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COMPUTER CODES FOR THE ENGINEERING DESIGN OF FUSION EXPERIMENTS

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Summary

A selective review is given of certain special purpose codes which have been devised for certain aspects of fusion engineering design and analysis, and also of some general purpose codes which are being increasingly used. Attention is drawn to the adoption of general purpose software tools particularly useful for exploiting the widely used finite element methods of analysis. Considerations and requirements in some ways special to the engineering design of the electromagnetic assemblies and power supplies needed for fusion experimentation are referred to. Examples are given of the integration of special and general purpose codes enabling a model of an entire system to be analysed and optimised for performance, having regard to various engineering considerations and interacting physical effects.

As even more complex and costly fusion experiments are designed and built by teams of engineers and physicists, who are frequently geographically separated, a greater effort is needed to improve the efficiency and integrate the functions of engineering design, analysis and simulated performance. This should be achievable with advances in the software technology used in computer aided engineering.

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1. INTRODUCTION

Nuclear fusion engineering, in which participation becomes increasingly international and geographically widespread, uses computational modelling for many aspects of design and the simulation of performance[1 2 3]. Below are listed examples of current activities which illustrate the extent of the application of engineering computation to:

(a) implement significant modifications to present generation experiments to extend performances and to simulate machine behaviour;
(JET, TFTR, Doublet III).

(b) design and construct new apparatus for further "proofs of principle" in physics and technology;
(MFTF-B, Tore Supra, RFX, COMPASS)

(c) conceptual design of next generation, reactor-like systems;
(NET, INTOR).

Many new computational tools, both hardware and software, are now available for design engineers who, while not themselves expert numerical analysts or programmers, wish to use codes effectively to solve their problems.

This paper surveys those theoretical methods and codes which have found widespread application to nuclear fusion engineering. In many cases these have not originated from within the fusion community itself, but have been adapted from other advanced fields of engineering to the requirements of fusion.

A significant trend is the increasing availability of major, general purpose codes, often proprietary ones supported by advanced software, now being used to perform mechanical and magnetic engineering design calculations. Another important trend is the combination of codes into integrated code systems to enable a more complete analysis of magnetic fusion devices to be performed.

2. ENGINEERING DESIGN PROCESS

Computational science and technology can be utilized nowadays at all levels of the engineering design process[4 5]. Consideration of the process itself indicates how codes and supporting software should function best to assist the design engineer at various levels.

A computer code is required to transform a mathematical model into an entirely numerical problem capable of solution by digital computer. At the conceptual level of design the designer has need for only rather simple codes that are not our principal concern here. These are to be found in the range of single user work stations[6] to personal computers[7] which are readily programmable and are also supplied with an ever-increasing number of codes for various engineering analyses. The emphasis is on ease of use, ability to change initial data quickly and rapid access to results albeit at a very coarse level of detail.

If the simple conceptual model looks promising, then it is enlarged, made much more detailed and subject to a more rigorous study. Many more questions are asked at the detailed design levels about performance limitations under both normal and possible abnormal or fault conditions, and about safety and environmental effects. To answer these it is necessary to construct a sufficiently detailed mathematical model in order to simulate a physical behaviour which may include many complex interactions. Unfortunately, not all of this behaviour is yet understood at a fundamental level. Correspondingly complex yet flexible models and codes are required by the designer to cover a wide range of possibilities.

Moreover, because of the constructional complexity in a fusion machine it is found in practice that it still requires many approximations and assumptions in order to fit the numerical problem into the limited capacity of present day hardware and software, even that available on supercomputers[1,3]. To make a reliable model at this detailed stage of engineering design still calls for a considerable exercise of skill and experience on the part of the designer. It is even more difficult fundamentally to reconcile the often conflicting design requirements for which there is no optimum solution possible in a mathematical sense. The designer then needs a diversity of information as a basis on which to reach a sensible judgement.

Both conceptual and detailed design studies and the draughting necessary prior to manufacture can be greatly assisted by computer aided design (CAD) tools[4] . CAD is a considerably more sophisticated and advanced idea than electronically automating the task of draughting, for it enables a designer to model accurately the geometry in three dimensions. The software provides geometric modelling capabilities. The mathematical description allows the image of the object to be displayed and manipulated at will. These CAD techniques go beyond the scope here, but they are mentioned in passing in connection with the construction and graphical display of the geometrical models which are an important preliminary part of mathematical modelling procedures[5].

3. FINITE ELEMENT METHOD AND RELATED SOFTWARE

Most modern engineering codes for computing the behaviour of fields (mechanical stress, temperature, electromagnetic field, etc) are based on finite element methods FEM[8 9 10]. In the FEM the region occupied by the field carrying medium (be it solid, liquid or a vacuum in the case of the electromagnetic field) is discretised into small, but finite size elements. The elements can be assembled in a variety of ways to represent exceedingly complex shapes. Here lies the importance and advantage of the FEM from the engineer's point of view when compared, for example, to the finite difference method. In particular, curved boundaries can be represented more easily and a more accurate result obtained with fewer nodes in the hands of a skilled modeller. The elements are imaginary and can be varied in size and density and chosen according to shape from the libraries of useful elements supplied with all modern FE codes. This discretisation procedure or mesh generation ('meshing') is crucial to the construction of a realistic model.

Special pre-processing software is available for mesh generation and is now being developed to a high level of sophistication[5 6]. It has been made a very fast semi-automatic procedure with sufficient control to enable the designer to exercise his experience and skill in modelling and with error checking to show up gross errors. Ever more sophisticated checking analysis is being developed for this software to make the mesh generation both a faster and more accurate tool.

The steps in the FEM go as follows[8 9]:

(i) discretize by generating a suitable mesh

(ii) select interpolation functions to represent the field

(iii) find the elemental equations and assemble them into a matrix for the entire complex model thereby introducing boundary conditions

(iv) solve the matrix of equations

(v) process the resulting data further, as required.

No matter whether the field equations are integral or differential the problem can be reduced by the FEM to the solution of simultaneous algebraic equations, ie. to a problem in matrix algebra. The only practical difference is that differential equations lead to sparse matrices and integral equations to full ones[9].

The numerical techniques required for the efficient solution of problems requiring the manipulation of large matrices is specialised and highly developed. The software incorporated into advanced FE codes ensures steps (iii) and (iv) are largely automatic and transparent procedures for the general user.

Post-processing software can provide various visual representations of the FE model results with interactive manipulations[4 6], eg. orthographic and 3D perspective projections, rotation, zoom, etc. Deformed and undeformed shapes can be displayed and compared by overlaying. Dynamic or static contour plots of field variables can be displayed. All the usual printing, tabulating and plotting routines will be available for output in batch mode.

4. PLASMA EQUILIBRIUM SHAPING

Apparatus for magnetically confining plasma must be designed so that the currents flowing in the external coils combine together with current flowing in the plasma itself to produce a confining magnetic field in equilibrium with the plasma pressure. The shape of the magnetic flux surfaces so produced, particularly between the plasma edge and the vacuum vessel, is of great practical and theoretical importance with consequences for plasma stability and containment.

For a model of toroidal confinement which is symmetric to rotation the Garching equilibrium (HF) code[11] can be used for solving the plasma equilibrium equation (Grad, Shafranov) for a free boundary and external vacuum magnetic field. The external boundary conditions are the plasma boundary shape and the positions and magnitudes of external currents in the poloidal and toroidal field coils (PFC and TFCs). This 2D formulation is only possible for axisymmetry, ie. the discrete nature of the TFCs is overlooked, which may be reasonable for tokamaks with many TFCs.

The HF code can be run in either a forwards or backwards mode. In the forwards mode the input data consists of the PFC configuration and currents and a partial specification of the plasma profile; HF then outputs the exact plasma shape and profile. In reverse, the input data is the distribution of PFCs and an approximation to the plasma shape; HF then outputs a selection of exact plasma shapes and profiles together with the currents required in the PFCs. The design process then iterates forwards and backwards until an acceptable compromise of the three design variables, plasma shape, PFC positioning and currents is achieved, usually with some constraint on the PFC currents[12 13].

The Garching workers[13] have reported that the standard HF code does not work well for magnetic divertor configurations (ie. stagnation points). For this they have developed a new version of HF which enforces certain conditions on the plasma surface while minimising the magnetic field energy of the PFCs.

5. MAGNETOSTATIC FIELDS, FORCES AND INDUCTANCES

The magnetic field coils of fusion assemblies require careful analysis to ensure that the magnetic fields so produced have the desired properties and the coils have sufficient strength to withstand the forces which act on them.

The electromagnetic forces on the coils must be calculated and used as the input to calculating the mechanical stresses in the material of the coils and their supporting structure. These forces and stresses have to be calculated not only for normal operating conditions, but also for current distributions in abnormal operation, which may arise from defects in the coils, such as electrical breakdowns, and from anomalous plasma behaviour (eg. 'disruptions'). The problem of transient phenomena is returned to in section 7.

There are several codes[14a, b, 15 16 18] in use for computing the magnetic field, force and inductance in coil systems when the current distributions are given, or else calculated. They are summarised in Table 1.

Note that many of the codes customarily used in fusion are based on integration of the Biot-Savart formula and are not capable of dealing with non-linear magnetic media (eg. iron). TOSCA is therefore an important exception because it calculates the magnetic field by solving Poisson's equation. It is particularly difficult, however, to calculate the forces exerted on an iron structure by, for example, integrating the Maxwell stresses[17].

6. ELECTRICAL CIRCUIT ANALYSIS

Electrical circuit analysis is required to model the overall control of plasma in a machine. It is also required to model aspects of the power supply systems driving currents in the machine and plasma. The codes used and referred to below are summarised in Table 2.

Plasma Positional Control

A toroidal plasma (tokamak or pinch) is part of an electrical system consisting of power supplies, coil sets and moderately conducting vessel[19a,b]. The coils and vessel are linked inductively to the plasma which may be modelled as a filamentary current[19a]. The plasma position is controlled by a combination of eddy currents in the vessel (which act on only rather short time scales) and external fields generated by the coils driven by a feedback regulation system actuated by the plasma displacement. The feedback control system must itself be modelled, eg. if a thyristor amplifier with a frequency response (~ 500Hz) is to be used. The plasma behaviour itself must also be modelled, eg. the perturbation due to a 'soft' disruption can be simulated by a step decrease of the internal plasma inductance in a time short compared to other circuit time constants.

Many circuit design codes exist which are appropriate to the network analysis outlined above and are, moreover, well adapted for use by electrical engineers:

CSMP[20] - Continuous system modelling program. This program provides a simple applications-oriented interface to the user, or alternatively accepts FORTRAN statements allowing application to non-linear and time-dependent problems of greater complexity. CSMP-III has been used to simulate the performance and optimise control of the FTU tokamak[19a]. The output shows all the control system parameters versus time.

SCEPTRE[22, 24] - a general purpose computer aided design program to study transient response of electronic circuits. SCEPTRE has been used for the circuit analysis and computer simulation of the toroidal pinch ZT-40M[25].

SUPER SCEPTRE[23] - a program for the analysis of electrical, mechanical and digital control systems. The ATF facility[26], a continuous coil, torsatron-like device, contains several closely coupled magnetic circuits and this code was used to model their transient behaviour. The code allows for the direct input of all electrical components as well as the mutual inductances.

Power Supplies

The modelling of power supplies for fusion devices presents some unusual problems. For example, in the case of AC to DC conversion systems it is necessary to simulate the behaviour of transients in bridge rectifier circuits containing many switches. The code CONNIE[27] was developed especially for this requirement. The user specifies initial conditions in the input to CONNIE which sets up and solves the circuit differential equations. Switching points controlled by electronic devices are located by interpolation. CONNIE, however, neglects semi-conductor effects at the device level. The post-processor for CONNIE is interactive, allowing the user to select output quantities for graphical display with quick access to any circuit parameter without need to rerun.

7. TIME VARYING ELECTROMAGNETICS

Time-varying magnetic fields induce transient eddy currents in the structure of fusion apparatus; these currents are important because of their mechanical and thermal effects, especially for super conducting coils, for vacuum vessels and supports and for the blanket of a fusion reactor. Notably, plasma current disruptions in Tokamaks can impose severe loadings on the structure which are by nature unpredictable, except in a statistical sense, and may limit the useful life of the apparatus. The aim, therefore, is to calculate the eddy currents induced in the structural components both during start-up and due to a plasma disruption in which the plasma current falls precipitously to zero in a few msecs.

The methods widely used are based on discretising the conducting media in suitable ways and then solving the resulting equations which may be integral, differential, or mixed. They are described in references 28 to 37 inclusive.

Some of the principal codes are shown in Table 3.

It should be noted that there are few codes which handle fully 3D, transient problems (eg. EDDY NET)[28 29] and <u>none</u> handles 3D, transient, electromagnetics in conjunction with non-linear magnetic materials, eg. steel. These developments will be required if the needs of reactor like systems are to be addressed properly[36] .

8. MECHANICAL ENGINEERING

Fusion assemblies are complex engineering structures subject to combined transient (~ msec) and quasi static (~ 10-100s) loadings, repeated periodically (~ 10^4-10^5) during the lifetime of the machine. Thermal loadings are likewise applied which are globally severe but controllable, eg. during bakeout of vacuum vessels. They are also global under normal pulsed conditions, but can be localized and intense under abnormal conditions.

The analysis of the stresses produced in the components by these loadings is not in any way special to fusion work and, as would be expected, there is by now a large selection of general purpose, proprietary codes developed elsewhere from which to choose. However, the choice of a particular code will in many laboratories be determined by what is available, taking into account the usually high cost of acquiring proprietary software. We list here non-exhaustively, therefore, those properties usually found in general purpose codes that are useful for the mechanical engineering of fusion assemblies and so should be sought. The features of three major codes are summarised by way of example in Table 4.

(a) Types of Analysis

(i) Structural Statics and Dynamics

Linear and non-linear elastic
Plastic, creep, swelling, cracking
Buckling
Transient response

(ii) Heat Transfer

Steady state and transient
Conduction, convection, radiation

(b) Element Geometries

Available in code libraries are a hundred or more elements of one, - two, - and three dimensions, for solids, shells, lines and points. Plate and shell elements can be utilised to model laminated composites.

(c) Large Program Capacity

(i) Sparse matrix routines

(ii) Multi level superelements processed automatically

(iii) Cyclic symmetry for identical components arranged around an axis

(iv) No limit on number of elements.

(d) Data Preparation

data input in free format by using keyword module descriptions.

(e) Mesh Generation

Automatic generation of finite element models of problems by defining a few key nodes to mesh surfaces and solids with any mesh density and spacing.

(f) Interactive Graphics Functions for Model Creation

(i) Viewing: perspective and orthographic projection, hidden surface removal, etc

(ii) Manipulations: rotation, translation, scaling, zooming magnification.

(g) Automated Functions

(i) Restart, when new data is supplied

(ii) Singularity suppression, for singular or nearly singular degrees of freedom

(iii) Resequencing of grid points to minimise the time for equation solution.

(h) Data Checks and Error Analysis

Ensure the user has described the problem correctly and unambiguously by flagging errors and giving warnings and information.

(i) Post-processing of Data

(i) Interactive Stress contouring options, deformed (static) or modal (dynamic) shapes superimposed

(ii) Print, tabulate and plot routines.

The general purpose code MSC/NASTRAN[38] is one of the foremost engineering codes. Its implementation on the MFECC network[39] will undoubtedly lead to its substantial use in fusion engineering, particularly for mechanical and structural engineering computations by FEM. Although NASTRAN is now provided with its own interactive graphics systems MSC/GRASP for pre and post processing an interesting development is its integration with the software PAFEC as a pre-processor.[46]

PAFEC, which is a FE code in its own right,[40] accepts free format input using engineering keywords, powerful automatic mesh generating facilities and extensive data validation checks. This is one example of a code system integration; others are described in section 10. Its value to the stress analyst is to free him from the laborious, error prone task of creating data according to the rigid format otherwise required.

The SAP code[42] and its variants was one of the first major FE codes to be made widely available to the fusion community and its use has been most widely reported[43 44 45].

9. NUCLEONICS

For fusion reactors and even moderately radioactive plasma experiments it is required to find the transport of neutrons and gamma photons through the wall, blanket, shield and external environment. From this may be calculated the resulting radiation damage, energy deposition, transmutations including the tritium production and the leakage of radiation and its environmental hazard. These calculations (called collectively 'nucleonics') are generally more difficult to carry out for fusion than for fission because of the higher energies of the neutrons (14 MeV) and the extreme anisotropy of the scattering, so that simple diffusion theory is not applicable. Nevertheless, many of the methods and codes which are well established for fission reactor calculations[47] have been developed for fusion, although of course the question of validation arises.

There are essentially two methods of solving the transport problem. The first is to solve the appropriate (Boltzmann) transport equation for the distribution functions in momentum and configuration space for neutrons and photons. The second is to use an equivalent Monte Carlo treatment to find the statistical distribution of neutrons and photons in momentum and space.

Transport Equation Method

This may be solved in one or two dimensions by making suitable approximations discretising the flux function in its dependence both upon energy (multigroup) and velocity angle. Discretising the flux dependence with velocity angle is known as the discrete ordinate (DO) method, symbolised by S_N, where N is the number of discrete angular directions allowed. The set of coupled group equations can be expressed in finite difference form and a number of codes are available for solving these, eg. ANISN[48] for 1D which is usually adequate for scoping studies, and DOT[49] and TRIDENT-CTR[54] for 2D. The latter is a finite element code particularly suited for toroidal geometries.

Monte Carlo Method

The Monte Carlo method is an entirely different technique for solving the transport problem based on following the history of a very large number of particles (neutrons and photons) individually. The interactions of each particle are determined statistically by random sampling, the probabilities being proportional to the appropriate cross-sections. The MC method does not require a space mesh and is therefore simpler for configurations which are essentially 2D or 3D in geometrical complexity. However, it requires a great deal of calculation to obtain statistically significant results. Monte Carlo codes include: MORSE[50 51 52] and MCNP[53].

Combined Methods for Transport Calculations

Neither the transport code method nor the MC method is wholly suitable for some fusion applications, particularly so for the design of toroidal shields penetrated by large ducts, which is required in fusion devices. Streaming effects through the ducts are particularly important and are not at all suited to solution by transport code methods. On the other hand, MC methods are well suited to 3D geometry and streaming problems, but do not give very accurate pointwise solutions without an excessive amount of calculations.

A hybrid method coupling the DO and MC methods can be used in these circumstances. The MC method may be used, for example, to determine source distributions incident on an external boundary and the DO to obtain the spatially dependent fluxes throughout the shields.

Applications of Combined Transport Codes

Many important applications using transport codes in combination for shielding and environmental calculations have been reported.

Urban et al[55] used MCNP and TRIDENT-CTR to study large ducts and their shielding. Special purpose codes were written to facilitate coupling the two codes and although to some extent these are problem dependent the authors believed the method could be generalised.

Ku and Kolibal[56] studied the neutron streaming through narrow hole ducts in the TFTR diagnostics room by means of a code system DOT DOMINO MORSE, where DOMINO[57] is a general purpose code for coupling DO and MC calculations. Boundary albedos were determined using the ANISN 1D code, Ueki[58], however, claims that a coupled Monte Carlo technique (MCC) dividing the MC calculation into steps offers advantages for duct type streaming calculations. A 'pseudo' detector is imagined at the duct inlet and the angular energy and total fluences calculated there as a first step. In the second step the random walk is taken to start from the pseudo detector. Thus it is not necessary to change the first part of the calculation whenever a duct configuration is changed. Also, the MCC does not require the complicated co-ordinate transformation arising in the DOMINO code for coupling the DO and MC codes, used in previous methods.

K Hayaski[59] et al have analysed the skyshine effect of neutrons (14 MeV) leaking from a fusion reactor by means of two multigroup MC codes, by S_N codes and by a design code for skyshine[61]. At the source area the neutron transport calculation through the concrete wall used the S_N codes ANISN and DOT 3.5 and the multigroup MC code NIMSAC[60]. The skyshine calculation in the surrounding environment used DOT 3.5, NIMSAC, MMCR-2 and SKYSHINE-2[62]. The NIMSAC and DOT 3.5 codes can calculate neutron transport in air over the ground starting from the neutron production source, but for the MMCR-2 and SKYSHINE-2 codes the neutron transport in air over the ground had to be calculated by using a neutron source given by DOT 3.5 and NIMSAC, respectively, because MMCR-2 and SKYSHINE can only treat transport in one kind of medium.

10. INTEGRATED CODE SYSTEMS

The combination of codes into completely integrated systems for handling analysis, data flow and information is becoming increasingly necessary. This is to deal both with the many requirements and considerations in the design process and also with the many complex physical interactions encountered in simulating machine performance.

The general idea of these systems is to organise the flow of data so that the output from one code can be passed to and received by another as required by the logic of the analysis procedure and that this should be done as automatically as possible to eliminate errors in inessential manual handling. Data should be processed and information made available at various stages of what are usually iterative or looped calculations. This improves the interaction with the user and should save much abortive effort, as well as speeding up useful results. We illustrate these procedures further by reference to two recent important examples of such systems; that for the analysis of the design of toroidal and poloidal field coils for NET[63] produced by the NET team, and that for the systematic study of the effects of transient electromagnetics in torus structures produced both at Mitsubishi[69 70] and at Princeton[68].

Field Coil Analysis

The analysis of the coils begins with the input of the overall machine parameters, such as the dimensions and shape of the plasma and its current. It covers equilibrium and transformer calculation for the PFCs and force and stress calculations for the TFCs and support structure.

In a previous section (Plasma Equilibrium Shaping) we indicated how the final PFC positioning and PFC currents for a certain plasma shape and current could be arrived at using the Garching HF code. The next stage is the calculation of the forces acting on the TFC due to the interaction of the current in the TFC with that of the PFC system. [These forces act perpendicular to the plane of the TFC, thereby producing a bending moment and resulting stresses which in fact are a severe constraint on the design of tokamaks]. Two codes EFFI[14] and HEDO[15] are available for calculating magnetostatic forces. On one of the computational paths, leading to a more detailed stress analysis of the TFC, HEDO produces the force distribution over the entire TFC, whereas the TFC is modelled in the FEM by 3D, 20-noded bricks[64]. In this case a further non-trivial code SHAPE[65] is required to find the equivalent nodal forces for the brick elements. Finally, data on the nodal forces and elements is passed to a FE code ADINA[66 67] for stress analysis of the TFC.

Transient Electromagnetic Loadings

Time varying magnetic fields induce transient eddy currents in the partially conductive structure of a torus. Especially serious are the transient forces exerted on the structure by these eddy currents acting with the magnetic field. Two code systems (MATEX[69] and EDDYTRAN[70]) have been developed at Mitsubishi to calculate the eddy currents and forces using the EDDYCUFF code and thence to do the stress analysis using the NASTRAN code. Usually different elements are used in the two main FE codes so that a module of code is required to generate elements for both so that they correspond with each other. Another module transforms the electromagnetic force data from EDDYCUFF into the load data to fit NASTRAN. The more sophisticated system MATEX has a CAD mesh generator. The manual input relates to the geometry and electrical and mechanical properties of the blocks used in the model. The output consists of plots of the finite elements and computed data; currents, forces and stresses.

A somewhat similar code system has been developed[68] at Princeton PPL to model the coupling of magnetodynamics and elastomechanics in structural analysis. Here the SPARK code is used to evaluate the changing magnetic flux through the torus structure. The structural response is then evaluated using NASTRAN. These workers recommend a code system for a complete electromechanical dynamic calculation be developed for use in fusion based on a combination of SPARK and NASTRAN. The basic surface geometry is described using nodes and mesh elements in SPARK and a great simplification is possible by using the same geometry as in NASTRAN. Processing is similarly improved by outputting mechanical loading as nodal forces and bending moments automatically. No direct user interaction with the branch network is needed.

Some Problems of Code Systems

There are numerous difficulties to assembling, interfacing, testing, and producing operational code systems. As many of the codes are obtained from external sources and usually are subject to extensive modification beforehand it is usually not possible to maintain any consistent programming standard, eg. Fortran. Some part of the source code, at least, may be required, but may not be available because it is proprietary. The codes require library storage in such a way that calculations remain independent of modifications introduced by other users, who should have read-only access to the files. The successful development of code systems puts an even higher premium on standardisation in programming and on good documentation and diagnostic data.

11. CONCLUDING DISCUSSION

1. Computational modelling by means of computer codes is now well established as a technique applied by the international fusion community to fusion engineering. It is used to:-

   - substantiate conceptual studies of fusion experiments and reactor systems on an engineering basis,

   - analyse and improve at a detailed level the design of fusion apparatus before manufacture,

   - simulate complex physical behaviour in fully operational fusion assemblies.

2. Codes now exist which greatly facilitate detailed and accurate work based, for example, on the finite element method. They incorporate sophisticated numerical techniques for solving equations with immense numbers of unknowns efficiently by advanced computers. The resulting data can be post-processed usually in graphical form to afford easy access to any particular information the design engineer may require. Many older codes were specially developed by the community to solve different aspects of what in reality is a complicated interaction of physics processes, material properties and geometrical configurations encountered in fusion engineering. In general these codes afford only a piecemeal

approach to these complex systems. Also, there remain some outstanding problem areas specific to fusion, to do with electromagnetic transients and with the nucleonics properties of high energy (14 MeV) neutrons not addressed at large by the nuclear (fission) industry.

3. Unfortunately, many of these special codes lack portability for various reasons and have therefore not been widely implemented or tested in use throughout the community. These problems go beyond our present scope, except to mention the more common failings; viz non adherence to accepted programming standards, obsolescent standards, inadequate documentation, dependence on peculiarities of some local operating systems, etc. Thus it appears that, in spite of the very large investment of resources made by the community over the years in special codes for fusion engineering, these are being increasingly supplanted by large general purpose codes, notably for use in structural mechanics, electromagnetics, electrical power systems and nucleonics.

4. General purpose codes have been developed for very wide industrial use. Codes which originated in universities or national laboratories are increasingly being developed and licensed by commercial proprietors. Generally speaking, these codes have the following advantages [(a) to (j)] and disadvantages [(k) to (n)]:

(a) broad range of functions and application

(b) easy to learn and powerful to use

(c) advanced supportive software for graphics, etc.

(d) good, up to date documentation

(e) support and maintenance available

(f) quality assurance, validation and standardisation

(g) broad user base and interest groups

(h) advanced numerical methods

(i) wide implementation on most computer systems, including super-computers

(j) full spectrum of computer technology.

(k) use of a method or assumption inappropriate to fusion physics in relation to its engineering

(l) cost of licensing

(m) source code unavailable

(n) inefficient execution.

5. The balance of advantage for increased use of general purpose codes will depend upon the local conditions of usage. However, as regards the disadvantages (at least as they are sometimes alleged), the following general comments can be made against (k) to (n) above:-

(k) many of the fusion engineering problems are commonplace and can be handled by general purpose codes. However, where this is manifestly not the case, as where there is dependence on plasma or nucleonic properties, the modules of code and databases specific to fusion should be made compatible with and interfaced as far as possible to general purpose engineering software.

(l) the cost of licensing a proprietary code (~ 30k$) for use can be high and is an immediate deterrent, although academic institutions may be offered discounts. The overt cost of implementation, subsequent improvements and maintenance should be compared, however, to a realistic (although possibly concealed) cost of providing programming support from in-house resources.

(m) access to sufficient source code can usually be obtained for interfacing purposes, particularly if the proprietor is persuaded this will widen the applicability of his code. A user's modification may be permitted, but unless it is endorsed by the proprietor and guaranteed his continuing support it will prove difficult to maintain or use widely.

(n) general purpose software is expected to execute less efficiently on account of its generality (analogously to the slower execution of compiled Fortran code compared to assembler code). There are many compensatory factors however; general purpose codes frequently provide the user with well optimised routines for numerical analysis and access to supercomputers on which computing operations can be made both fast and economical.

6. The integration of codes and databases into unified code systems becomes increasingly necessary to tackle the correspondingly wide interactions of physics and engineering encountered in fusion. A large general purpose code is itself a highly modular, but integrated system. MSC/NASTRAN, for example, comprises nearly 200 modules. The needs of code system integration will put a higher premium on standardisation throughout the community. Scarce programming specialists are required to integrate code systems as well as to carry out the further special code development needed specifically for fusion. This effort can be made available within the community from resources presently employed on maintaining and developing older codes as general purpose ones are introduced.

7. The employment of geographically dispersed design teams on major international projects becomes more feasible with the introduction of standardised codes and code systems, together with a single physics and engineering database. It would be further simplified by the wider availability in the community of standardised computer hardware and operating systems. For smaller institutions it may be possible to use high speed data links to computer centres or bureaus which offer facilities to run large general purpose codes and code systems on supercomputers when necessary. However, much of the preparatory and interpetative work may be done locally on more modest equipment.

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	Calculates	Dimensions	Method	Restrictions, etc	Examples of use
EFFI [14a] [14b] MAGINT	magnetic field, flux lines force, inductance	3D	integration of Biot-Savart for distributed currents	none on coil shape no iron	W7AS coils NET TFC MFTF COMPASS
HEDO 2 [15]	magnetic field and force distribution	3D		symmetric coils no iron	ASDEX and NET TFCs
TOSCA [16]	magnetic field	3D	solves Poisson equation by FEM Hexahedral mesh	fields not well terminated at boundaries, forces on iron difficult	wide ranging, especially for iron structures and magnets

Table 1: Codes for Calculating Magnetostatic Fields, Forces and Inductances

Code	Transient	Non-Linear	Power or Electronic Circuits	Special Uses	Examples of Use
CSMP [20]				continuous process modelling	simulate plasma positional control in torus
NAP [21]	✓	✓	e		
SCEPTRE [22 24]	✓	✓	e	general purpose CAD	1) DC power supply (MFTF) 2) Analysis, simulation (ZT-40)
SUPERSCEPTRE [23]	✓	✓	e	electro, mechanical, digital control systems	simulates magnetic field circuits (ATF)
CONNIE [27]	✓		p	multiple, rapid switching	AC DC conversion, bridge-rectifier (COMPASS)
EMTP	✓		p	electromagnetic transients	

Table 2: Codes for Electrical Network Circuit Analysis

Code Name	Application	Dimensions	Mesh	Method	Example of Use
EDDYNET [28] [29]	thin plates curved shells long prisms	2D (or quasi 3D) - true 3D	quadrilateral - hexahedral	network integral form	electro-magnetic forces on tokamak limiter
SPARK [30]	conducting 3D surfaces	3D generally	quadrilateral	network mesh differential equations	toroidal sheet, TFTR vacuum-vessel
PE 2D [18] [31]	rectangular, or axisymmetric sections	2D only	triangular irregular	FEM differential equations	non-linear (steel) magnets
(Rubinacci) [32]	thin shells (fast penetration)	quasi 3D, 2D orthog co-ord	quadrilaterals	FEM integro-differential equations	INTOR, IGNITOR Vacuum Vessels
(Blum et al) [33] cf. also EDDYCUFF	thin shells (fast penetration)	quasi 3D, 2D orthog co-ord	polyhedron of triangles	FEM integral equations. Semi-implicit scheme in time	TORE SUPRA Tokamak Magnet Casings and Vacuum Vessels

Table 3: Codes for Calculating Time Varying Eddy Currents

	Types of Analysis	Main Features	Pre and Post-Processing Software Facility
MSC/NASTRAN [38]	Static and dynamic structural analysis. Heat transfer, electromagnetism.	Widely used. Highly modular. Library of standard options. Superelements for large problems.	MSC/GRASP Interactive Graphics System. FEMGEN.
PAFEC [40]	Static and transient stress analysis. Thermal, fracture mech.	Comprehensive input uses engineering keywords. Uses advanced database methods. Developed as a pre-processer for NASTRAN.	PAFEC Interactive Graphics Suite (PIGS). CAD Interface. Free format data input.
ABAQUS [41]	Static and dynamic structural and heat transfer analysis.	Efficient solution of non-linear problems.	Supported by the FE processor, SUPERTAB.

Table 4: General Purpose Codes Used Mainly for Mechanical Engineering