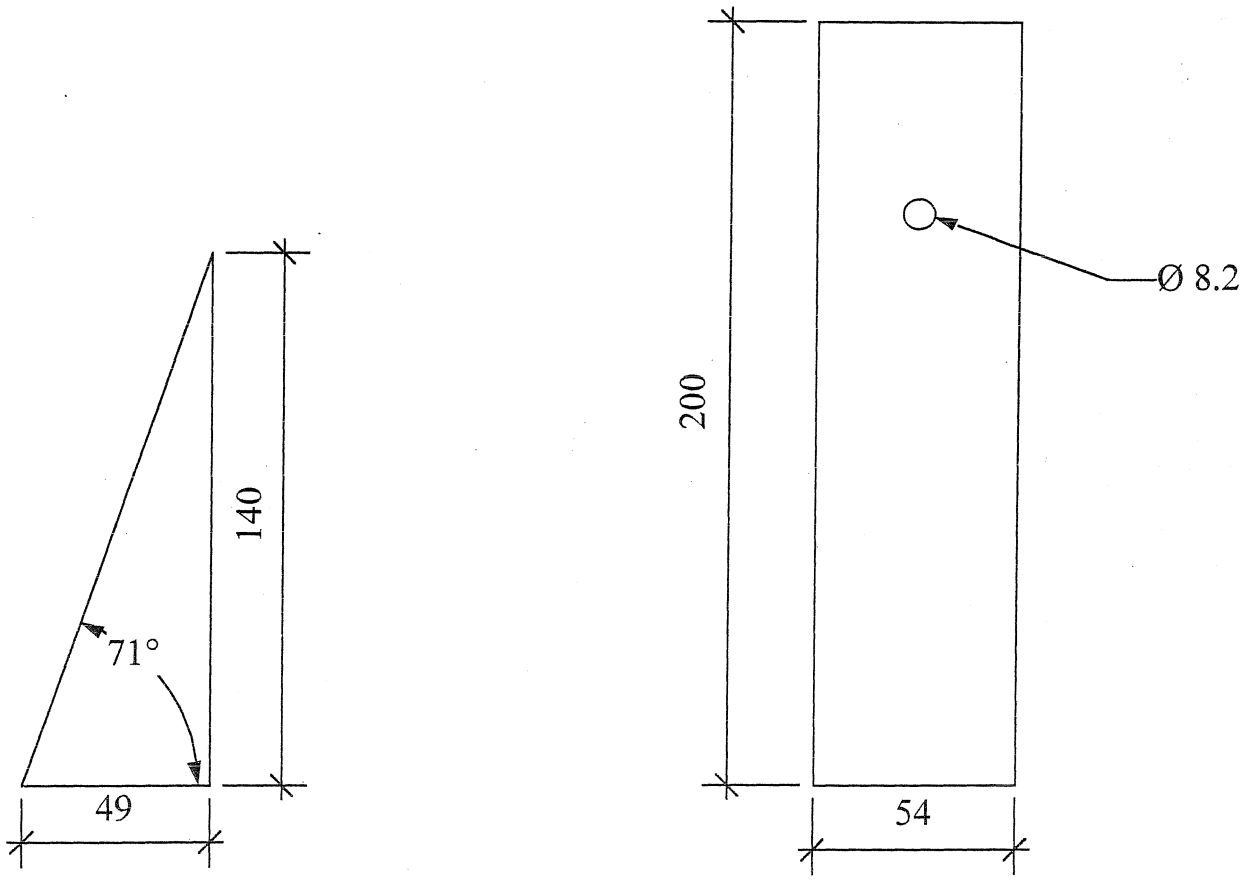


Top view

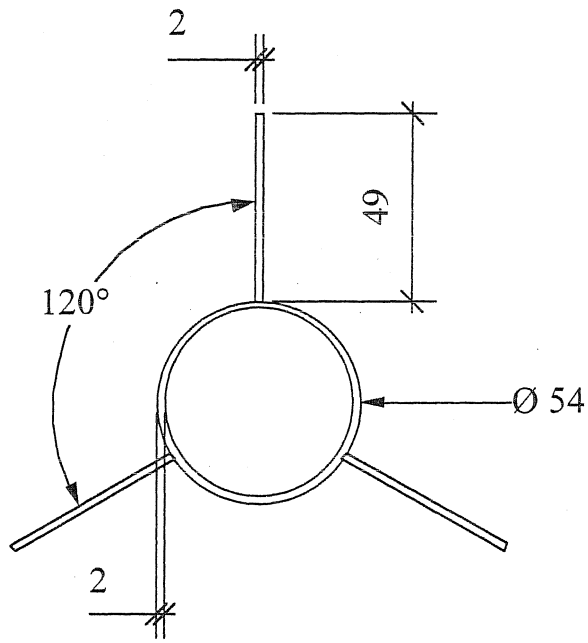


Part: antenna holder		Nr: 2.8.4
Scale: 1:2	View(s): all	
Material: 316-6 Steel		Date: 24.1.97

Side view

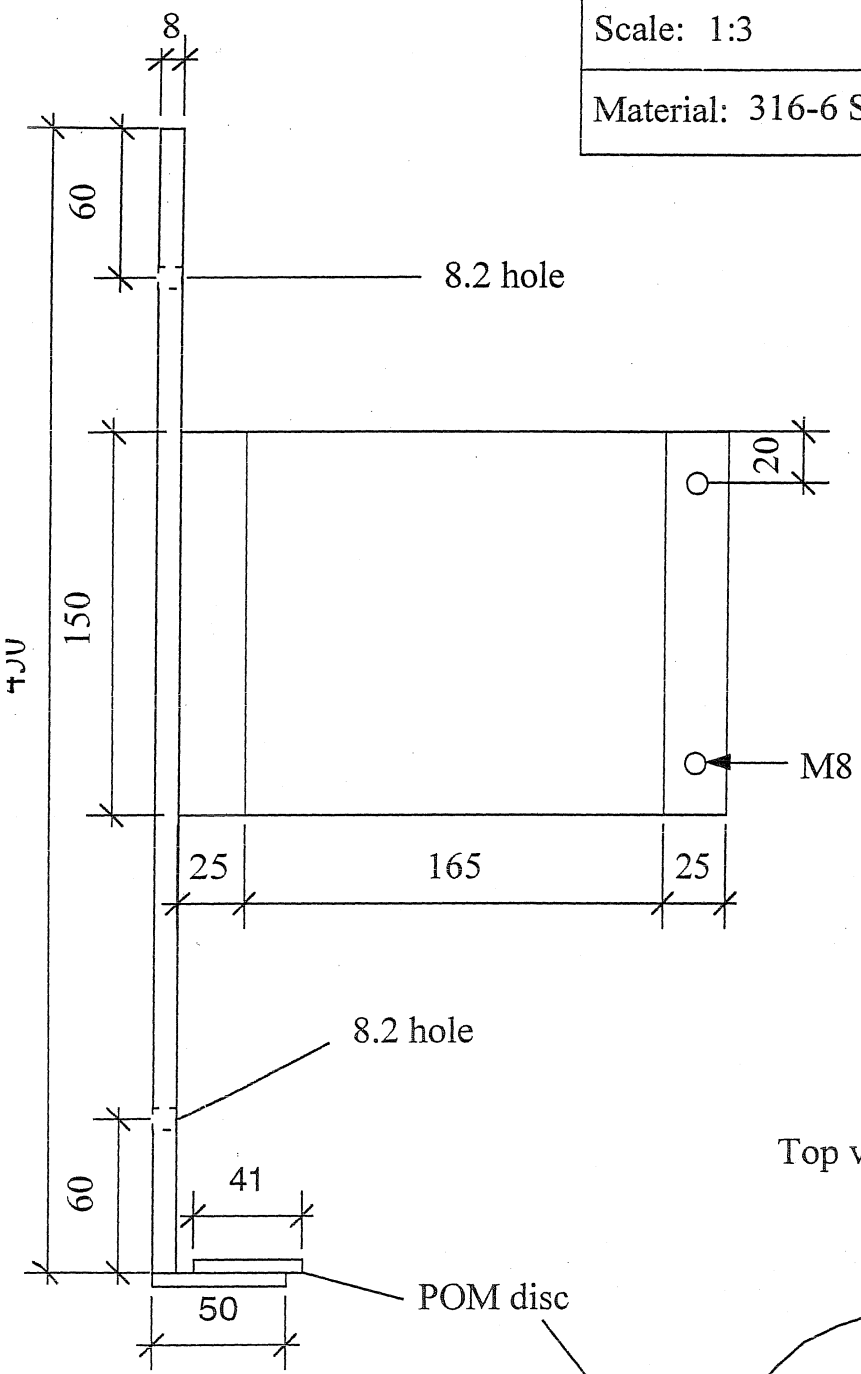


Top view

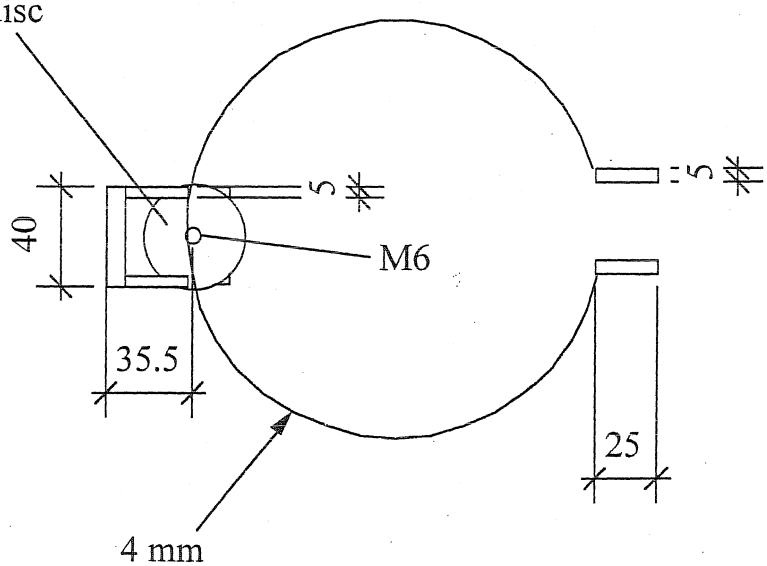


Part: holder for electronic cylinder		Nr: 2.8.5
Scale: 1:3	View(s): all	
Material: 316-6 Steel		Date: 24.1.97

Side view

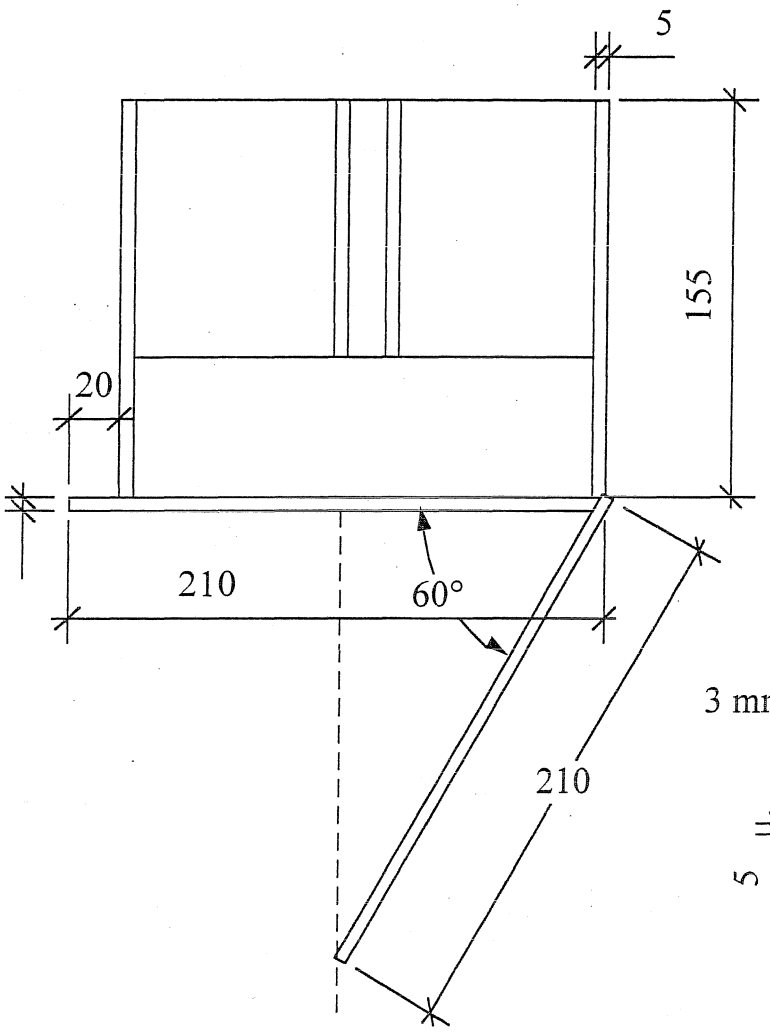


Top view

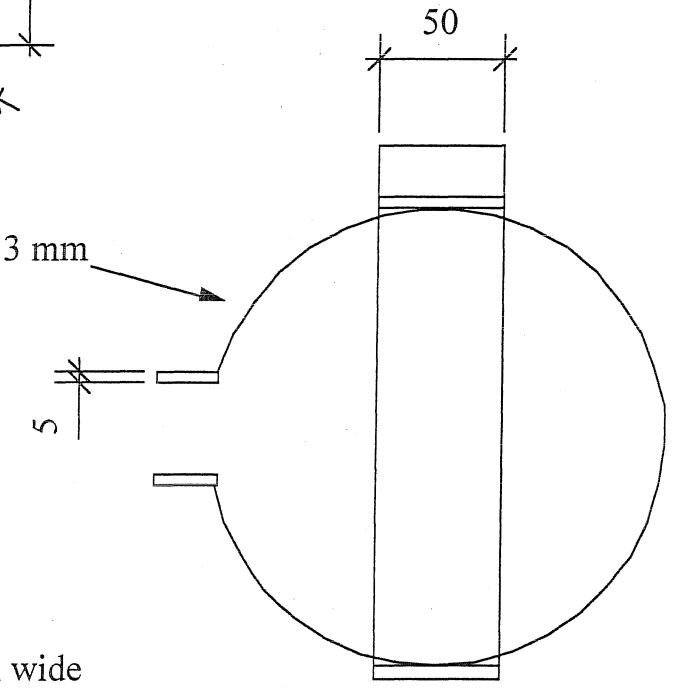


Part: holder for transducer		Nr: 2.8.6
Scale: 1:3	View(s): all	
Material: 316-6 Steel		Date: 24.1.97

ide view with frame

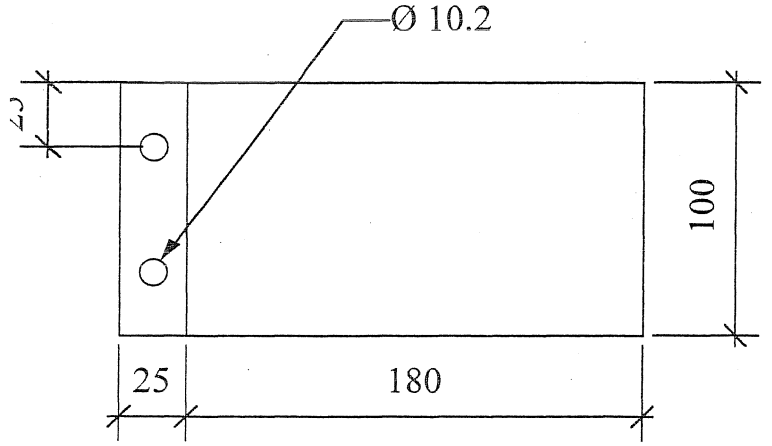


Top view



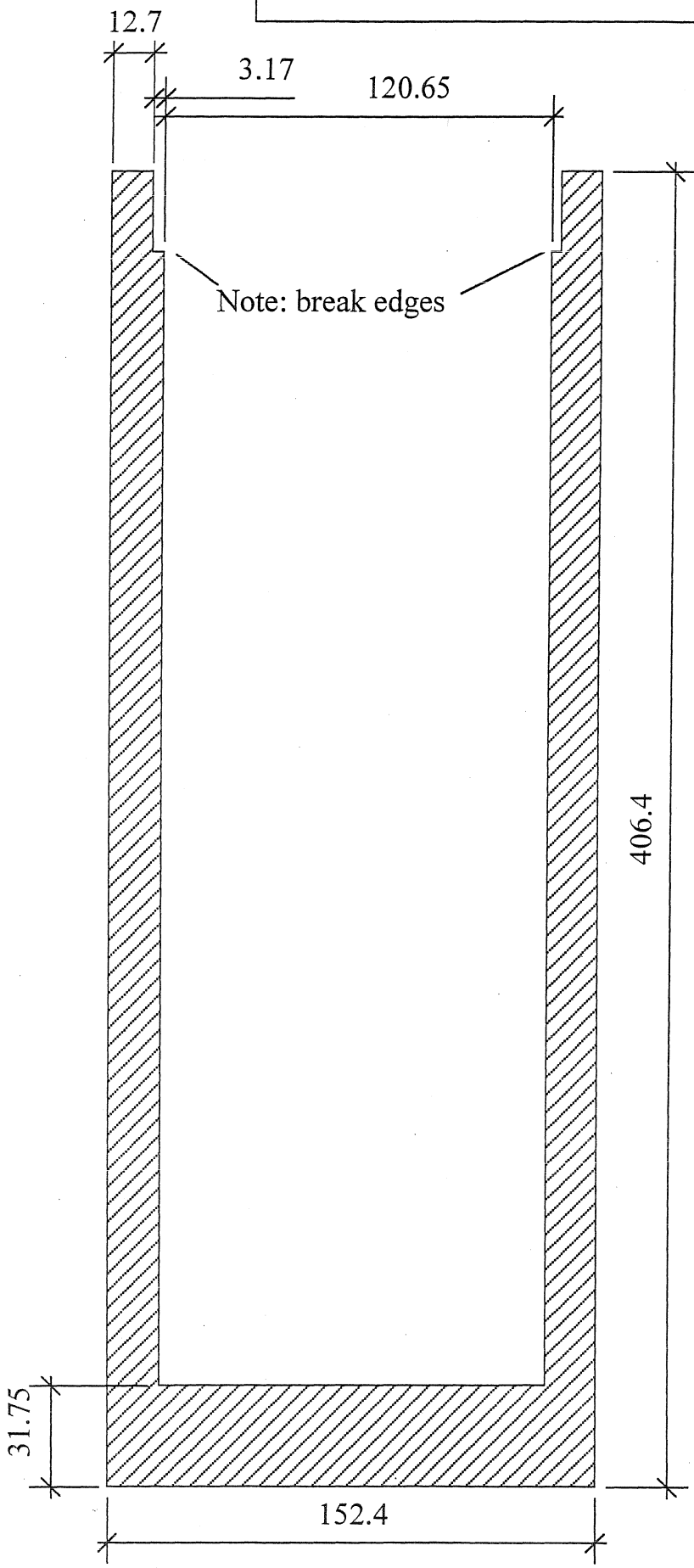
ote: all profiles of 5 mm thickness are 50 mm wide

0 deg side view without frame

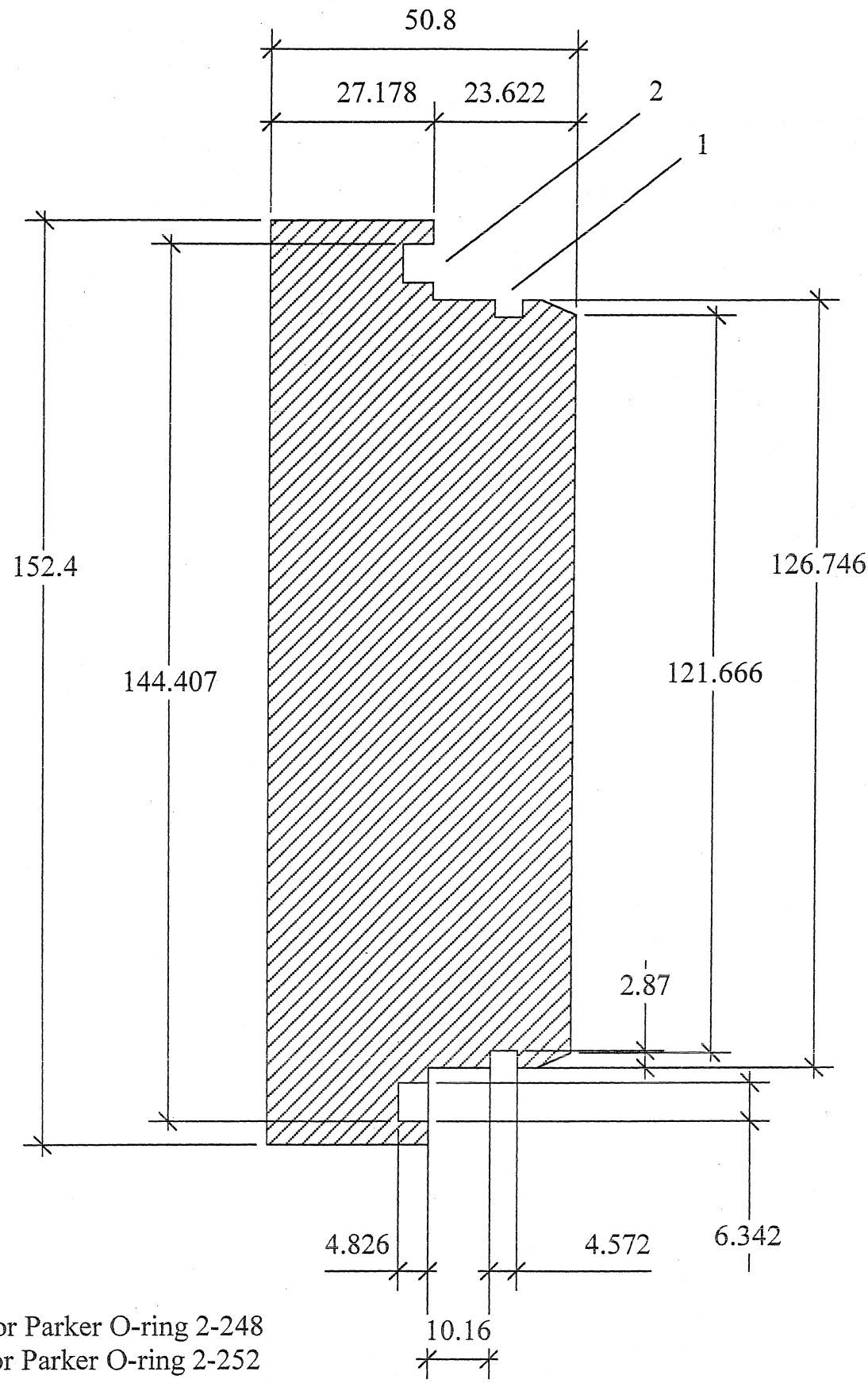


Note: clamp and clamp screws are not indicated

Part: electronic cylinder		Nr: 3.1.1
Scale: 1:2	View(s): center section	
Material: 7075 T6 Aluminium		Date: 24.1.97



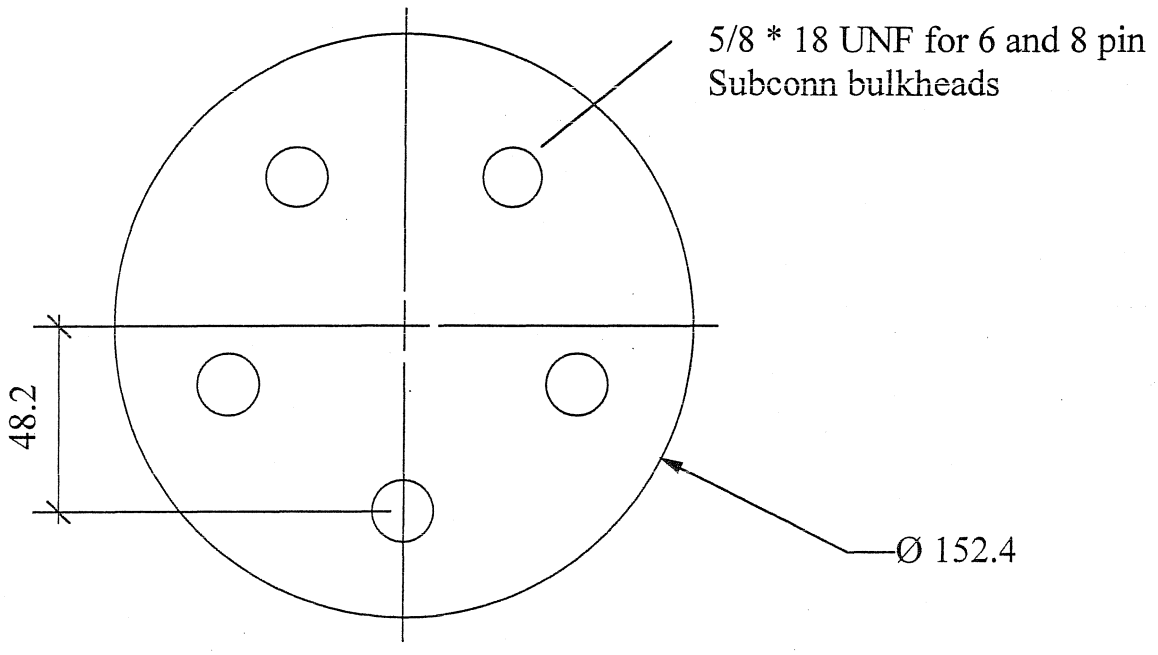
Part: electronic cylinder, lid		Nr: 3.1.2
Scale: 1:1	View(s): center section	
Material: 7075 T6 Aluminium		Date: 24.1.97



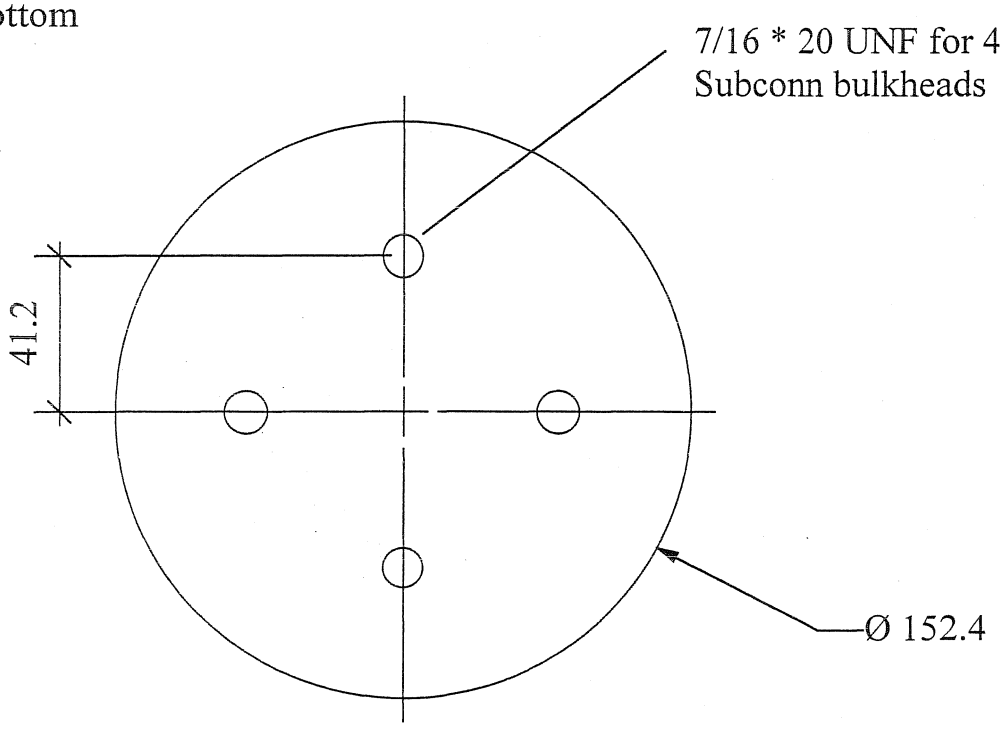
es : 1) groove for Parker O-ring 2-248
2) groove for Parker O-ring 2-252

Part: array of holes for connectors		Nr: 3.1.3
Scale: 1:2	View(s): top/bottom	
Material: 7075 T6 Aluminium		Date: 24.1.97

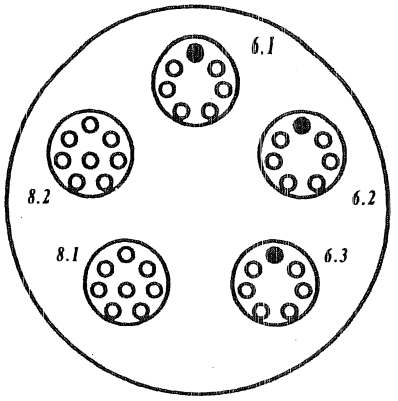
Lid



Bottom

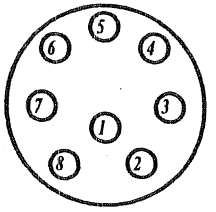


Deckel vom "Luise-Electronik-Zylinder"



8.1

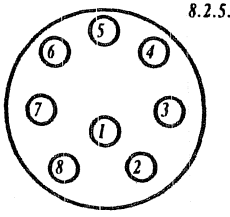
Female



8.1.1: Drucksensor gelb und weiß, 4-Pin Molex P 4
8.1.2: Drucksensor graublau, 4-Pin Molex P 3
8.1.3: Drucksensor rot, 4-Pin Molex P 2
8.1.4: Drucksensor schwarz, 4-Pin Molex P1
8.1.5: Temperaturs.+Ub,gelb, 3-Pin Molex P3
8.1.6: Temperaturs. T-Out,orange, 3-Pin Molex P2
8.1.7: Temeraturs. GND,rot, 3-Pin Molex P1
8.1.8: frei

8.2

Female

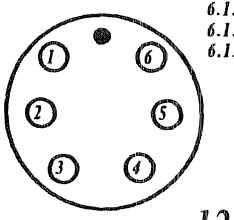


8.2.1: Stagemotor 1 (Up & Dn) Up:+ Dn:-
8.2.2: Stagemotor 1 (Up & Dn) Up:- Dn: +
8.2.3: Stagemotor 2 (UP only) Up: +
8.2.4: Stagemotor 2 (Up only) Up: -
8.2.5...8: frei

24 Volt 8A gesichert

6.1

Female

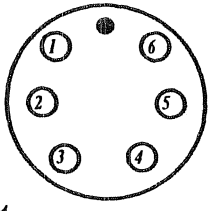


6.1.1: Nadel 1 Up:+ Dn:-
6.1.2: Nadel 1 Up:- Dn:+
6.1.3: Nadel 2 Up:+ Dn:-
6.1.4: Nadel 2 Up:- Dn:+
6.1.5: Nadel 3 Up:+ Dn:-
6.1.6: Nadel 3 Up:- Dn:+

12 Volt 3A gesichert

6.2

Female

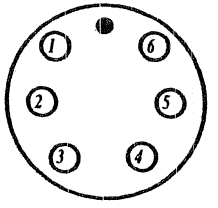


6.2.1: Nadel 4 Up:+ Dn:-
6.2.2: Nadel 4 Up:- Dn:+
6.2.3: Nadel 5 Up:+ Dn:-
6.2.4: Nadel 5 Up:- Dn:+
6.2.5: Nadel 6 Up:+ Dn:-
6.2.6: Nadel 6 Up:- Dn:+

12 Volt 3A gesichert

6.3

Female

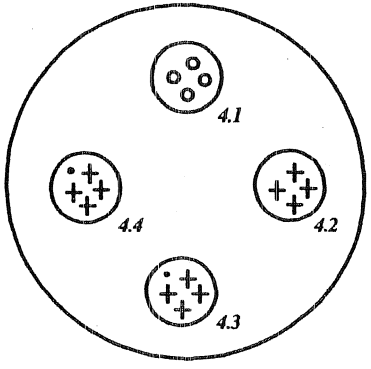


6.3.1: Burnwire Ballast +
6.3.2: Burnwire Ballast -
6.3.3: Endschalter OBEN
6.3.4: Endschalter OBEN
6.3.5: Endschalter UNTEN
6.3.6: Endschalter UNTEN

Draufsichten von außen

Bezeichnung		Zeichner	
Pinbelegung Deckelkontakte "Luise"		V. Meyer	
Maßstab	Nr.: 3.2.1	Datum	Sign.
		30.08.95 Rev 1.1, 23.07.96	

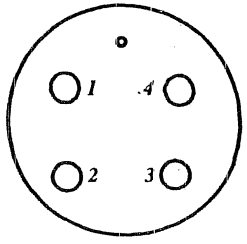
Außenansicht des Bodens vom "Luise-Electroniccylinder"



4.1: Female -Computer-Verbindung
4.2: Male Computer-Batterie
4.3: Male Motor-Batterie
4.4 Male free

4.1

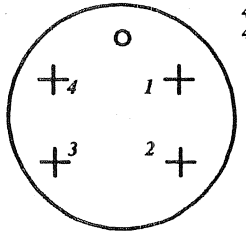
Female



4.1.1: Flachbandkabel 21
4.1.2: Flachbandkabel 22
4.1.3: Flachbandkabel 23
4.1.4: Flachbandkabel 24

4.2

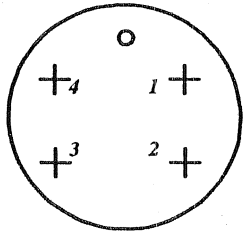
Male



4.2.1 : 0 Volt
4.2.2: +24 Volt
4.2.3: +24 Volt
4.2.4: 0 Volt

4.3

Male

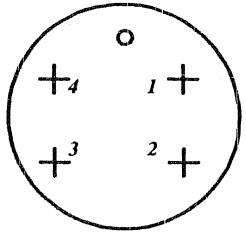


4.3.1: 0 Volt /1
4.3.2: +12 Volt/2
4.3.3: +12 Volt /1
4.3.4: 0 Volt /2

Brücke von 3-4

4.4

Male



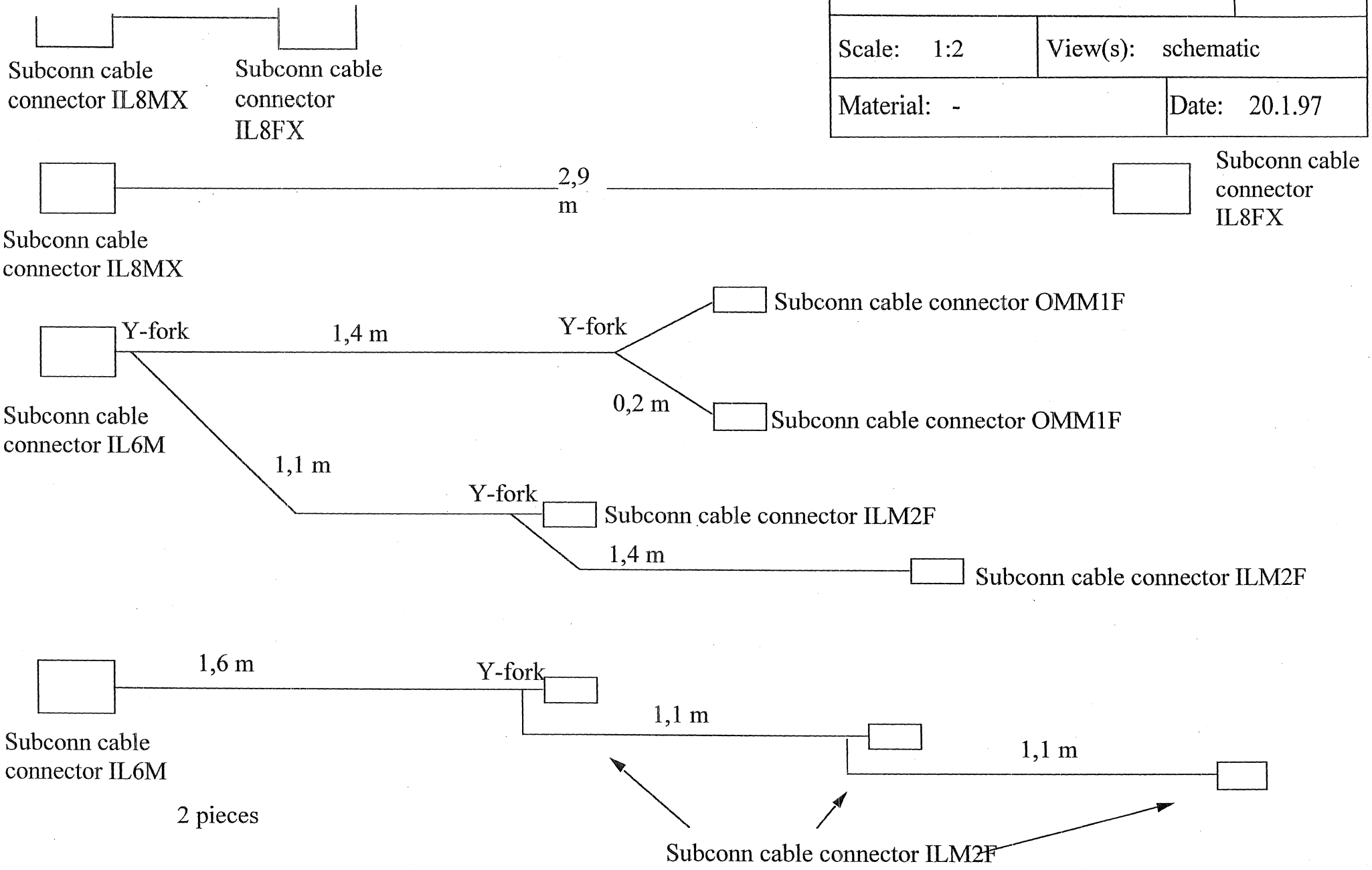
frei

Draufsichten von außen

Bezeichnung		*Zeichner*	
Pinbelegung Bodenkontakte "Luise"		*V. Meyer*	
Maßstab	Nr.: 3.2.2	*Datum*	*Sign.*
		30.08.95	

Part: cable plan | Nr: 3.3

Scale: 1:2	View(s): schematic
Material: -	Date: 20.1.97



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