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REPORT 26-01-R-001

SAFETY FACTOR ANALYSIS FOR CENTRIFUGE SYSTEMS

FINAL TECHNICAL REPORT

by

A N Schofield and R S Steedman

24 July 1991

United States Army

EUROPEAN RESEARCH OFFICE OF THE U.S. ARMY

London England

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Matters requiring clarification include the air conditioning and location of the containment structure, the crane and alterations to the existing office and control buildings, and the management structure.

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Integrated Quality Assurance will cover the centrifuge, buildings, instrumentation and equipment, the introduction of safe operating procedures, and the management of change. It is anticipated that an outstanding centrifuge with a unique range of capabilities will be in operation under full control by WES by December 1994.

ANS&A Report 26-01-R-001

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SUMMARY

ANS&A recommends that WES should buy the Acutronic 684-1 centrifuge and optional items apart from the additional large platform listed in their Proposal 9530A (February 1991), subject to Quality Assurance (QA) procedures which will involve ANS&A in all stages of design, manufacture, installation, commissioning and operation of the centrifuge facility at WES.

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ANS&A envisage that their Project Engineer in France will achieve a close collaboration with Acutronic France during the final design process, inspecting and reviewing all phases of design and manufacture within well defined procedures for Quality Assurance.

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LIST OF KEYWORDS

centrifuge
test
model
capabilities
quality
assurance
containment
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equipment
instrumentation
safety

CONTENTS

1.0 DEVELOPMENT OF CENTRIFUGE MODEL TEST CAPABILITIES

1.1 ACUTRONIC PROPOSAL 9530A (FEBRUARY 1991)

During the period of ANS&A's Phase 1 project questions have been raised and answered over the specification of the Acutronic 684-1 centrifuge and its potential range of capabilities. Changes have been made to the outline design which reflect more closely the needs of WES in creating new capabilities for physical modeling. The WES draft Miscellaneous Paper which studied the feasibility of a WES centrifuge included contributions from a number of authors at WES who expressed intentions to undertake centrifuge model tests at accelerations above 200g. The centrifuge as now proposed can test a 2 tonnes mass at up to 350g, and a 4 tonnes mass at up to 150g, on a 1.3 m x 1.3 m swinging platform.

ANS&A recommends that the operations of this centrifuge be divided into two ranges of acceleration. There shall be a normal range of operation up to an acceleration designated as g-normal, or gnorm = 280g , and there shall be a maximum range of operation up to an acceleration gmax = 350g . The revised Acutronic Proposal 9530A, dated February 1991, has on page 16 a load/acceleration operating map from which permitted loads in the gnorm and gmax ranges should be deduced: the scale on the curved portion of this map is unusual and Acutronic will be asked to provide a larger scale map or table of values, more precisely defining the permitted load, when their design becomes more precisely detailed. In some cases the magnitude of the load may depend on the area of the platform to which the load is applied.

Consideration should be given in detailed design to the possibility of increasing the 'head-room' between the platform and the boom divider. More space will be valuable for example in tests with pile driving.

Consideration must also be given in the detailed design to the use of space above the central axis of the centrifuge for mounting flight computers to handle A/D conversions and multiplexing of data and to control in-flight systems.

ANS&A's second interim report included an Appendix C with the title "Establishing a new Centrifuge Facility"

by Dr R N Taylor; the proceedings of Centrifuge 91 included an article by Professor M F Randolph et al.[1], with the same title. In these papers the authors refer to experiences with recently installed Acutronic 661 centrifuges at the City University, London and at the University of Western Australia, Perth. It is important that, during the detailed design of the WES facility, Acutronic should take account of all comments made on the performance of mechanical and electrical and control equipment, and ensure that problems encountered in the past are overcome in the design of the centrifuge for WES.

The contracting officer of WES will note that in the following pages of this report a procedure is set out for the review and acceptance by ANS&A of Acutronic France's detailed design documents. The contract that is entered into by WES and Acutronic USA should reflect the essential research and development that is involved in the creation of a facility for WES that will involve advances in the state of the art. The contract should refer both to the transfer of existing technology from Acutronic France to Acutronic USA and from ANS&A to WES, and to the new advances of technology that are intended in the creation of a potentially outstanding centrifuge and a world class centrifuge centre. The contract should be written so as to reward close cooperation and high achievement of the parties involved.

ANSA propose the selection of a WES Project Manager, and of a procedure by which ANS&A assists WES in achieving Quality Assurance and Quality Control of the project. The contracting officer will define the manner in which the achievement of successive stages in the Quality Assurance and Control procedures is used by the WES Project Manager to control the succession of payments to Acutronic USA under their contract with WES.

The revised Acutronic Proposal 9530A, dated February 1991, consists primarily of an outline specification of the centrifuge and its associated and optional equipment but it also introduces a conceptual design for the containment structure.

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1 M F Randolph, R J Jewell, K J L Stone and T A Brown (1991), Establishing a new centrifuge facility, Proceedings Centrifuge 91, Boulder, June 11-13, Balkema.

In this section comment is made on the optional equipment proposed by Acutronic. Section 1.2 addresses the question of the containment structure and section 2.0 provides a detailed set of technical and performance specifications which Acutronic should be required to meet.

ANS&A recommend that the Acutronic centrifuge should be bought together with all optional items, with the exception of the large platform, subject to Quality Assurance as discussed below.

Optional equipment (references as Proposal 9530A)

III.2,1 Air conditioning

There are two causes of temperature variation to consider. In a typical long duration centrifuge test on a clay specimen the initial warming up of the pit, centrifuge, soil and water, occurs in the same initial period of running as that which is needed in any case for the pore water pressures to approach initial equilibrium states. Once equilibrium is approximately achieved the model test perturbation can begin; for example it may be the introduction of contaminent into a land fill and the slow movement of a contaminent plume into the ground water. However, in general the changes of temperature from night to day during a long duration test are more significant than initial changes during warming up.

Acutronic's proposal, page 12, item III 3, and page 18, item IV 3, refers to air conditioning and to room temperature; it should explain how the low speed fans, thermostat, motor power relay and automatic controller will achieve environmental control of ambient conditions in the centrifuge pit and around the model. ANS&A has not yet had the opportunity for discussion in detail with all potential users of the WES centrifuge and therefore cannot define precisely what temperature limits should be requested, however in general when US research workers work in "air-conditioned" laboratory

conditions they would normally expect full air conditioning.

III.2,2 Closed circuit television

The CCTV will be mounted in the front shroud; consideration will be needed concerning the lighting arrangements to avoid bounce-back of reflected light. The CCTV system must be compatible with the proposed computer system such that a future upgrade would allow digitial image processing.

III.2,5 Centrifuge interface

All computers and all computer controlled items should be the subject of a special review to ensure that hardware and software conform to US standards and that all systems are compatible and maintainable and capable of upgrading in future as required.

III.2,6 Computer system

This should be selected in consultation with WES to be compatible with similar systems on the Station. The make of equipment should be specified.

III.2,7 Software

Acutronic should consult with WES and specify the language used for code development.

III.2,9 Large platform

An optional additional counterweight, and a larger 1.6 m x 1.3 m swinging platform for tests of up to 3 tonnes mass at 200g and 6 tonnes at 100g are offered but should not be bought. If the limiting tests on the standard 350g platform and on the optional additional 200g platform are scaled up to prototype parameters, it is clear that the optional platform is not necessary:

Comparison between standard and optional platforms

Scaled up prototype dimensions and masses	standard 350g platform (1.3m x 1.3m) 2T at 350g	4T at 150g	optional 200g platform (1.6m x1.6m) 3T at 200g	6T at 100g
length (m)	455	195	320	160
breadth (m)	455	195	260	130
area (hundreds of square metres)	2070	380	830	210
mass (megatonnes)	86	14	24	6

The additional 300 mm on the length of the 200g platform would only be useful for a long item of equipment. However, considering for example a hydraulic tank, it would be better to make a special item which could perhaps be a swinging tank of over 2m length, customised to the actual needs of the user, rather than a 1.6 m tank made to fit on a rarely used 200g platform. Alternatively there may in future be a special swinging container for earthquake model tests, which would be better value than the 200g platform. Hence WES should not buy the 200g platform but are recommended to divert such resources as are available for development of instrumentation and equipment to the creation of items for use on the 350g (1.3m x 1.3m) platform for which the machine is now designed, or for the development of special items designed with specific tests in mind.

1.2 CONTAINMENT STRUCTURE

The construction of the containment building and the changes and alterations to the existing office and control building will be the subject of contracts that are separate from the contract for centrifuge manufacture. ANS&A, and potential users of the facility, must be involved in detailed discussion and

planning of those works before contracts for the works are placed.

Acutronic Proposal 9530A (February 1991) suggests a containment building which places the foundation of the centrifuge on filled ground and moves the building away from the original location shown on WES Drawing No. C-3398-1. From these drawings it appears that the centreline of the arm is at an elevation of 192.5 ft which is the same level as the road surface between the centrifuge and the Casagrande building. This elevation for the centrifuge must be changed. A centrifuge of the power proposed for WES should be in a pit. The original 200g centrifuges at Nantes is at the same level as their office and control building. This scheme is not appropriate for WES now that a 350g centrifuge is proposed.

In the existing terrain at WES beside the office and control building there is a gulley which will minimise the need for excavation with the containment building returned to its original location. The formation level for excavation for the foundation of the cave below the centrifuge should be no higher than elevation 157 ft. The cut soil will be useful in making safety berms beside the building.

There should then be a passenger lift and stairwell from the crane access point down to a small door in the wall of the chamber. The air vent passage above the chamber roof will be at right angles to the direction of the crane access way. A separate stairwell will connect the air vent and passage and the motor room in the cave below the centrifuge. There will be no need for large access doors in the wall of the chamber. Neither stairwell shall be open to people during a centrifuge test.

It will be essential for Acutronic to be able to lift heavy objects in the centrifuge chamber, not only during the installation of the centrifuge, but also in future maintenance and possible centrifuge alterations. It remains to be resolved if this has to involve a large access door and a roadway at an appropriate level, or if it may be achievable by other means.

In some centrifuge model tests it is normal to discharge water from test packages in flight. In some tests a blast may cause ejection of solid material. In some tests objects may detatch. In the design of the

containment structure, consideration must be given to collection of all fluids and solids that are discharged. The possible use of polystyrene lining blocks on the pit wall should be considered.

1.3 THE CRANE

The crane in the existing office and control building must be examined to see if it is capable of accurate positioning of models on the centrifuge platform. With such a crane there will be no problem in level separation between the access and pit roof level. There can be a low wall or lip, say about 2 ft high, over which the packages can be lifted before being lowered vertically through the hatch in the chamber roof on to the centrifuge platform. The height of the wall will be dependant on the exact elevation of the centrifuge.

Although ANS&A does not recommend purchase of the optional 200g (1.6m x 1.3m) platform offered at present by Acutronic it is possible that at some future date the crane will be required to carry loads greater than the 4 tonnes permitted on the 350g (1.3m x 1.3m) platform. If it is necessary to replace the crane in order to have more accurate and careful positioning of models on the centrifuge platform then consideration should be given to a change of crane to 6 tonnes rather than the present (10000 lbs) capacity.

1.4 ALTERATIONS TO THE EXISTING OFFICE AND CONTROL BUILDING

The interior of the existing office and control building will require changes and additions to fittings. The padded insulation is soft and will tear and collect dust. There will need to be a suspended ceiling because of dust in model making. ANS&A will review the use of rooms and space, the positioning of windows and so on, and will make detailed proposals for alterations.

1.5 PROGRAMME FOR FUTURE ANS&A RESEARCH CONTRACTS

To assist WES during the project ANS&A have proposed a series of contracts which are linked to different phases of work. These are as follows:

Phase 1 In Phase 1 ANS&A has set out detailed proposals for aquisition of an Acutronic centrifuge by WES.

Completion is achieved with this final report.

Phase 2 In the agreed Phase 2 contract ANS&A will set out detailed proposals for aquisition of centrifuge instrumentation and equipment. ANS&A will comment on dynamic actuation and the achievement of capabilities in the area of blast and earthquakes and on the achievement of other capabilities required and identified by WES;

Target completion end December 1991.

Phase 3 In Phase 3 there will be activities by ANS&A following the decision by WES to proceed further with the aquisition of an Acutronic centrifuge. To assist Acutronic in achieving an efficient design process ANS&A will not wait to comment on the evolving calculations until a book full of all calculations is complete. ANS&A envisage that their Project Engineer in France will continuously review successive portions of the detailed design calculations, month after month, in a manner acceptable to Acutronic, ANS&A and WES. This process will be initiated during the first of the Phase 3 scopes of work, identified as 3A, and will be completed during the second stage, Phase 3B.

3A Agreed lump sum contract (a) to report on the proposed design and construction of the containment structure and on the alterations of the office and control building, (b) to review the needs of potential users of the centrifuge center with a view to identifying areas which may have an impact on the detailed design of the center and (c) to initiate the review of the final detailed centrifuge design calculations.

Target completion end October 1991.

3B Proposed contract for ANS&A to complete the review of the Acutronic centrifuge design

calculations, and to complete the QA and QC procedures for the centrifuge during the fabrication, installation and commissioning phases.

Completion coincides with Acutronic completion of centrifuge commissioning.

Phase 4 In Phase 4 there are activities by ANS&A additional to and extending beyond the Phase 2 consideration of centrifuge instrumentation and equipment, to assist WES in achieving centrifuge capabilities. As with Phase 3, Phase 4 will also consist of two scopes of work, 4A and 4B.

4A Proposed ANS&A assistance to the WES Project Manager and Chairman of the WES coordinating Committee, specification of equipment, development of management structure, assistance with proposals and marketing activities. Assistance with project management and with integration of QA over entire facility.

4B Proposed ANS&A assistance to WES during period of ANS&A custodianship for first and second years of operations and commissioning of capabilities on WES centrifuge.

Completion 1 to 2 years after Acutronic completion of commissioning.

1.6 COMMISSIONING BY ACUTRONIC

Section 4.5 describes the nature of the commissioning tests that will be required before acceptance of the centrifuge by WES. These tests will be carried out under the supervision of ANS&A.

1.7 CUSTODIANSHIP BY ANS&A

For a period following commissioning ANS&A propose to operate the WES centrifuge on behalf of WES whilst training and the development of capabilities is undertaken. This period of custodianship may last for 1 to 2 years. During this time new equipment will be commissioned and tests undertaken to establish the new

facility as a center of excellence in centrifuge research. At the end of this period WES will have a unique facility with outstanding capabilities for new advances in the field of physical modeling.

1.8 MANAGEMENT STRUCTURE

The achievement of capabilities will require the development of an experienced and effective management structure in the period between the commissioning of the Acutronic centrifuge and the handover to WES. ANS&A expect the process to start with the selection of a WES Project Manager.

ANS&A have proposed that a Committee be formed based on the list of authors of the December 1990 draft WES Miscellaneous Paper "Feasibility Study: WES - a centrifuge test facility", to coordinate the involvement of all potential DOD centrifuge users. ANS&A have proposed that Dr Ledbetter be appointed Chairman and that ANS&A participate in all meetings (Drs Steedman and/or Schofield). At the first meeting the Committee should review and revise the list of initial tasks proposed by ANS&A in 1989 in their response to the BAA in the light of their own evolving needs and Acutronic's revised technical proposal 9530A of February 1991.

ANS&A propose that Dr Ledbetter combine the roles of WES Project Manager and Chairman of the Committee. To fulfill both roles he will need to have time allocated to the work, and be able to travel both within the USA and abroad when this is essential.

The Committee's work will lead to an improved definition of the equipment needed for the initial tasks and of potential funding for instrumentation and equipment. The Committee would create a user group, identifying initial and later users. The Committee would clarify the needs for training of USAE personnel.

The Committee will discuss the need for early experience with blast loading. ANS&A propose that contact is established with Tyndall AFB at an early date and that this facility or a similar unit be used to provide early experience for WES users.

The Committee will consider sources of funding for future research and the marketing activities necessary

to build up a strong user group.

ANS&A strongly advise WES to designate a mechanical or other engineer as early as possible in the project who will eventually take responsibility within WES for all mechanical engineering and safety aspects of the centrifuge facility and its operations.

This person would play an important role in project management, assisting the WES and ANS&A Project Managers, in all phases of the quality assurance. However, if such a person is not in place, ANS&A will carry out the tasks that such a person would be required to perform. ANS&A strongly recommend that WES put forward their own engineer by the end of September 1991, but if not then ANS&A must carry these project management responsibilities on behalf of WES as a new activity within the scope of work for Phase 4A (see section 1.7).

During the period of custodianship by ANS&A following commissioning, the new capabilities will be achieved and research data from the new facility will become available. The full range and scope of the new capabilities will not become apparent until experiments start to be completed on the new centrifuge during ANS&A's period of custodianship. At this stage it will become necessary to define the final management structure. The appointment of a WES Director of the facility and of a WES facility Manager shall not be made until the end of the period of custodianship by ANS&A.

1.9 ANNOUNCEMENT

Following the placing of the next contract with Acutronic it will be appropriate to make an announcement that WES are initiating the construction of a major new facility. This centrifuge facility will be unique in certain respects but there are already other centrifuges under order which will rival it in certain features.

ANS&A advise caution in wording, as follows :

> WES are to establish a centrifuge model test facility which will house an Acutronic 684-1 Centrifuge, to be supplied by Acutronic USA Inc. of 139 Delta Drive, Pittsburgh 15238 PA.

1.9 (contd.)

This very powerful centrifuge is expected to operate normally up to 280 gravities with maximum capacity up to 350 gravities with 2 tonnes payload. Installation and operation of the centrifuge in a new special building is expected to be by October 1993.

Capabilities of model testing will be achieved in various fields, including geotechnics, hydraulics, coastal and environmental and cold regions engineering. The relevance of centrifuge model tests to US needs can be judged from consideration of the scale factors in 1/280 scale centrifuge modeling at 280 gravities; the movement of a groundwater contaminent plume in 12 hours in a model represents the movement of a full-scale plume in 100 years in the field; the explosion of a 5 gm charge in a model represents the explosion of 100 tonnes of explosive at full-scale in the field. Such tests can be made scientifically, economically, quickly and repeatedly, and should result in a greater accuracy and lesser number of field tests.

In the achievement of model test capabilities, WES will receive assistance from Andrew N Schofield & Associates Limited of Cambridge, England. Dr Schofield and his associate Dr R S Steedman are authorities on centrifuge model testing; they expect that a unique range of capabilities will have been achieved by December 1994.

2.0 DETAILED SPECIFICATION OF THE CENTRIFUGE

2.1 INTRODUCTION

The objective of providing a system of quality assurance for the centrifuge is to ensure that the new facility will be capable of achieving the new capabilities in physical model testing identified by WES. To achieve a long life the documentation must be structured and complete, assessed independently as meeting appropriate standards for a unique and powerful research facility. Two main components provide the backbone of quality assurance procedures for the centrifuge itself:

1. The definition of a set of technical and performance specifications that will serve as a reference frame for the contract, in the discussions with Acutronic, and for commissioning the centrifuge;

2. The definition of a frame-work of procedures for independent control of the manufacturing and for commissioning of the machine.

2.2 DEFINITION OF A SET OF TECHNICAL AND PERFORMANCE SPECIFICATIONS

Acutronic's proposal 9530 and Technical note 5971 give a detailed presentation of the 684-1 model. However these documents do not include all the information that is needed to define exactly WES requirements, but on the contrary contain information that may change during the design phase and which then should not be made contractual.

Specifications of the facility which can be fixed at this stage are detailed below together with a set of characteristics that Acutronic should define during the course of the design phase.

ANS&A envisages that their Project Engineer in France will apply all the lessons that have been learned from the design, construction and operation of the Acutronic 661, 665 and 680 centrifuges to the process of design of the Acutronic 684 centrifuge. Some of these matters are detailed in sections 3 and 4 on Quality Assurance. However it must be emphasised at the outset that the ANS&A budget does not cover the cost of an independent

fully detailed recalculation for the 684 centrifuge. Reliance is placed entirely on Acutronic calculations, and these calculations relate to a 684 centrifuge specification that greatly exceeds the specification of the 680 centrifuge. The function of the ANS&A Project Engineer in France is to inspect and to review all documents, and to interact positively with Acutronic at all stages of design.

It should be noted that in this report the words "swinging platform" refer to the 1.3 m x 1.3 m platform and to its supporting hangers, and are equivalent to the words "swinging basket" in the Acutronic proposal.

2.2.1 Radius of the centrifuge

Two radii should be specified for operations:

- A "nominal radius" to the centre of mass of a payload of 6m from the axis of rotation at which the performance of the centrifuge is defined;

- A radius of 6.5m to the platform of the swinging basket from the axis of rotation in flight.

2.2.2 Centrifugal acceleration

The centrifuge shall generate controlled accelerations from 10 to 350 gravities (1 g = 9.81 m/s^2) at 6 m radius.

2.2.3 Payload

The payload is the mass that can be carried on the standard swinging platform with a centroid at 6 m radius.

The maximum payload depends on the centrifugal acceleration and should be specified as follows:

2000 kg at 350g.

The nature of the increase in allowable load with reduction in acceleration should be defined by Acutronic (it was noted above that Fig. VI of their proposal has a change of scale on the g axis which is unclear).

The specified values of payload will correspond to a uniform distribution of pressure over a circular or rectangular standard footprint on the swinging platform. The circular footprint will be of diameter 1.2 m and the rectangular footprint is to be 1.3 m x 0.5 m, both located in the centre of the platform.

Acutronic will supply charts defining the maximum allowable values for concentrated or other distributions of load together with values for the maximum allowable local pressures on the platform.

2.2.4 Dynamic tests

Since the centrifuge is to be used to model dynamic problems such as the simulation of strong earthquakes or blast loads, Acutronic will define what dynamic loads are acceptable on the platform in terms of amplitude and frequency range for the three directions (radial, orthoradial and vertical).

2.2.5 Run-life

The centrifuge will be designed for a minimum run-life of 10 years.

For fatigue analysis the centrifuge shall be considered to be rotating for 500 hours per year with the following breakdown of test conditions:

50 % at 100 g
30 % at 200 g
20 % at 350 g

In a typical year the centrifuge will start from rest and stop from full speed about 1000 times.

2.2.6 Factors of safety

Two situations shall be considered for design purposes:

- a **"serviceability limit state"** corresponding to normal operating conditions but under the maximum permitted imbalance of the centrifuge;

- an **"ultimate limit state"** corresponding to the

loss of the whole payload and swinging platform.

For the serviceability limit state all parts of the centrifuge will be designed with a factor of safety of 2.7 to the elastic limit. In addition, a factor will be applied to the masses of the different parts of the centrifuge to cover uncertainties associated with the determination of the actual values. Acutronic will make proposals on this point.

In every conceivable ultimate limit state, the centrifuge should be brought to a complete stop without catastrophic failure of the machine or its support. In the selection of appropriate factors of a safety for the different components (at least a minimum of 1 to the elastic limit), Acutronic shall take in consideration ductility and fatigue requirements, providing the necessary justification in each case.

2.2.7 Characteristics of the 0 - 350 g swinging platform

2.2.7.1 Platform

The dimensions of the available area for packages on the swinging platform are to be:

- width of 1300 mm (horizontal direction perpendicular to the radius);
- length of 1300 mm.

The maximum error in flatness over the platform will be 0.2 mm, ie. ± 0.1 mm.

The maximum deflection between any two points of the loaded area on the platform for all g levels will be less than 1.0 mm, for a uniformly distributed payload over the whole platform or over the standard payload footprints defined in section 2.2.3 .

The design should allow for easy future inspection of all welds.

Acutronic will provide threaded holes on the platform in order to allow fixing of service

plates or positioning of equipment in a matrix to be agreed during the final design.

*2.2.7.2 **Free height***

The platform must accommodate test packages 1300 mm wide, 1300mm long and at least 1100 mm high: additional height would be valuable.

*2.2.7.3 **Lateral supports***

The lateral supports or hangers for the platform should also serve as supports for :

- the hydraulic and electrical lines that run from the hinge to the platform and the test package;
- video CCD cameras.

*2.2.7.4 **Windshield***

The swinging platform should be protected by a windshield comprising the following different parts:

- A front shroud with mountings for a CCD camera or cameras. With the viewing window of a package facing forward, to be seen by the CCD camera, there must be provision that dirt will not be deposited on the window.
- Lateral doors which can be easily and securely installed and which do not restrain the useful volume on the platform;
- a rear shroud largely open to provide easy access to the test package.

*2.2.7.5 **Maximum friction at the hinge***

The swinging platform should oscillate freely at the end of the rotor arm of the centrifuge. During rotation, friction at the hinge will result in an angular shift between the actual direction of the perpendicular to the platform and the resultant of the centrifugal acceleration and earth gravity. Friction should be low enough to limit the angular shift to a maximum of 2°, regardless of the acceleration

and payload.

2.2.8 Vibration of the swinging platform

During rotation the platform should not oscillate or vibrate due to aerodynamic effects or induced mechanical vibrations. The amplitude of vibration along three perpendicular axes should be less than 1% of the imposed centrifugal acceleration on the platform.

2.2.9 Imbalance

The centrifuge should be designed to run with a permanent imbalance of 200,000 N under its serviceability limit state condition.

Under the ultimate limit state the maximum imbalance will correspond to the loss of a whole payload and swinginging platform.

2.2.10 Dynamic balancing system

During rotation a dynamic balancing system will permit slow variations of the moment of inertia of the payload to be compensated. In ANS&A's second interim report a maximum imbalance compensation of ± 1,000,000 N at 200g was specified; in Acutronic's revised Proposal 9530A a maximum imbalance of ± 200,000 N is quoted (without identifying a specific g level). This discrepancy will need to be resolved at an early date during the detailed design phase.

2.2.11 Counterweight

The various payloads are balanced by a combination of fixed and moving elements of counterweights. The selection of masses for the counterweight should correspond to the different ranges of operation of the centrifuge. The presence of the fixed elements of the counterweights on the rotor should be automatically detected by the safety management system.

The moving parts of the counterweight should be shiftable manually or by using a small electric motor placed on the side of the centrifuge axis.

2.2.12 Rotor arm

The rotor arm, between the central axis and the swinging platform, is covered with shrouds on the upper and lower faces. These shrouds should be removable to give access to the space between the two tubes.

The rotor arm is equipped with service channels that carry the hydraulic and electrical (power and low level measurement signals) lines from the pivot to the arm end. Service channels for electric power supply and measurement signals should be well separated. Crosstalk between signal and power channels must not be detectable.

The space close to the axis of rotation will be arranged to accommodate the installation of data acquisition systems and electronic equipment. This area should be defined in more detail in discussion with Acutronic.

2.2.13 Access on to the centrifuge

The stationary part of the centrifuge and the rotor should be equipped in such a way that it is easy for someone carrying small loads to reach and get on to the pivot area and rotor arm.

2.2.14 Motor drive system

The motor drive system consists of an A.C. brushless variable speed induction motor and a gear reducer.

The characteristics of these elements and of the command system will be selected by Acutronic to meet the following specification:

1. Tests must be capable of being run at any g level between 10 and 350g with the maximum payloads defined above in section 2.2.3;

2. The centrifuge must be capable of continuous operation for periods of at least 1 month in duration;

3. A g rate of change (up or down) of 0.55 g/s from 10g to the maximum centrifugal acceleration is to be provided under the computer control. Under manual operation this

rate may be decreased up to 30%. No criteria is specified below 10g.

4. The drive system and motor controller must be demonstrated to be electrically quiet since "the centrifuge testing environment is highly sensitive to electrical noise", Randolph et al. (1991).

5. The drive system must not introduce vibrations into any part of the centrifuge or the building at any stage of operations from rest to maximum acceleration and back to rest. Vibrations at low speed have been known to cause damage to sensitive models.

2.2.15 Control of the specified acceleration

The difference between the actual acceleration and the prescribed value should be less than 0.2% of the prescribed value or 0.1 rpm, whichever is greater, the measurements being made at 10 second counting intervals. This applies without limitation of the duration of rotation of the centrifuge.

2.2.16 Command of the centrifuge

The centrifuge must be capable of being controlled either:

- manually (in which case a given rpm value is prescribed by the operator and the centrifuge speed is ramped automatically),

- or under computer control (the operator defines an acceleration profile).

2.2.17 Orientation of the centrifuge at a stop

It should be possible to rotate the centrifuge manually when the motor is at a stop.

2.2.18 Behaviour of the centrifuge during power cuts or surges

In the case of micro power cuts or power surges that do not cause the motor to stop the command and safety systems must be designed so as not to cause the centrifuge flight to be interrupted.

2.2.19 Sliprings (hydraulic, fibre optic and electric)

The number and and nature of slip rings will be defined at an early date following agreement with WES on their required capabilities.

2.2.20 Safety

Acutronic will provide safety facilities and a safety management system that will reduce the likelihood and consequence of any accident. Human safety and the safety of the facility are considered separately below.

2.2.20.1 Safety of persons

Safety systems will be provided to include:

- the prevention of centrifuge start-up until the operator has positively checked that nobody is in the centrifuge chamber and that the doors are correctly closed;
- the prevention of access to the centrifuge chamber whilst in rotation;
- a signal to the operator that someone is entering the motor chamber or other rooms in the restricted area.

Acutronic will provide emergency push buttons and their integration in the safety management system to inhibit operation of the centrifuge from the centrifuge chamber, the motor pit, the power control cabinet, the centrifuge control desk and restricted access areas.

2.2.20.2 Safety of the centrifuge

Safety of the centrifuge itself is primarily concerned with the detection of imbalance, the prevention overstressing of the centrifuge, the detection and management of the centrifuge operation and environmental conditions.

2.2.20.2 (contd.)

1. *Detection of imbalance*

   The imbalance of the centrifuge is to be measured continuously. The sensitivity of the measuring system should be equal to 1/100th of the maximum allowable permanent imbalance. If this maximum value is reached, the centrifuge should be automatically stopped.

2. *Prevention of overstressing of the centrifuge*

   Since the maximum payload depends on the acceleration level, the safety management system should prevent the risk of overstressing the centrifuge because of an operator error. Operation ranges will be defined by the mass of the payload and the mass of the fixed counterweights.

   The prevention of this risk should be coupled with the automatic detection of the presence of the adjustable fixed elements of the counterweight.

   Acutronic will supply a redundant system of encoders to determine the velocity of rotation of the centrifuge and to detect overspeed.

   When the manual mode is used, the command system should incorporate devices that prevent unacceptable changes in operation ranges by the centrifuge operator.

3. *Monitoring of operating and environmental conditions*

   Detectors will be included as part of the safety management system for monitoring:

   - temperature, humidity and smoke in the motor pit, centrifuge chamber, power supply cabinet and control room in appropriate locations as necessary;

   - flows in the lubricating loops of the

bearings and gear;

- vibration on the centrifuge;

A closed circuit television system with 4 video cameras will be installed to survey the restricted access areas.

All systems will be monitored from the operator's control desk.

Whenever possible the safety management system will warn the operator when an intermediate value is reached and before the centrifuge is automatically stopped. Alarms should trigger audible and visual signals, and be logged by the operator's computer.

All safety devices should be protected against power cuts and surges and should stay operational until the complete stop of the centrifuge.

Under all reasonable circumstances access to the centrifuge chamber should be possible as soon as the centrifuge has stopped.

2.2.21 CONTROL DESK

The command and control desk will include :

- the centrifuge commands and controls,
- the computer interface,
- a desk calculator,
- the safety management system, instrumentation and displays,
- a TV rack and TV monitors of the closed circuit system,
- meters for counting the number of hours of rotation of the motor and of the centrifuge,
- display of the acceleration when using the computer command mode.

2.2.22 INTERFACES WITH THE BUILDING

Acutronic will declare whatever data is critical for the design and construction of the building, including:

- critical dimensions and tolerances of the centrifuge chamber and motor pit;
- limiting aerodynamic pressure distribution in the centrifuge chamber;
- calculated positions and areas of the apertures for air conditioning of the centrifuge chamber in order to limit the temperature increase in the centrifuge chamber;
- maximum forces developed in the foundations of the AC motor, the gear reducer, the centrifuge concrete base and in any other anchoring parts, both for the service and ultimate limit states;
- electrical supply requirements;
- layout of all the conduits and requirements for reduction of electrical noise resulting from currents in all electrical connections between the different areas;
- critical requirements for mechanical access and all procedures and handling requirements for installation of the centrifuge and of the motor drive system in the building, and for all future maintenance.

2.2.23 MISCELLANEOUS

In the contract to Acutronic for delivery of the centrifuge it will be necessary to specify in detail:

1. The roles of Acutronic USA and Acutronic France, and the relationship of the WES Project Manager and the ANS&A Project Manager to them;
2. The manifest of items to be delivered by Acutronic USA;
3. the list of documents to be supplied by Acutronic USA;

4. the extent of the activities of Acutronic USA and Acutronic France on site;

5. the procedures and type of tests necessary for commissioning and acceptance of the centrifuge (discussed in section 4 of this report).

6. The relationship between the flow of payments by WES to Acutronic USA and their performance or their failure to perform the requirements of their contract.

3.0 QUALITY ASSURANCE: GENERAL REQUIREMENTS

3.1 INTRODUCTION

A Quality Assurance (QA) Programme which will provide WES with a general framework for formal quality assurance for the whole centrifuge facility is discussed below. The provision of this facility, its design, fabrication and commissioning, together with the necessary model test equipment and technology transfer will place severe demands on both client and contractor. The implementation of this programme will ensure that the facility which is purchased will be of an appropriate quality for WES's requirements, with a carefully documented history and strict operating procedures which will provide the basis continued safe operations into the future.

Specific requirements relating to the centrifuge, the containment and laboratory building, and to the equipment and instrumentation follow this section.

The QA Programme detailed below provides an overriding quality plan which allocates responsibilities with respect to Quality Assurance, ensures that a consistent and reliable documentation of the project is built up, and provides procedures for the implementation of the programme with respect to the project. The objective is to achieve efficient Project Management and to minimise the risks to all parties which are inherent in such a large and unique development.

The Quality Assurance Programme is based on the requirements of British standard BS 5750:Part 1:1987[1] which is identical to the International Standard ISO 9001-1987 "Quality Systems - Model for quality assurance in design/development, production, installation and servicing" published by the International Organisation for Standardisation (ISO).

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1 BS 5750 : Part 1 : 1987,

Quality Systems, Part 1. Specification for design/development, production, installation and security, British Standards Institution.

3.2 IMPLEMENTATION

The implementation of the QA Programme will be the responsibility of ANS&A, acting on behalf of WES.

The company organisation and reporting responsibilities for this project detailed below. The responsibilities of individuals with respect to the Quality Assurance Programme are defined as follows:

- *Dr A N Schofield, Managing Director and ANS&A Project Manager, Principal Investigator.*

  The Managing Director is responsible for establishing company policy and the Quality Assurance Programme. This includes ensuring the authority and independence of the QA Manager and monitoring the adequacy of the QA Programme.

- *Dr R S Steedman, Associate Investigator.*

  Dr Steedman will act as QA Manager for the WES Project both in Europe and in the USA. The responsibilities of the QA Manager are:

  1. The initiation, development and modification of practices affecting quality;
  2. Monitoring the compliance of project tasks to QA requirements;
  3. Monitoring the implementation and accuracy of the QA Programme with periodic review and audit of QA files, records and WES input;
  4. Evaluation of nonconformance reports;
  5. Definition of remedial measures and follow-up action.

- *Project Engineers.*

  ANS&A will appoint Associates to act as Project Engineers on the WES project. Their responsibilities with respect to the QA Programme are:

  1. Formulation of job tasks and task numbers, such that the project is broken down into well defined elements;
  2. Establishment and maintenance of project QA files;
  3. Investigation, documentation and correction of conditions of non-compliance to the quality

plan;
4. Filing, control and distribution of all project quality related documents;
5. Assuring implementation of the Quality Assurance Programme and procedures.

3.3 PROJECT QA FILE

A project QA file will be established for each project, such as the supply of the centrifuge or for specific projects concerned with equipment development.

The QA file shall be the focus of all project documents. It may be necessary to file project related technical documents, calculations or correspondence files separately for reasons of space and these would form an extension to the project QA file.

The establishment and maintenance of the project QA file is the responsibility of the Project Engineer.

The project QA file shall contain the following information and logs thereof, such that the completeness of the QA file can be verified:

- Contents list specifying the location of any extensions;
- Incoming correspondence and other technical input;
- Calculations;
- Outgoing correspondence;
- Reports;
- Name, specimen signature, specimen initials and start date for all project personnel;
- Documentation of Quality Assurance audits for the project;
- Any other project specific quality related documents.

3.4 DOCUMENT CONTROL

The logs for incoming and outgoing drawings, calculations, specifications and reports shall contain the document number, title, revision and date. All quality related project correspondence shall have document control numbers written or stamped on the front sheet with the receipt date for incoming correspondence and the transmitted date for outgoing correspondence. Correspondence shall be logged in or

out as applicable. Superseded documents shall be clearly marked "SUPERCEDED" and all project personnel using such documents shall be provided with a copy of the updated documents.

3.5 CALCULATIONS

One or more Project Engineers are responsible for assuring that the preparation, review, and approval of calculations is in accordance with the quality procedures. Calculations shall be checked and approved by authorised engineers who did not originate the work for accuracy and adequacy.

All calculations shall be performed, signed and dated by the originator. Calculations shall be approved by direct checking, and the approver shall also sign and date the calculations. The calculations are not considered final until a unique calculation number is assigned. Approved and numbered calculations shall become part of the project files. Computer or spreadsheet runs shall be supported by an explanatory calculation sheet and approved as above.

3.6 REPORTS

The preparation, review, approval and revision of reports shall be in accordance with the quality procedures.

Reports prepared shall be subject to independent review and approval by the ANS&A and WES Project Managers.

Each report shall carry a unique number and the level of revision shall be clearly stated.

3.7 AUDITS AND NONCONFORMANCES

The Quality Assurance Manager shall be responsible for performing internal audits. The purpose of an internal audit is to ensure that the quality requirements of the project are properly implemented and to determine their effectiveness.

A schedule of audits shall be maintained in a log. Requirements for corrective action shall be detailed in an audit report together with a schedule for

implementation. Audit reports shall be maintained as part of the project QA file.

3.8 DOCUMENTATION

Standard forms shall be used to log quality related documentation on each project.

Document control numbers shall be assigned as follows:

Incoming correspondence shall be identified using the project number, the letter I and the number of the correspondence. For example, the first incoming correspondence will be assigned the control number, #-I-001, where # is the Project Number.

Technical input shall be logged using the Project Number, the letter D and the number of the document. Hence the first technical input will be assigned the control number, #-D-001, where # is the Project Number.

Outgoing correspondence shall be logged using a similar control number but using the letter C. Outgoing reports shall be logged using the letter R. Internal inspection or Site reports shall be logged using the letter S. Calculations shall be assigned a unique four letter code followed by a number. Computer or spreadsheet runs will be assigned the code and number corresponding to their explanatory calculation sheet followed by a final number identifying the run. For example, a calculation relating to the centrifuge boom might be identified as, TUBE-01. A spreadsheet run based on the same calculation would be identified as, TUBE-01-01.

Each page within a document or report should be uniquely identified such that the completeness of the document can be checked.

3.9 APPLICATION OF PROCEDURES

Within the framework of the QA Programme procedures have been developed to meet the specific needs of WES for the supply of the centrifuge and for other projects based on the development of equipment.

Section 2.0 discussed the performance specification for

the centrifuge; this can be seen as one aspect of the formal QA requirements for the facility. Section 4.0 describes the centrifuge specific procedures for independent control of manufacturing and commissioning which it would not be appropriate to include with these general requirements.

However, it should be noted that the available documentation for the 684-1 centrifuge is based on pre-design calculations made by Acutronic. It is to be expected that the detailed design of the facility will introduce changes to the specification. The objective of the QA procedures is to minimise the influences of such changes on the centrifuge performance required for WES.

The design, fabrication and commissioning of the centrifuge shall be approved by ANS&A on behalf of WES under the procedures specified in Section 4.0 . The formal structure of documentation and approval (described below) is based on the QA Programme outlined above.

Periodic review of adherence to these procedures, and internal QA audits, will be performed by the Project and QA Managers.

Development of equipment by Acutronic or other contractors will be subject to the same QA Programme. Separate projects will be identified and a Project Engineer assigned to oversee the design, fabrication and commissioning of the equipment. A separate QA file will be maintained for each project detailing the quality related documents.

The QA Programme described above, together with the specific procedures for the centrifuge project described in Section 4.0 will ensure that the design, fabrication and commissioning of the centrifuge and other equipment can be adequately demonstrated and that decisions taken on behalf of WES relating to the centrifuge will be adequately recorded. The objective of the QA Programme is to achieve efficient project management with provision for external inspection, and to minimise the risk of non-acceptance of the facility. The QA Programme is therefore of vital interest to the client, the consultant and the contractor.

4.0 QUALITY ASSURANCE PROCEDURES FOR THE CENTRIFUGE

4.1 BACKGROUND

It is the intention of ANS&A that the ANS&A Project Engineer in France will achieve as close collaboration between ANS&A (acting on behalf of WES) and Acutronic France (acting on behalf of Acutronic USA) as was achieved in the creation of the original LCPC Acutronic 680 Centrifuge.

The design of the LCPC 680 centrifuge was the result of a very close collaboration between Acutronic and LCPC, and the final machine incorporates ideas and concepts from both parties. This collaboration was concluded to have been beneficial to both client and contractor since, firstly, the resulting 680 model met all LCPC's requirements; secondly, comments made during the design phase could be incorporated in a structured manner despite not being detailed in the initial contract; and thirdly, it reduced the possibility of litigation.

There are significant differences in the current proposal for the supply of a centrifuge to WES as compared to the situation at Nantes. A prototype is not being defined from scratch but an existing detailed preliminary design is being finalised and optimised using concepts that have been validated by experience. However there are a number of reasons why it is still vital to establish a close interaction with Acutronic from the very beginning of the design phase:

1. The 684-1 model represents a significant increase in capacity and performance as compared to the 680 machine. As it has been seen from the assessment of Acutronic's proposal there are certains points for which further modifications are necessary.

2. Certain important aspects such the final design of the 350 g swinging platform will need to be discussed again, and the design will need to take into account the way this will be used and how models will be prepared. Acutronic has no specific expertise about geotechical model testing.

3. The efficiency of the centrifuge will be dependent in the integration of the needs for instrumentation and anciliary equipment in the design of the machine. From LCPC's experience it appears also that

significant savings and better arrangements would have been obtained if equipment could have been detailed and incorporated during design instead of at the late stage of installation on site.

The definition of a frame-work for the Quality Assurance procedures for WES will therefore be based on discussion in the following sections of:

- the follow-up for the LCPC machine during the design phase and fabrication;
- a follow-up organization adapted to the context of the WES machine,
- the procedures of quality assurance to be followed by ACUTRONIC,
- the tests and verifications to be performed for commissioning the centrifuge.

4.2 DESIGN AND FABRICATION OF THE LCPC CENTRIFUGE

4.2.1 Design phase

LCPC and Acutronic had regular meetings (minimum of 1 per month) to discuss the progress of the design and to make decisions. Acutronic was asked to pass on details of computations and drawings to LCPC.

For certain important questions such as the stress analysis of the platform and the lateral supports or the modal analysis of the centrifuge, LCPC made independent finite element calculations to improve and check the design, but the responsibility for the design calculations rested with Acutronic. These checks were used to confirm the correctness of Acutronic's analyses.

At the end of the design phase a complete file was submitted to LCPC for approbation, before authorization was given to start fabrication. This included a description of the fabrication and control procedures planned by Acutronic.

4.2.2 Fabrication phase

Regular progress meetings also took place throughout the fabrication phase.

Acutronic was required to obtain approval from LCPC for the use of all subcontractors.

A representative from LCPC made visits to the subcontractors to inspect the manufacturing process, and was present during the commissioning by Acutronic of the different component parts. LCPC expected to be informed directly and as early as possible about the progress of the manufacturing and about any problems that could affect the programme.

Only standard approved materials were acceptable and all material deliveries had to be accompanied by the appropriate certificates of conformity. In some cases, tests were requested of Acutronic to confirm the elastic limit or the weldability.

For all welding work, LCPC required that the qualifications of the subcontractors' workers and their welding procedures be attested by the French Welding Institute, all welds be checked.

For all components, LCPC was informed of the procedures of fabrication and control that Acutronic intended to prescribe to its subcontractors, as part of Acutronic's internal Quality Assurance system. A draft was prepared and discussed with LCPC at the completion of the design phase, following which the final procedures were set up with the subcontractors. This procedure allowed a series of reports to be prepared for LCPC detailing the complete history of all component parts.

4.3 PROCEDURES FOR THE DESIGN AND FABRICATION PHASES FOR THE WES CENTRIFUGE

The conditions for creation of the centrifuge for WES are slightly different in so much as the 684-1 centrifuge is already generally defined, based to a considerable extent on the earlier 680 model. However whilst the LCPC centrifuge is a 200g facility, the WES 684-1 will be designed for maximum operation at up to 350g. Consequently it will be necessary, as with LCPC, to carry out an intensive independent oversight of the design, fabrication and commissioning stages to ensure as far as possible that a facility is delivered which

4.3 (contd.)

can meet WES's requirements.

The following procedures will be adopted:

- regular meetings (at least 1 per month) will be held with Acutronic during which progress of the work will be certified and adherance to the programme discussed. The meetings will provide an opportunity for technical questions to be addressed and for difficulties to be resolved. Problems of the interface between the centrifuge, the civil engineering work and instrumentation or testing equipment will be discussed.

- visits to subcontractors will be made as required, including specifically attendance during commissioning by Acutronic of important components.

ANS&A strongly recommend that a WES appointed mechanical engineer is involved in this procedure, and that WES engineers should participate in meetings in France and Cambridge during the design and fabrication stages.

During this phase Acutronic will be responsible for:

- communicating to ANS&A the necessary information about the design and fabrication;

- informing ANS&A of the subcontractors and enabling ANS&A to gain access to the subcontractors' sites;

ANS&A reserve the right to request that additional quality control tests be carried out.

The design review will involve close collaboration and regular meetings between ANS&A and Acutronic at which calculations will be presented and discussed. Analyses which are regarded as inadequate will be required to be reworked for presentation at a future meeting. In this manner it is anticipated that the flow of Acutronic work should not be interrupted for any significant period at the completion of the design stage as ANS&A will already be quite familiar with the record of calculations which have been performed for the new centrifuge.

The fabrication phase will end following the complete assembly and integration of the centrifuge in France and on shipping to WES.

Progress meetings and special meetings will be documented by brief written reports from ANS&A to WES. A final report will be prepared by ANS&A at the end of the fabrication phase to provide a commentary on the Acutronic documentation concerning design and fabrication.

As the contract for the purchase of the centrifuge has been placed directly with Acutronic, it will be advisable for WES engineers to be present at the factory acceptance test at the end of integration and clearly oversee acceptance at the WES facility at the time of installation and commissioning. ANS&A will provide support for WES for these activities during the commissioning phase at WES and for a period following.

4.4 REQUIREMENTS FOR ACUTRONIC

The contract with Acutronic should include in an appendix details of the system of quality assurance that Acutronic will apply. This should in particular identify all the controls that are to be carried out by Acutronic.

In summary, certain requirements can be clearly identified (the number of copies of documentation will be determined at an early date in agreement with WES):

1. All materials will meet appropriate standards. All deliveries of materials must be accompanied by the appropriate certificates of conformity;

2. For welding work, the subcontractors' workers and procedures will meet that appropriate standards of the Institut Français de Soudure (French Welding Institute);

3. All welds will be checked;

4. Acutronic will inform ANS&A of the commissioning of the different elements produced by its subcontractors;

5. Acutronic will provide, with the centrifuge, files containing all information related to the procedures

of control and fabrication of each component part;

6. Acutronic will provide on a monthly basis in a written form an updated detailed schedule covering the design, fabrication and installation phases;

7. Acutronic will supply complete sets of general drawings with the nomenclature of all parts at the end of the design phase together with a technical report including calculations.

8. The final documentation will be supplied by Acutronic after commissioning of the centrifuge; these documents will include all the modifications made during the installation and commissioning phases, User's guides and maintenance guides for the centrifuge.

4.5 ACCEPTANCE AND COMMISSIONING TESTS FOR THE WES CENTRIUGE

4.5.1 Static tests

For the LCPC machine a certain number of static tests concerning the stiffness of the arm and the swinging platform were imposed in the contract with Acutronic for the following reasons.

A loading test was performed on the swinging platform once assembled (but before its installation on the site) in order to check that its stiffness met the stated deflection criteria. The purpose of the test was to check that the numerical analysis of the swing gave correct estimates of the strains and deflections.

This was considered necessary because of the complex 3-D structure of the platform and the fact that the deflection of the platform was to a large extent a function of the compliance of the lateral supports.

On the LCPC machine the platform is supported at 3 points on each side; there were uncertainties associated with the actual behaviour of the links between the platform and the lateral supports, and concern that the corresponding analytical assumptions would have a significant influence on the deflections since the structure was hyperstatic.

Prior to commissioning the platform could not economically be submitted to loads as high as during rotation with the maximum payload, but this was not necessary as it was considered adequate for the LCPC centrifuge to limit the checking to the elastic platform stiffness.

The tests performed on the LCPC platform in Paris showed than the predictions with the finite element model were in very good agreement with the experimental results both for deflections and strains, and that the platform as designed would meet the technical specifications on elastic deflections.

This experience is encouraging but noting that, although simpler in form, the platform for the WES centrifuge will be required to operate at 350g it will be necessary to confirm computational predictions of the platform stiffness with a static test. These tests will be ordered and paid for by Acutronic, and carried out to a procedure proposed by Acutronic and agreed by ANS&A.

The centrifuge is to be completely integrated in France before it is shipped to WES.

4.5.2 Commissioning tests

Commissioning tests will be required under the contract to be carried out at the WES facility once Acutronic have declared that the centrifuge is ready for operation. The tests are designed to check that the centrifuge performance meets the specification laid down for in the contract:

The tests will include:

1. Operation from 10 to 350 g in 10 g steps with the maximum authorized payload. For each step the centrifugal acceleration will be maintained constant for 10 minutes;

2. Operation from 0 to 100, 150, 200 and 350g with the maximum payload, at the maximum rate of variation of g;

3. A check of the imbalance measurement system with known masses placed on the platform up to the maximum permitted permanent imbalance. This

includes determination of accuracy and linearity;

4. A check of the behaviour of the automatic in-flight balancing system up to its maximum capacity;

5. Two tests of endurance of 48 hours each will be made, with the appropriate maximum payload on the swinging platform at 200 g and at 350 g, and with detailed measurements of temperatures, stresses, vibrations and all other relevant parameters;

6. A test will be required at at least 100g to demonstrate that the angular shift between the perpendicular to the platform of the swinging platform and the resultant of the centrifugal acceleration and the direction of earth's gravity is less than 2°.

7. Tests will be made to identify the first modes and frequencies of vibration of the centrifuge in flight;

For all these tests, Acutronic will:

- place strain gauges on the rotor, and on the swinging platform, at locations agreed upon with ANS&A;

- provide all the necessary instrumentation to measure and record the following parameters:

  a. acceleration as function of time;
  b. strains on the centrifuge;
  c. vibrations on the base of the centrifuge, and in the swinging platform;
  d. power consumption of the motor;
  e. temperature changes in the motor drive system;
  f. temperature level in the centrifuge room as compared to the ambient value;

WES will provide the payloads necessary for the commissioning tests at WES.

The satisfactory operation of all accessories will be demonstrated. The safety management system will be will be shown to be fully operational. Power cuts will be simulated during rotation.

5.0 INTEGRATION OF QUALITY ASSURANCE OVER THE CENTRIFUGE, BUILDINGS, INSTRUMENTATION AND EQUIPMENT

5.1 INTRODUCTION

Development of the full range of capabilities in centrifuge modeling at WES will require careful consideration of the interaction between the centrifuge, the containment structure and the laboratory building. For example, future development of a capability to run substantial water flows through a model would be inhibited if adequate provision was not made at the design stage for water drainage from the centrifuge chamber.

Acutronic's Proposal 9530A shows the centrifuge located in a containment structure adjacent to the office and control building. This containment structure will need to meet design criteria associated with a limit state event such as the loss of the swinging platform and its payload at 350g. In its detailed design it will need to provide adequate anchorage, even under these stringent conditions, to ensure the centrifuge does not become disconnected from its foundation.

5.2 QUALITY ASSURANCE AND PROJECT MANAGEMENT

During ANS&A's Phase 1 activities attention was focussed on the outline design of the centrifuge. Once the detailed design phase has begun there will be a series of decisions that need to be taken quite rapidly as questions on the specification of the centrifuge and its associated equipment arise.

These decisions will not be taken in isolation but will have consequences for the containment and laboratory building. Similarly, decisions concerning the containment and laboratory building will have an influence on the development of capabilities.

Close management of these different activities will be necessary to ensure that, for example, calculations carried out to meet Quality Assurance procedures for the centrifuge, its equipment and instrumentation are integrated with the design approach for the containment structure.

5.3 PROCEDURES

ANS&A will be responsible for carrying out the Quality Assurance procedures for the centrifuge and for items of equipment and instrumentation. The information arising from this process will become a part of the safety information of the facility where it will be integrated with further information on the containment and laboratory building which will arise during the design and construction phases.

ANS&A is therefore well placed to assist WES with the coordination and management of the overall project. The advantages of this approach are that prior to the appointment by WES of a mechanical or other engineer (who will untimately take responsibility within WES for all mechanical engineering and safety aspects of the centrifuge facility and its operations) expert advice will be on hand concerning the integration of the centrifuge and the remainder of the facility. Information which will ultimately form part of the safety information for the facility will need to be identified and approved within the Quality Assurance system. This would be achieved most efficiently by the development of a single QA system.

Following commissioning of the centrifuge by Acutronic, ANS&A will work with WES (during a period of custodianship) to achieve the outstanding capabilities planned for the facility. Close involvement by ANS&A during the design and construction of the facility as well as in the management of all early operations of the centrifuge, its instrumentation and equipment will greatly facilitate that task. ANS&A will be responsible for the integration of the facility safety information.

6.0 QUALITY ASSURANCE PROCEDURES FOR INSTRUMENTATION AND EQUIPMENT

6.1 INTRODUCTION

Quality Assurance is as necessary for all items of centrifuge equipment and instrumentation as it is for the centrifuge facility itself. New equipment, introduced to the facility, constitutes a change and creates an increased risk of an accident. The management of the introduction of new equipment or instrumentation must therefore be rigorous, based on established procedures.

In section 3.0 of this report a specification for the general QA requirements was laid down. This provided a framework of procedures for the management of change within the facility, applying equally to the centrifuge and to the introduction of any new equipment.

This section provides an interpretation of these procedures as they are applied to equipment and instrumentation and gives some explanation of the background to the required calculation procedures.

6.2 FUNDAMENTALS

All equipment or instrumentation for use in a centrifuge facility will have an intended function and its designer will have had to consider the mechanics which underly that function. For example, in the case of the centrifuge, the physics which lies behind the accelerations acting on the rotating boom are well understood. However, in the case of an instrument such as a cone penetrometer, or in the case of an item of equipment such as a downward hydraulic gradient consolidometer these principles are not so well established and careful consideration is needed before such items of equipment can be designed and commissioned.

The principles of a particular class of centrifuge model test are usually explained in the theses of research students or in the proceedings of specialty conferences or in specialty journals; in all these examples there is public debate and peer review. However, with the diverse, and in some cases possibly classified, range of capabilities that are expected to

be developed at WES these opportunities to scrutinise the theory behind equipment development may be lacking. For this reason it is particularly important to construct and enforce a rigorous and formal assessment of the function and performance of equipment proposed for use on the centrifuge facility.

For example, in cases such as those identified above, it will be necessary to generate a statement of the principles underlying an item of equipment in a way that is intelligible both to the engineers and scientists who are intending to use that equipment and to the engineers and operators who are responsible for the safe operation of the centrifuge. In some cases it may be necessary for a special study to be made with experiments and calculations to prove that principles that are stated will apply to the item under consideration.

6.3 REQUIREMENTS OF EQUIPMENT QA

Quality Assurance procedures applied to equipment and instrumentation will provide a structured approach to their safe management and utilisation. The use of a QA project file for each item of equipment or instrumentation will address five major requirements. These are:

1. To provide a statement of purpose for the equipment or instrumentation;

2. To provide a statement of the mechanics and physics that underly that purpose;

3. To provide approved calculations or demonstrations of the strength or power and performance of the equipment;

4. To record the manufacture, commissioning, utilisation and modification of the equipment;

5. To record the performance and maintenance of the equipment.

6.4 CALCULATIONS FOR SAFETY OF EQUIPMENT

Section 7.4.3 describes in detail the nature of the stress checking calculations required for equipment to demonstrate its safety in centrifuge flight. The calculations which are required for QA purposes, concerned primarily with safety are thus based as far as possible on full plastic stress redistribution. Where an item is made of ductile plastic material its strength is therefore determined by a calculation of upper and lower bounds to plastic collapse loads.

Where an item is made of brittle material a calculation of maximum stress and of risk of failure is required. A calculation of stiffness involves knowledge of elastic properties of the materials from which the item is made. These calculations can be verified by physical tests of deflections under load. However it is important to state that if in fact a measured deflection, for example of a loaded platform, agrees with an elastic finite element calculation, this does not prove that the item is safe. There may be a stress concentration that will in time initiate cracking, but does not affect deflections.

The uncertainty surrounding stress concentrations in brittle materials is a further reason why the consequences of failure of such items needs to be carefully defined. In particular it must be established that failure of a brittle item will not lead to consequential failure of other items.

7.0 SAFETY OF OPERATIONS

7.1 INTRODUCTION

In 1980 Professor Schofield delivered the Rankine Lecture to the British Geotechnical Society in which he described the operations of the Cambridge Geotechnical Centrifuge Centre[1]. The Appendix to the Rankine Lecture presented in detail the requirements established at Cambridge University for the safe operation of the beam centrifuge facility.

The design, fabrication, installation, commissioning and operation of a centrifuge and its associated equipment and instrumentation represents a process which is vulnerable to catastrophic accident. There have been several examples of centrifuge accidents in recent years, such as at the Sandia Laboratory and at NASA AMES. It is significant to note that both of these involved large centrifuges at US Government laboratories. Both of these accidents were avoidable and it is therefore essential that the new WES centrifuge facility is subject to a management system which establishes an effective safety regime for all operations.

In this report a distinction is drawn between general requirements for safe work practices within a laboratory and requirements which are specific to the centrifuge facility. For example within the new office and control building the power supplies, cranes and other mechanical and electrical equipment will all pose hazards in a general sense to workers and to visitors. Clearly WES will require the new laboratory to conform to its own safety regulations and to any applicable federal state or local regulations.

This report will concern itself with management safety systems which relate to the centrifuge facility and its operation. The approach adopted here is to identify separately the questions of management of change, normal operating procedures and training.

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1 Schofield, A.N. (1980),

Cambridge Geotechnical Centrifuge Operations, Geotechnique **30**, No. 3, 227-268.

7.2 SAFETY INFORMATION

7.2.1 General

Within the centrifuge facility there will be a range of hazards from equipment and materials. For example there will be hazards to safety from chemical contamination, dust and explosives. A documented compilation of safety information should be developed and maintained for the facility describing the hazards presented by all materials and equipment. This would include toxicity information, physical properties, corrosivity data and so on. The safety information should also include information on mechanical design of equipment.

7.2.2 Mechanical Design Information

All systems of equipment, such as the centrifuge and custom built model test equipment, should be documented and design details maintained as part of the facility safety information. Information on the centrifuge would include design drawings and calculations, material certificates, fabrication records and safety information on systems for shutdown and inter-lock. Information on off-the-shelf items such as pumps or cranes would include the manufacturer's specifications and instruction manuals.

7.3 HAZARDS ANALYSIS (HAZAN)

Prior to first start-up of the centrifuge a Hazards Analysis (HAZAN) should be performed for the facility with the object of minimising the likelihood and consequences of an accident.

The HAZAN should consider accident scenarios and assess their likelihood and consequences. Changes which could reduce these risks would be identified. As the centrifuge will be a new facility particular attention should be paid to the design process and to any changes in the design team or in the design which may have had unforeseen consequences.

The HAZAN should be performed by a team knowledgeable in engineering, centrifuge modelling, storage and use of explosive and toxic materials, mechanical design and

operations. At least one member should be experienced in HAZAN techniques, and at least one should not have participated in the design process.

A written report would present the team's findings and recommendations which should be implemented by the facility management team. Depending on the changes in technology or use of the facility the HAZAN should be reviewed at intervals not exceeding three years, but more frequently if appropriate.

7.4 MANAGEMENT OF CHANGE

7.4.1 General

Accidents are frequently caused by change and the management of change is therefore a critical part of the safety process. Thus the start-up of the facility itself, the proof testing of new equipment, the arrival of a party of visitors are all examples of change which create an increased risk of accident. Management of change covers three broad topics: facility management, equipment qualification and safety checks, both before a flight and after any changes that may have been induced by events occurring in flight.

7.4.2 Facility management

In the Appendix to the Rankine Lecture a management structure comprising a Director, authorised engineers, centrifuge operators and research workers was defined as applicable to the Cambridge beam centrifuge facility. In recent years the increased workload and complexity of model tests in Cambridge has led to a further position of Beam Manager who takes day-to-day responsibility for the safety of the facility on behalf of the Director.

At the WES facility it is anticipated that a similar group of 'resident' experienced workers and 'temporary' visiting workers will evolve over time. The large size of the facility and of the model test equipment will also lead to operations which are similar in style to those at Cambridge. A similar management structure to Cambridge is therefore proposed for WES, with the following duties and responsibilities. While the centrifuge

7.4.2 (contd.)

is under the custody of ANS&A the functions of the Director, Centrifuge Manager and Centrifuge Engineers, will be discharged by ANS&A.

Director The Director of the WES Centrifuge Center will retain overall responsibility for the facility and its operations, including the authorisation of centrifuge engineers and modelers.

Manager The facility Manager of the WES Centrifuge Center will be responsible for day to day administration and safety of operations, including the test programme.

Engineers Engineers employed by WES who have sufficient experience of centrifuge model testing to give engineering approval to the tests of others, to train other users or operators, to operate the centrifuge themselves or to act as centrifuge modelers themselves. The approval of a pre-flight safety check will only be made by an authorised centrifuge engineer who is not also the centrifuge modeler.

Operators Engineers or technicians employed by WES who have sufficient experience of centrifuge operations to advise and assist other authorised users, to verify test documents, to mount packages, to start the centrifuge and to undertake activities as directed by an authorised centrifuge modeler within an agreed programme.

Modelers Research workers, engineers or visitors with sufficient experience of the operation of the centrifuge to propose and undertake programmes of approved model tests. It is the responsibility of the centrifuge modeler to prepare, and to gain authorisation for, a pre-flight safety check.

The wide range of capabilities available on the centrifuge will mean that users of the facility are changing frequently. The list of authorised engineers, operators and modelers will only include those with current experience and with a need for authorisation; authorisation will only be given by the Director.

The pre-flight safety check, described in Section 7.4.4, is a critical aspect of the management of change. Its authorisation by the facility management will permit the initiation of a model test series on the centrifuge.

7.4.3 Equipment qualification

The initial or proof test flight of new equipment is one of the most severe aspects of change that can endanger the facility. The qualification of new or modified equipment prior to use is therefore of paramount importance.

To obtain written approval from an authorised centrifuge engineer for equipment to be used on the centrifuge a stressing check for the equipment must be carried out.

7.4.3.1 Stress checks for centrifuge equipment

Self-weight loading under high gravities is calculated on the basis either of the acceleration of each mass at its actual radius or on the basis of all masses at a nominal radius of 6 m for the Acutronic 684-1 centrifuge.

Calculations will assume that all containers are filled with saturated soil to their maximum working level and that this soil may become fluidised and apply pressures equivalent to a fluid of density 2100 kg/m^3.

Fluid reservoirs or supply lines should be assumed to be filled either back to the rotor axis and above or to their vent levels if they are vented into the chamber.

In the Rankine Lecture the 'first flight' of an item of equipment was described as a proof test. As a proof test constitutes the

7.4.3.1 (contd.)

deliberate introduction of change the authorisation and execution of a proof test flight was defined rigorously. For the WES facility the concept of a proof test is extended to cover all centrifuge flights that accelerate any exposed equipment to within 20% of its maximum past g level. This class of test is called a gmax test and operating procedures for these tests are defined in Section 7.4.3.2 .

Centrifuge flights which accelerate equipment to 80% of its past maximum g level or less are classified as gnorm tests and are subject to the normal operating procedures described in Section 7.5 .

This differentiation of higher/lower risk flights is based on safe working practices which have evolved at Cambridge and at other major centrifuge centres. At these facilities experience has led to a policy of testing models at the lowest practical g level based on considerations of model size. It has been found from experience that within 20% of the proof test acceleration operator stress rises rapidly and the concentration of the modeler shifts from concern over the quality of the model under test to concern over the structural integrity of facility.

In general, then, the maximum g level for stress checking and equipment design will be 1.25 times the planned test g level. In circumstances where it is absolutely necessary to use the centrifuge facility or its equipment near to their maximum design capacity the regulations relating to gmax tests will be adopted and the maximum g level for stress checking will correspond to the test g level.

Following the guidance above on self-weight loading, equipment design will be approved on the basis of calculations showing full plastic stress redistribution at the maximum design g level. Elastic calculations will provide valuable information on stiffness and

7.4.3.1 (contd.)

deflections of equipment under high g but will be regarded as insufficient for the authorisation of exposed equipment for testing.

Standard properties for common materials will be adopted as follows:

mild steel specific gravity 7.83, working stress 136 MN/m^2;

dural specific gravity 2.82, working stress 130 MN/m^2.

These working stresses, to be used with full plastic stress redistribution, include a safety factor of 2.5 .

Bolts, such as Unbrako type, are considered ductile if not stressed above 30 MN/m^2 in tightening up and are designed for 275 MN/m^2 under maximum design g loading. This working stress includes a safety factor of 3.5 . If highly torqued, to ensure a seal or friction joint, bolts must be discarded after 30 uses.

Where perspex is used for windows it must be secured by a metal frame with rounded edges not less than 6 mm radius. The perspex must be kept free from scoring. Under maximum design g loading perspex is considered to have a specific gravity of 1.3 and may reach 7 MN/m^2. This includes a safety factor of 2 and a stress concentration factor of 2. In other conditions the stress concentration factor may rise to 3.5 or greater and the working stress will be reduced accordingly.

The design of windows as flat plates will follow Roark[1]. For example Roark Case 70 gives stresses and deflections in a flat plate under triangular loading with all edges fixed. For

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1 Young, W.C. (1989),

Roark's formulas for stress and strain, 6th Edition, McGraw-Hill.

the calculation of deflection perspex will be assumed to have a Young's Modulus of 2.8 GN/m^2.

The objective of the authorising engineer in this process is the prevention of secondary damage to the centrifuge facility through failure of equipment components. Plasticity calculations with a requirement for material ductility provide a safe and simple approach to stress checking, allowing for the detection of

overstressing through deflection rather than through brittle fracture.

7.4.3.2 Centrifuge flights under gmax conditions

The term gmax is used to identify centrifuge flights where the structural integrity of the facility is deliberately put at risk in order to fully achieve the maximum capabilities of the centrifuge and its equipment.

This section describes the management of a gmax test. Pre-flight safety checks are considered in Section 7.4.4 .

During the gmax flight the centrifuge will be under the command of the Authorising Centrifuge Engineer, who will be present at all times. The flight will follow a previously agreed program of activities as directed by the Authorised Centrifuge Modeler. The Centrifuge Operator will seek approval from the Centrifuge Engineer for each instruction. Each instruction will be noted in the flight log.

At the end of the flight the Centrifuge Engineer will sign the flight log as a true and accurate record of the flight.

The agreed program of activities may include a high g proof test of equipment followed by a slowing of the centrifuge to conduct a model experiment. If the centrifuge acceleration is reduced to 80% of the flight maximum or less and the Authorising Engineer is satisfied as to the continuing safety of the facility the Engineer may declare that gnorm procedures are to be followed for the remainder of the flight.

Any change in flight status will be noted in the flight log.

7.4.4 Pre-flight safety check

Prior to each flight the Centrifuge Operator will carry out a Safety Check. This will include the following :

7.4.4.1 Inspection of documentation

For gmax flights, the documentation will comprise

1. A summary sheet giving the total mass of the package, the required fixed counterweight, the likely change in balance during the flight, the previous maximum g level, the services required and the flight programme. The summary sheet will be signed by the Centrifuge Modeler and by a Centrifuge Engineer.

2. A flight manifest detailing all components of the model test equipment, their masses and centroid position. The likely change in balance during the flight for each component will be identified and the overall change in balance calculated. The manifest should be supported by sketches of the model test equipment clearly indicating the coordinate axes and direction of travel.

3. Stressing calculations separately approved by a Centrifuge Engineer qualified in the appropriate field. These calculations should be in accordance with the requirements of Section 7.4.3.1 . Stressing calculations are not required for gnorm tests.

7.4.4.2 Loading of equipment

The Centrifuge Operator will be responsible for loading all test equipment onto the centrifuge and for ensuring that it is adequately secured. The weight of the equipment and the fixed counterweights will be positively checked by the Operator against the Flight Summary.

7.4.4.3 Systems safety check

Immediately prior to centrifuge start, the Centrifuge Operator will evacuate the secure areas, inspect the model and the centrifuge and check that the chamber is clear of loose objects. The centrifuge operator will note in the log the details of the flight, including the names of those present. The centrifuge operating systems will be checked and warning systems initiated in a prescribed sequence.

7.5 NORMAL OPERATING PROCEDURES

Under gnorm conditions the Centrifuge Engineer need not be present in the control room. However, it is required that the Engineer be "on call" at all times during a gnorm flight; it is the responsibility of the Centrifuge Modeler to provide the Operator with information on the location and availability of the engineer prior to the start of each flight.

During the gnorm flight the Centrifuge Operator will follow instructions from the Modeler provided that these fall within the agreed flight programme and subject always to being satisfied as to the safety of the facility. The Centrifuge Operator may stop the centrifuge at any time if there is cause to suspect a malfunction or to prevent an accident.

With these exceptions, the safety management of a gnorm flight will be identical to that of a gmax flight.

7.6 TRAINING

The training of new Modelers, Operators and Engineers will be carried out under a defined programme of objectives. The most effective form of training will involve periods of formal instruction and periods in which trainees work alongside experienced Modelers, Operators or Engineers.

Centrifuge Engineers and Operators will be trained in accident and emergency procedures.

Authorisation of Centrifuge Modelers, Operators and Engineers is the responsibility of the Director.

Refresher training will be provided as required, and in particular on each occasion when a change in operating procedures or new equipment is introduced.

Individual training records will be maintained as part of the Safety Information of the facility.

7.7 EMERGENCY RESPONSE AND CONTROL

An emergency which arises during whilst the centrifuge is not operational will be covered by the general procedures established for the facility.

There are a large number of hazards associated with equipment and materials, some of which have been outlined above, which could contribute to an increased risk of accident. However human factors, such as fatigue brought about by the stress of long runs, may be equally serious in threatening the safety of the facility and must be considered carefully in any accident scenario.

A plan to deal with emergencies which occur whilst the centrifuge is operational will be established and the Centrifuge Operator will be responsible for taking the necessary actions.

7.8 INVESTIGATION OF ACCIDENTS

All incidents which did result in an accident, or could reasonably have resulted in an accident, will be investigated by a team appointed by the Director.

The findings of the investigation will be recorded and kept as part of the Safety Information of the facility.

A system will be established to ensure that agreed-upon actions which arise from the investigation are implemented.

7.9 AUDIT

An audit of the Safety Management Systems will be carried out periodically to ensure their effective operation. The interval between audits should not exceed three years. The Audit team will be appointed by

the Director and their report will be kept as part of the Safety Information of the facility. A system will be established to ensure that agreed-upon actions that arise from the audit are implemented.

7.10 DISCLOSURE OF INFORMATION REGARDING SAFETY

The intention of WES to create a world class facility, and to attract internationally distinguished visitors in many fields of activity to WES, may lead to a conflict of interest. On the one hand generally it will be of advantage to WES to receive expert comment and advice and therefore to disclose details of centrifuge model test operations to visitors. On the other hand in particular instances it will be in the national interest of the USA or in the local interest of WES not to discuss details of model test operations with visitors.

In all cases there must be full disclosure of all operations to one or more members of the WES Safety Audit team: in particular all blast, shock or other serious loading or toxic contamination must be kept under review by the Audit team and must be fully documented. In any case, where an item of equipment that is made available to a visiting centrifuge modeler has been subject to blast, shock or other serious loading or toxic contamination in the past, there must be a disclosure to the visitor of any matter which may jeopardise the visitor's project or themselves.