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No. 4

Safe Operation of Critical Assemblies and Research Reactors

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CONTENTS

1. INTRODUCTION .. 9
   - 1.1. Purpose .. 9
   - 1.2. Scope .. 9
   - 1.3. *Limitations* .. 12
   - 1.4. Definitions .. 13

2. CRITICAL ASSEMBLIES .. 15
   - 2.1. Safety of Design of Critical Assemblies .. 15
   - 2.2. Safety in Instrumentation of Critical Assemblies .. 21
   - 2.3. Safety of Construction of Critical Assemblies .. 27
   - 2.4. Safety in Operation of Critical Assemblies .. 27
   - 2.5. Radiological Protection Instrumentation .. 35

3. RESEARCH REACTORS .. 38
   - 3.1. Safety of Design and Instrumentation of Research Reactors .. 38
   - 3.2. Commissioning of Research Reactors .. 41
   - 3.3. Safety in Operation of Research Reactors .. 42
   - 3.4. Experimental Use of Research Reactors .. 47
   - 3.5. Radiological Protection Instrumentation .. 50

4. PERSONNEL .. 51
   - 4.1. Introduction .. 51
   - 4.2. Qualifications .. 51
   - 4.3. On-Site Training .. 52
   - 4.4. Examination and Control .. 53

5. ADMINISTRATIVE PROCEDURES .. 54
   - 5.1. *The Safety Committee System* .. 54
   - 5.2. Duties of the Safety Committee .. 56
   - 5.3. Composition of the Safety Committee .. 56
   - 5.4. Safety Committee Procedure .. 58
   - 5.5. Duties of the Operations Safety Committee .. 59
   - 5.6. Composition of the Operations Safety Committee .. 60
   - 5.7. Operations Safety Committee Procedure .. 61

6. SAFETY DOCUMENTS .. 63
   - 6.1. Safety Reports .. 63
   - 6.2. Form for Routine Irradiations .. 68
   - 6.3. Form for Simple Experiments .. 70
   - 6.4. Core Certificate .. 70
   - 6.5. Other Documentation .. 73

7. **EMERGENCY PROCEDURES** 74
7.1. General 74
7.2. Local Incident 75
7.3. Site Emergency 77
7.4. Public Emergency 79
7.5. Requirements of the Health Physics Service 80

ACKNOWLEDGEMENT 81

APPENDIX I: BIBLIOGRAPHY 82
Section A: General References 82
Section B: Safety Reports 85
Section C: Siting and Containment 85

APPENDIX II: REACTOR STANDING ORDERS AND OPERATING INSTRUCTIONS 87
Section A: Reactor Standing Orders 87
Section B: Reactor Operating Instructions 92

APPENDIX III: SYLLABUS OF A REACTOR TRAINING COURSE 95

1. INTRODUCTION

1.1. PURPOSE

1.1.1. This Manual is provided as a guide to the safe operation, as defined in Section 1.4.4., of critical assemblies and small research reactors. It is intended that it should be used by all authorities and persons concerned with, or responsible for, the use of such equipment, in addition to the scientists and technologists who are actually working with, or operating it. It is suggested that it will be of use to those wishing to design and manufacture, or purchase, critical assemblies or research reactors, as well as those already in possession of them, and that it will prove particularly helpful to those users who have no direct access to other collected sources of information.

1.1.2. This Manual is not a set of rules or a code of practice, but a series of recommendations which must be interpreted with scientific judgement in their application to any particular problem. The guiding principles are given from which good operational procedures may be established and improved. The promulgation of rigid standards is both impossible and undesirable at the present time, since the topics discussed form part of a rapidly growing science and technology. Therefore, any recommendations made should not be used to restrict or inhibit future developments.

1.1.3. The Manual is intended mainly for use in those Member States where there has been little experience in the operation of critical assemblies and research reactors. It has been compounded from the best practices which exist in Member States having a large amount of such experience, so that nothing in it should conflict with the best practices to be encountered in the field of safe operation.

1.2. SCOPE

1.2.1. The safe operation of critical assemblies and research reactors involves very many fields of information and experience. Many of these are covered in this Manual. Not all of them are directly concerned with safe-operation. The fields included in this Manual are the administrative procedures required, safety in design and construction, the commissioning of critical assemblies and research reactors, staff training, qualifications and experience, the operation of such equipment, and (especially for research reactors) their experimental use. An Appendix* describes the detailed application of the Manual to a hypothetical research reactor, and a Bibliography** is also included.

1.2.2. The ultimate safety of critical assemblies and research reactors can only be ensured if due attention is given to safety at all stages in the life of the critical assembly or reactor. The design and material selection must meet acceptable standards and must incorporate such special safety features as are judged necessary; the construction must be of the requisite quality and use the material specified; the operation of the system must take into account the possibility of accident due to error or to the system itself; and finally, experiments performed with the aid of the system must be designed and carried out so that neither the system nor the experiment is in any way endangered.

1.2.3. For the purpose of this Manual, some of the subject-matter has been divided into two parts. This division occurs naturally because some systems require separate operating and experimental teams for their efficient use, whilst others may be better utilized by means of a single team. However, in the latter case, particular personnel within the team may be primarily responsible for operation or experimental use.

1.2.4. Section 2, headed "Critical Assemblies", includes discussion of the safety of critical assemblies themselves, zero-energy reactor systems (i. e. those operating at power levels up to a few watts), and so-called sub-critical assemblies when sufficient fuel and moderator is present to enable criticality to be achieved, even if only accidentally. All these systems are usually utilized by a single team.

1.2.5. Section 3 of the Manual, entitled "Research Reactors", will be applicable to small- and medium-sized research reactors primarily used by physicists rather than by engineers involved in large-scale experiments. It will be applicable also to reactors which have facilities for small-scale engineering experiments, but it is not intended that this Section, or the Manual, would cover those high-power, high-flux reactors which are used for large-scale engineering experiments. It is difficult to set an upper size limit in terms of power level, since this is very dependent upon the reactor type. It is anticipated that the scope of this Section will

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* Appendix II, p. 87.
** Appendix I, p. 82.

include those reactors operating in the kilowatt region, and may include some reactors operating in the megawatt range. It is expected that these reactors will be staffed by separate teams for operation and experimental use.

1.2.6. In the Section headed "Critical Assemblies", design and construction have been discussed in some detail, but for the "Research Reactor" Section the general principles only have been given, although attention has been drawn to the design of experimental equipment. The design and construction of a research reactor is necessarily a complex procedure requiring a large and highly experienced design organization, together with well-developed manufacturing facilities. The details of design and construction of research reactors are felt, therefore, to be beyond the scope of this Manual.

1.2.7. A Section of the Manual is devoted to emergency procedures. This Section is not to be regarded as a complete guide to such procedures. However, those sections of this work which are necessary to minimize hazards in the event of an untoward incident with the assembly or reactor are considered. Similarly, the Manual is not a complete guide to the radiological protection organization of an establishment, although this subject has been discussed where it is necessary.

1.2.8. The Section concerning training is intended to serve as a guide to the qualifications and experience which are to be expected of experimental and operating staff at the various levels. The training methods are also briefly discussed.

1.2.9. One Section has been devoted to administrative procedures. This is regarded as a most important Section, since good organization can prevent many accidents. Experience to date has shown that most reactor accidents, and especially those occuring in critical assemblies, might have been avoided if adequate written proceduces had been available and adhered to, and if sufficient emphasis during training had been placed upon the requirements of personal discipline during operations. This Manual is primarily concerned with nuclear safety and not with what might be termed "conventional safety". It is assumed, therefore, that administrative procedures governing conventional safety will be carried out as has been the practice in the past, and in accordance with national legislation. Examples of such matters are safe design of pressure vessels; inspection of such vessels and piping during and after manufacture; mandatory building require-

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ments; and regulation of operations with explosive or flammable materials.

1.2.10. Three appendices are included. The first contains a bibliography of freely available reports, and is divided into three sections. Section A contains general references and references to operating and administrative procedures. Section B contains references to safety reports, whilst Section C is a bibliography of important references to the problems of siting and containment (Paragraph 1.3.1.). The second appendix provides examples of reactor standing orders and operating instructions, involving the application of the principles contained in this manual to a particular reactor system. A third appendix gives a suggested syllabus for a reactor training course.

1.3. LIMITATIONS

1.3.1. The subject of siting research reactors has not been considered in this Manual. Similarly, the related problem of containment of reactors has not been discussed. These two omissions are deliberate and have been made for two reasons. Firstly, the basic approach to these subjects is not yet clearly defined. There are considerable differences in practice between Member States. Much work remains to be done in this field before an international series of recommendations could be produced. Secondly, these two questions are at present a matter for national policy and are associated with the problems of national licensing procedures and control of reactor siting. These problems should form the subject of a separate manual. It has been assumed in this Manual that the site for the reactor has been chosen and that the question of containment has been agreed. Because of the importance of these problems, a bibliography of freely available documents has been included as Section C of Appendix I.

1.3.2. Research reactors used in fast kinetic experiments (such as BORAX) have not been included in this Manual. Such reactors from a very small class of their own; their design and operation are intimately connected with their siting and containment. Often they are designed in the knowledge that the experiment to be performed on them in order to obtain certain dynamic information might lead to their self-destruction.

1.3.3. Fast-neutron critical assemblies are excluded from discussion in this Manual.

1.3.4. Similarly, critical assemblies primarily used for the determination of physical parameters for use in chemical plant design have not been included in this Manual. However, it is hoped that the guiding principles laid down may prove useful in this connection.

1.3.5. The question of radiation exposure of personnel has not been dealt with in this Manual. For details of maximum permissible occupational exposures, reference should be made to the Recommendations of the International Commission for Radiological Protection (ICRP) published in 1954, and subsequently amended in 1956 and 1958. It is strongly recommended that these recommendations be adopted. Some portions of them are summarized in "Safe Handling of Radioisotopes", IAEA, Vienna, 1958 (STI/PUB/1).

1.3.6. Conventional safety requirements have not been dwelt upon in any great detail since in most cases these are already the subject of national standards or regulations, and may become subject to discussion by international organizations such as the International Organization for Standardization (ISO)

1.4. DEFINITIONS

(The definitions which follow are included in order to clarify the contents of this Manual, and are not necessarily exhaustive.)

1.4.1. A **subcritical assembly** is an assembly of nuclear fuel and moderator where insufficient fuel and moderator is present to enable criticality to be achieved, even if only accidentally.

1.4.2. A **critical assembly** is a neutron multiplying system which is flexible in character, assembled from fissile and other materials used in nuclear techniques, and used mainly for the determination of critical mass and other characteristics of the assembly or materials.

1.4.3. A **research reactor** is a more permanent system used mainly for the generation of neutron flux and ionizing radiations used for research purposes and irradiation of materials.

1.4.4. **Safe operation** is defined as operation in accordance with recognized nuclear and conventional safety procedures in order to provent hazard to any person.

1.4.5. **Reactivity,** $\Delta k/k$, is defined as the value of the expression $(k_{eff} - 1)/k_{eff}$, where k_{eff} is the effective multiplication constant. Reactivity is a measure of the departure of a reactor or a portion of it from the critical condition.

1.4.6. A **local incident** is one confined to one building or part of it and means any deviation from the foreseen operational conditions involving radioactive materials which may imply a hazard for personnel or equipment.

1.4.7. A **site emergency** means any incident involving escape of radioactive materials from the local area or the presence of ionizing radiations which may constitute a hazard to personnel or property within the boundaries of the establishment.

1.4.8. A **public emergency** is any set of circumstances involving radioactive materials which may cause hazards or damage to persons or property outside the boundaries of the establishment.

2. CRITICAL ASSEMBLIES

This Section of the Manual, which is intended only for the reader who has had previous experience in the nuclear field (but not necessarily of critical assemblies), is devoted to the specification, design and construction of critical assemblies as well as their actual operation. The advice of the appropriate Safety Committee should be sought as described in Section 5, whilst safety reports should be written as described in Section 6. The operation of such an assembly is intimately connected with its specification and design, and it is not possible completely to separate the two. Fast-neutron critical assemblies are not covered by this Section, since it is not expected that they would be designed and operated by users of this Manual. The essential dangers inherent in critical assemblies but not found in research reactors arise from the element of uncertainty of the critical parameters, the large excess reactivities which may be possible and the frequent direct access to fuel elements. The designer and manager of a critical experiment have always to be aware that the expected calculated values may be in error, and may differ greatly from the actual values. The safety of the system has to be assured much more by instrumentation and safety devices than by calculated values. Neither safety circuits, interlocks, mechanical design nor administrative control can possibly be a sufficient condition to ensure the safe operation of a critical assembly or a research reactor. There can be no substitute for intelligence, alertness, discipline and training of the operating staff.

2.1. SAFETY OF DESIGN OF CRITICAL ASSEMBLIES

2.1.1. Reactor physics considerations

The specifications of a critical assembly should, if possible, include estimates of the excess reactivity in the system, values of the maximum rate of reactivity addition, temperature coefficients, void coefficients, speed of heat transfer from fuel to moderator, etc. The physicist in charge must specify these quantities as well as the geometrical layout of the cores and rod removal speeds corresponding to predetermined safe reactivity addition rates. These specifications must be incorporated in the design.

2.1.1.1. For normal static or dynamic critical assemblies, or for one particular lattice in reactors having variable lattices, the maximum excess reactivity must in no case exceed the amount that can be compensated by the permanent available shut-down system, nor must it be more than that estimated to be required for the experiment, and the design and construction must be such as to ensure that accidental increases of reactivity due to mechanical failures are impossible.

2.1.1.2. Reactivity additions to a system when it is not in the shut-down condition should be in discrete amounts, each addition being followed by a period of time during which the effect of the addition may be observed. The design should incorporate features to ensure this. The maximum value of such an addition should be less than that required to cause prompt critical conditions when added to the assembly at the point of criticality, since under these conditions the effectiveness of the control devices may be inadequate. The assembly must be designed so that each addition of reactivity requires further deliberate operational action before a further separate addition can be made.

2.1.1.3. The rate of reactivity addition during the critical approach procedure must be limited so that the safety features of the system have time to become fully effective before unsafe conditions are reached. The value normally used is $2 \times 10^{-2}\%$ $\Delta k/k$ per sec at any time. When fuel additions are made by hand during the critical approach experiment with one bank of shut-down rods within the reactor, the subsequent withdrawal of negative reactivity should also be limited to the same value.

2.1.1.4. When the additions of reactivity are made by increasing some fundamental parameter which cannot be varied in sufficiently fine increments or in a sufficiently accurately controlled way (e. g. fuel loading, moderator height), a variable control parameter (e. g. moderator height, control rod) is also necessary. In these cases, the control parameter must be designed to prevent criticality ever being achieved during the increase in fundamental parameter; the incremental additions of fundamental parameter must be limited to less than the worth of the control parameter; and the limiting conditions of subparagraphs 2.1.1.2. and 2.1.1.3. will apply to the control parameter.

2.1.1.5. The design should incorporate features to permit the approach to criticality to be achieved within a reasonable period of time. To this end the values of both the addition and the rate of addition may be increased during the first part of the addition operation. These increased values must not be used beyond a safe limit. The value of this limit is difficult to define generally, as it will depend upon the nature of the assembly, and the parameter which is variable (e. g. mass, moderator height, etc.). It is suggested, however, that it be not more than $k_{eff} = 0.9$. In the case of a variable core design, it must be possible to preset these features to the calculated level before commencement of a particular experiment.

2.1.1.6. It must be possible to shut the critical assembly down under all circumstances. Normally, there must be two separate shut-down systems, each capable of shutting the assembly down. They may be of different design, including the operating mechanism to eliminate the possibility of similar simultaneous failures. Each system should be capable of absorbing 125% of the maximum reactivity release. The time of operation of the shut-down devices, including detection and operating time before they are fully inserted, should be less than 50% of the reactor period when the maximum permissible single addition of reactivity is made above the critical value. One widely used method is free fall of absorbers from a position above the core and as near to it as possible. There may, of course, be other or secondary shut-down devices (e. g. a water-moderated assembly fitted with two systems of shut-down rods may have a moderator or reflector dump valve as a secondary shut-down device). The time of operation of such a secondary device need not be as short as that specified for the main or primary shut-down devices. Where the possibility exists that the system may become critical as a consequence of fuel addition during loading, some shut-down rods must be in the "out" or suspended position during loading. For this purpose additional shut-down rods may be necessary. If so, a neutron flux above the lower level of adequate sensitivity of the detectors must be present and the rate of fuel loading should be such that the protective system is able to act with adequate rapidity.

2.1.1.7. The temperature coefficient of reactivity should also be investigated and the worst conditions should be estimated. If a choice is available, it is of course preferable to ensure that this coefficient be of negative sign, since this would assist the safety devices in shutting down an assembly in the event of an accident.

2.1.1.8. The void coefficient of reactivity should similarly be investigated.

2.1.2. A neutron source must always be used during an approach to criticality, on starting up the assembly or when the shut-down

2

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