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Scientific and
Technical Review
of the European
Communities
(ex-Euratom-Review)

Our review is now ten years old. This is not really very much, but in relation to the lifetime of the Community it does mean something.

Euro-spectra first saw the light at Euratom and has had its scope extended since the merger of the Executives ; it has seen the beginning of European cooperation in scientific matters and has witnessed the numerous advances, as well as the standstills, hesitations, uncertainties and vicissitudes which have been, and still are, incidents in the march towards the realisation of the European ideal.

Neither encouragement nor criticism have been wanting. Strong in the conviction that what is not discussed is dead, we feel more alive than ever, and figuratively raise a glass to critics and supporters alike, placing them in the single great category of readers. For this is the only category which really counts for us and which we have at heart.

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Biomedical engineering : quo vadis?

In the field of biomedical engineering scientists are valiantly cobbling away on all sides, often with great individual dedication and all too frequently with excessive confidence, but—do we really know what we want to achieve?

WINFRIED BECKER

Just how big is biomedical engineering?

A great deal has already been written about the astonishing achievements in biomedical engineering and even more about the practical or utopian prospects in this field.

Whether it be a question of artificial hearts, myoelectric prostheses, pneumonic pacemakers, blood-pressure regulators, aids to vision or automatic monitoring systems for dangerously ill patients, be it complicated diagnostic and surgical equipment, self-adjusting training appliances or complex models of physiological functions for medical research purposes, the reports nearly always suggest something awe-inspiring, some welcome liberation, yet at the same time some hint of inner conflict and of the loss of the sense of security.

The man on the job, however, takes a far more matter-of-fact view of the situation. He is aware of the labyrinthine difficulties that arise, more than anywhere else, in this borderline zone between living organism and machine: he sees the frequently poor adaptation of the apparatus to the physiological requirements, the totally inadequate design—usually due to the state of the art—of, for example, prostheses which to the patient are often more of a hindrance than a help; or the insuperable cost problems that are encountered in converting ideas into reality.

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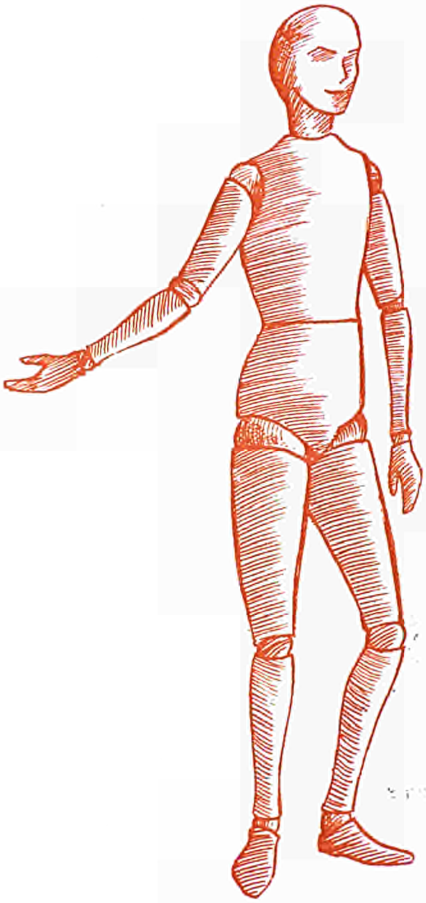
These problems are as thoroughly familiar to the engineers working in this field as they are to the interdisciplinary biomedical engineering teams at the *Highland View Hospital* in Cleveland, Ohio, at the *Medisch-Fysisch Instituut* in Utrecht, at the *Technion* in Haifa, at the *Polytechnikum* in Warsaw, or anywhere else in the world, since the tasks involved and the difficulties of solving them are truly international.



Consequently, anyone who deals with the "real" problems of biomedical engineering will give a very modest answer if he is asked about spectacular developments, since he is conscious of the very special difficulty of working in this no man's land.

Is this simply because interdisciplinary collaboration between physicians and engineers does not come easily to either side, or because the technological requirements frequently extend up to or beyond the limit of what is at present possible? Or is it because the engineer, as an imitator and adapter, is forced to capitulate before the sheer complexity and multiplicity of the bodily processes?

The suspicion is increasing that this is not all, but that biomedical engineers have largely neglected to reflect, in the light of the knowledge built up over thousands of years concerning the essential factors of human life, upon the ultimate goals towards which they should strive.

In short, biomedical engineering today is not a homogeneous structure and is not orientated towards that single image of man which the specialists in this branch have failed to make their guiding vision. Even its sole aim of serving man has sometimes become blurred through negligence or vanity, so that today for the most part it unfortunately does not present a particularly impressive picture.

In fact, what aims should be pursued in biomedical engineering? This question will probably cause much scratching of heads. Nevertheless, the answer seems quite clear: to make sick or injured people healthy and to give, or restore, to them the full possession of their faculties. This would be the end of the matter—if only biomedical engineering were capable of doing so, be it only in a majority of cases. In actual fact, however, this capability is often far beyond its grasp. From this situation, which in theory could continue for ever or at least for a very long time, there arises the necessity to consider giving a less categorical answer.

As regards the *applications of biomedical engineering to diagnostics,* it is an advantage for the doctor to be backed up by highly developed instruments, provided he is in a position to make effective use of them, as they are often complicated. Consequently, it is more usual to find concentrations of such instruments at special diagnostic centres, where they can be operated by experts. Other diagnostic aids such as computers which, in the service of the physician, could complement the sum total of medical knowledge and constantly keep it up to date, will undoubtedly soon become a common feature of medical practice: by way of example mention can be made of random-access systems made available to the public in special emergencies where speed is essential, e.g. cases of poisoning, where a diagnosis is formulated on the basis of a list of symptoms and remedial action (in this specific case, possible antidotes) promptly suggested. However, these are not really a concern of biomedical engineering in the narrower sense.

Diagnostic techniques can be extended to the *preventive mass screening of entire populations,* which is becoming possible as a result of automation. As it can be seen from Fig. 1, special interest is being aroused by methods for the early diagnosis of pathological—and perhaps even psychopathological—changes in the body as a result of the ever-growing impact of environmental disturbances brought about by man himself. However, it is not only a matter of averting the already known pathological changes due to environmental influences, but above all of detecting the eventual onset of new ones, thus combating their causes before any serious effects occur. To do this, the screening of whole populations is, as we have said, necessary, but obviously it is not feasible without appropriate technical means.

The position seems clearest as regards the *implantation of artificial vital organs or parts thereof.* Here it is simply a matter of life or death. If the patient wishes to go on living and the implanted device has reached such a state of development that he can in the circumstances regard as acceptable the restrictions by which he will henceforth be bound, or if no such restrictions arise, then the decision as regards implantation is merely a question of feasibility. If, on the other hand, these organs cannot be implanted or even connected to the patient externally and transportably, that is to say if he is likely to be permanently tied to a fixed apparatus in order to stay alive, then the question as to the sense of such a procedure is not always easy to answer this is particularly true in the case of very old patients whose general constitution, owing to senile decay, is no longer fully capable of sustaining other vital functions, or again in the case of patients who in addition, owing to irreversible mental deterioration, are living a purely vegetative life.

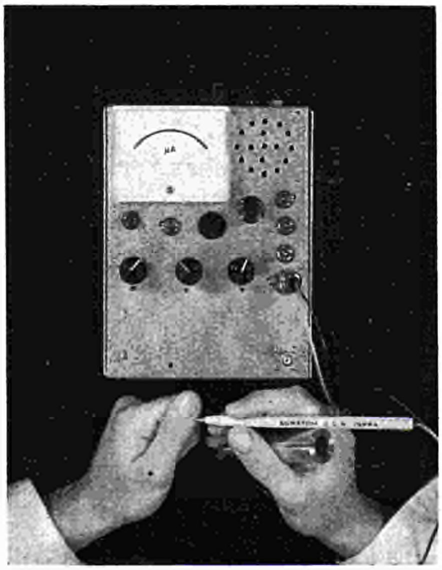
Certainly, it is only with extreme caution that we dare embark upon such a train of thought: it is but a short step to the misuse of the responsibility involved; nevertheless, the often inevitably limited possibilities of helping and also a reverence for death, which is inseparably linked with a true respect for life, enjoin us to think upon these things. The physician is bound by the Hippocratic oath not to injure the patient deliberately nor to kill him, but he is not thereby bound to prolong at all costs a life which is restricted, for instance, to the persisting of the heart beat as its only expression.

As far as biomedical engineering is concerned, it follows from these considerations that every stage in the technical development of artificial organs, organ parts or extracorporeal devices designed to perform vital bodily functions is in itself sufficient justification for considering its clinical use as long as this offers the patient the "*best*" chance of survival. Technology's task, in this case, is to provide equipment which—even while development work is still going on—reflects the latest state of the art, for possible use in urgent cases, since the patients in need of help cannot wait until the work of technical development has been completed.

A different situation obtains with regard to *implants which are meant to improve the patient's health,* or make existence easier for him, *but which are not essential to life.* In these cases the

Fig. 1: *This equipment is currently under development as a pilot project in the Electronic Division of the* Joint Research Centre's *Ispra Establishment. It is used for measuring the fine structure of the distribution of electrical parameters on the skin, since different areas of it may correspond to internal body parts and organs and variations in their electric potential might give valuable indications about the physio-pathological conditions of the latter even before they can be detected by traditional medical examination or through the use of classical diagnostic aids.*

In the form intended such equipment could potentially be used for simple, quick and inconvenience-free mass screening of large sections of the population for the early diagnosis of many different kinds of organic damage; it might hence be employed for detecting the first signs of harmful environmental effects long before the symptoms appear, and possibly also for tracing and identifying a number of yet unknown environmental effects on the human organism.



perfection of the technical design as regards the device's ability properly to take over the original function or to perform an intended replacement function, is frequently a factor that must be weighted against the operative and post-operative risk.

Here it seems advisable to introduce degrees of urgency for the necessary technical developments on the basis of physiological and psychological experience from medical practice. Such lists of priorities should wherever possible be drawn up in collaboration with interdisciplinary teams who are free of any commercial ties and whose primary concern must be the optimum provision of genuine medical aids to ease the patients' lives.

Consideration must be given both to the broad-spectrum effect, i.e. the possibility of providing aids for use on the maximum number of patients, and to the gravity of the affliction in rare and isolated cases. Wherever there is a lack of interest on the part of industry owing to limited demand or the need for protracted preliminary research, the task must be taken up by state or, better still—in view of the universality of the problems—by international bodies with balancing support and their own research facilities (not least out of respect for the right of every individual to a life which is acceptable to him in his particular circumstances). The moral justification for such action would at any rate be obvious. Furthermore, since these cases will usually call for complicated developments, the level of the generally available know-how could be raised in this way.

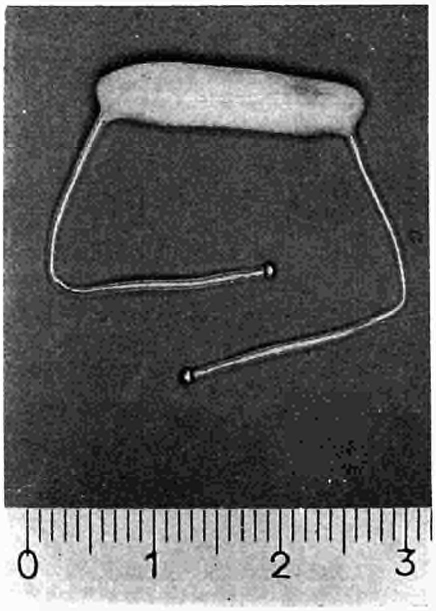
So far as *prosthetic or orthotic devices* (e.g. artificial arms or legs) are concerned, there are generally still other factors to be considered, and the correct assessment of these will determine the degree of acceptability to the patient. These factors are closely bound up with the particular circumstances of the disabled person: for instance, these could be the case of a child who was handicapped before or during birth or as the result of an accident, or of a worker who worked predominantly with the limbs that are now impaired or missing, or of a person who works chiefly with his brain, or of a girl or young woman for whom the question of her appearance is, of course, particularly important, or of patients who have lost various combinations of limbs—in all these cases there will be differences of emphasis as regards what the prosthesis is expected to do.

This in itself would not constitute so great a problem if presentday prostheses were capable of imitating, even approximately, the overall function of the extremity, or part thereof, to be replaced and at the same time of providing a large measure of aesthetic compensation. Unfortunately, technology is in many respects still a long way from reaching these goals. The reserves of mechanical performance, the number of degrees of freedom of movement and their controllability, the variability of speed and power, the silence of operation and the grace of movement—all these and many other parameters are inadequate to simulate nature.

Our optimism was misplaced when, with apparent success, pneumatic and myoelectric prostheses were fitted to the malformed children of the thalidomide disaster, who were then four or five years old. The children played happily with them, but for the most part they were isolated in groups in special clinics where they had been taken for training and observation, and they simply played with these devices without being able to compare themselves with healthy people outside. When, as was often the case, they subsequently went to normal primary schools and were faced day after day with the reality of their handicap as compared with their healthy classmates, they were frequently reluctant to make use of their prostheses. Biomedical engineers were utterly perplexed. Was it that the children had not become accustomed at a sufficiently early age to accept the constantly readapted artificial limbs as parts of their body? Had there been insufficient accompanying psychological care to prepare them for the massive confrontation with their healthy companions? Or was the technical design too poor to be accepted?

Fig. 2: *Implantable coil with an iron core of high permeability and two gold electrodes which can be mounted on or in the muscle, developed at the Electronics Division of the* Joint Research Centre's *Ispra Establishment in collaboration with the Orthopaedic Clinic of the University of Frankfurt.*

It creates electrically stable and differentiated percutaneous transmission lines for electromyographic signals (the muscle response potentials), offers the advantage of volitional control and is intended to be used for amputees undergoing long-term treatment. In this case there is no need to implant a battery and percutaneous infection (such as sometimes happens along galvanic conductors) is avoided by the use of a magnetic coupling system.



It is certain that no one factor is entirely responsible; nevertheless, it cannot be denied that present-day prostheses, to continue with the example we have chosen, are still so primitive from the medico-technical point of view that the responsible and compassionate biomedical engineer is filled with helpless shame at having to offer a patient one of these monstrosities with humming electric motors and heavy batteries, such as an artificial arm, with which the patient, at the cost of great mental concentration, can carry out only a very limited number of unnatural movements (Figs. 3a and 3b).

In biomedical engineering the road to technical maturity is usually extremely slow and costly and it is not possible to manage without interim tests and trials with imperfect apparatuses which readily expose the biomedical engineer to criticism from those who are unaware of the hard struggle for improvements that has already been fought.

But contemplation of the present state of the art only becomes really depressing when one realises that, to the wearer, even the best prostheses of this kind are bound to remain largely unacceptable lifeless tools in the long run, if only because they provide no feedback of information: feedback concerning position in space, acceleration of motion, contact pressure, nature of a touched surface, temperature, draught, and so on.

Although many efforts are being made to provide built-in feedback channels, at least as far as the sense of touch in artificial arms is concerned, the number of technical channels is infinitesimal compared with that in nature and even if it is increased, how can one provide a durable means of access by which the information can reach the nervous system? Medical technology has not yet been able to devise a "nerve plug" with which a large number of electric feedback wires from the prosthesis could be connected to the correct ends of the sensory nerve fibres, say in the stump of an amputated limb, permanently and without degeneration of the nerves. For the

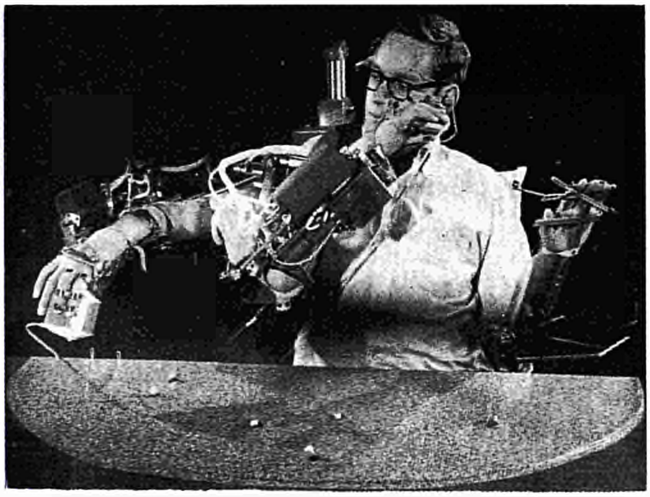


Fig. 3a:
View of a "mechanised" patient: in this case the orthotic device, a so-called "Exoskeleton", was developed merely for research purposes at Case Western Reserve University *(Cleveland). The pneumatic system shown allowed five degrees of freedom through the shoulder, arm, and wrist.*

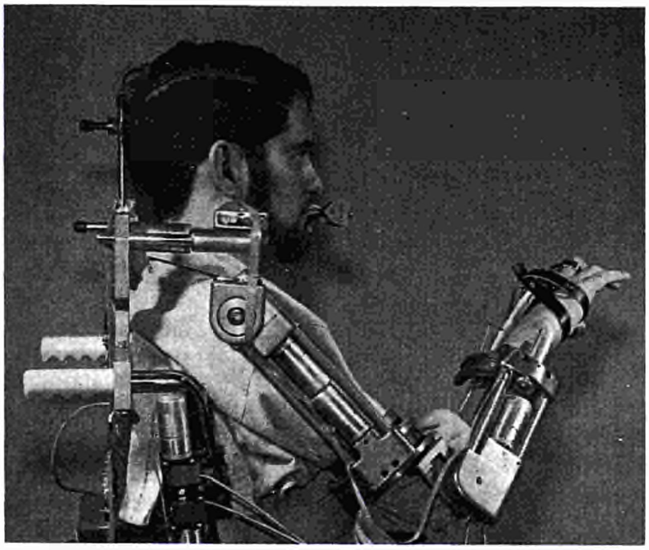


Fig. 3b:
"Mechanised" patient ("Exoskeleton" developed at Rancho Los Amigos Hospital, *California). In this case the various degrees of freedom are actuated by a series of bidirectional microswitches placed in front of the patient's mouth and operated by his tongue.*

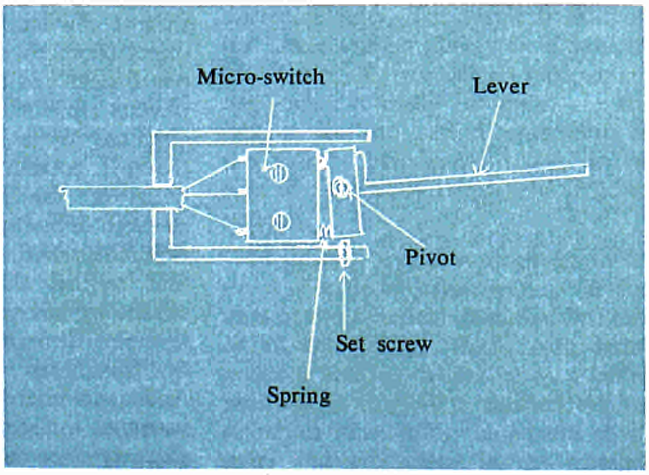


Fig. 3c:
Sensitive micro-switch.

present, therefore, other substitute access paths to the body must be sought.

So far, however, only very unsatisfactory results have been obtained in attempts to provide feedback, e.g. by mechanical or electrical stimulation of the sense of touch in areas of healthy skin which are less essential for it. In the case of prostheses or aids intended to compensate for the loss of senses such as sight or hearing, the task becomes even more difficult owing to the greater flow of information involved.

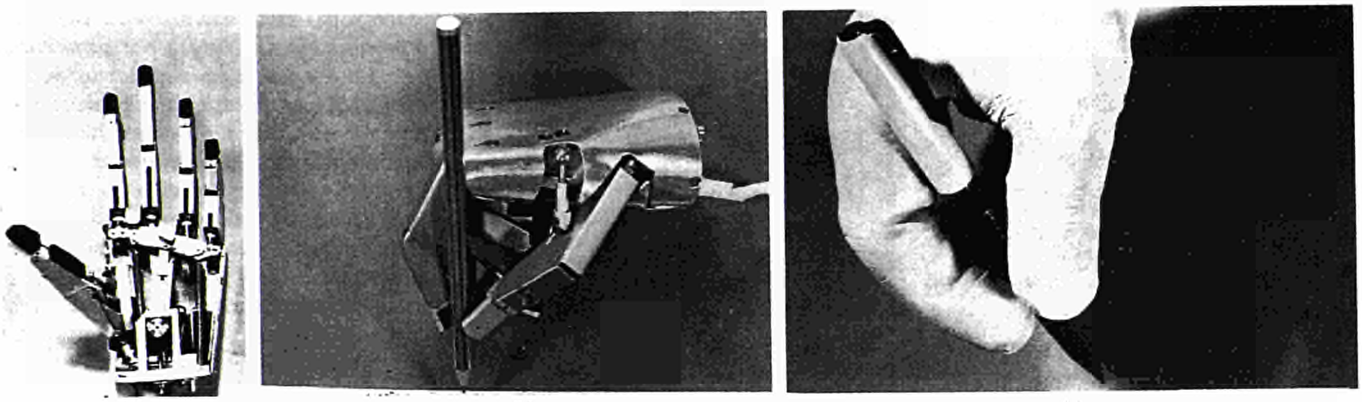
The frequently attempted method of enabling the blind to "see" by hearing and the deaf to "hear" by sight can help the afflicted person only when he can concentrate entirely on using the substitute sense for picking up the converted information coming from the realm of the defective sense (e.g. when a blind person is engaged in "reading" a book or when a deaf person is "listening" to a concert). In everyday life, on the other hand, he is more than ever dependent on his remaining senses so that he is unable to accept—and is sometimes more hindered than helped by—any narrowing of these still serviceable channels for the communication of information from his surroundings for the purpose of performing tasks arising from the realm of another sense. These are typical examples of how the biomedical engineer, in his enthusiasm, may possibly develop complicated appliances the subsequent application of which is more of a herculean task for the patient than an alleviation of this troubles. The direct feedback of signals *to* the nervous system and the drawing of signals directly *from* it, in both cases in long-term use for rehabilitation purposes or therapy, constitute a very important field for application-orientated basic research in biomedical engineering. The difficulties involved, however, are such that success should not be left to chance by having this work conducted in minor laboratories or institutes with a "subcritical" number of staff or inadequate interdisciplinary coverage; it warrants a broad-based backing, particularly since the solution of this man-machine interface problem offers the key to success in the development of nearly all the complex bioelectrical devices which are in close symbiosis with the patient for a considerable period.

The difficulty of such signal communications from and to the nervous system will probably emerge most clearly of all in the task of restoring the communication channels in the spinal cord of paraplegics, for example by using electrical conductor systems to bridge the site of the lesion. Since this will probably not be accomplished for some time, owing not least to the vast number of such channels present in a small space, for the time being other solutions have to be sought.

Attempts at motor stimulation of the extremities and certain other muscles (e.g. sphincters) have met with some degree of success, but there is always the problem of opening up a sufficient number of control sources for the commands.

This problem becomes really acute in desperate cases of severe quadriplegia (due to lesions of the first cervical vertebrae as the result, for instance, of traffic accidents or sports injuries). Except for being able to work their facial muscles, these people can neither move nor have any active contact with the world around them, since frequently they cannot even speak. Their facial perceptions, however, are keen and mentally they are in full possession of their faculties, so they live in such a state of imprisonment that anything more distressing can hardly be imagined. These patients are a compelling example of the justification, to which reference has already been made, for costly state-aided research in respect of such cases which, although relatively few in number, are of such gravity as to merit a high priority on humanitarian grounds and in which industry may be prevented, by commercial considerations, from readily taking an interest.

With reference to these people it can also be shown how easy it is for the biomedical engineer, either from a lack of alternatives or sometimes as the



(a) (b) (c)

Fig. 4: *Multifunctional hand for four-channel control (thumb and finger setting). Developed by the* Rheinisch-Westfälische Hochschule *at Aachen in collaboration with the* Orthopaedic Clinic of the University of Frankfurt *and the* Joint Research Centre *at Ispra, it provides a good imitation of the most varied types of prehension with deliberatly simple control conditions.*

The three pictures show: a) the skeleton of the multifunctional hand, volar face; b) the hand in writing position; c) the hand equipped with cosmetic glove.

result of an unsuitable theoretical approach, to pursue solutions which are of doubtful value to the patients.

If these patients are fitted, for instance, with extra-oral tongue switches and electrodes for writing by means of their eye movements, these constitute admirable feats of medical technology, but they cause the one part of the body over which the otherwise completely immobile patient still has control—namely the head—to disappear totally within a machine.

Despite the alleviation obtained, the patient is no better off if he feels that he is being manipulated like a machine. Fortunately, the problem of the above-mentioned signal transmitters is susceptible of solutions which are technically more elegant and hence aesthetically more appealing, such as fitting a tongue pressure transducer system inside the mouth together with a microtelemetry transmitter, or mounting the electro-oculography electrodes for the utilisation of the eye movements on a special pair of spectacles.

If, however, it is desired to open up a large number of differentiated communication channels for the patient, this relatively "simple" method is of no avail, nor can it be done purely by making use of electromyogram specimens on the scalp; instead, it is again a question of the long-term coupling of electrical apparatuses directly to the nervous system, perhaps directly to the brain, with all the protracted and costly basic research that this entails.

Role for international research

Application-orientated research of the kind mentioned in the foregoing examples, which is nevertheless still quite a long way from the production stage in the industrial sense, is, understandably, risked only by very large enterprises, and then only in exceptional cases. Research which is near the production stage, on the other hand, is being carried out by industrial firms, but the intermediate results, again understandably, are not published. In Europe, the only state-aided research worth mentioning is conducted at a few major institutes; the scale of their activity, however, is not such that tasks of the magnitude indicated above can be handled with reasonable prospects of obtaining in a sufficiently short time results that can be used in practice.

The lack of internationally sponsored institutions operating on a major scale in this field is deeply felt. Such lack can only be described as astonishing in view of:

- —the clear internationality of the problems;
- —the universally recognised importance to mankind of dealing with them;
- —the great expenditure required for research and development;
- —the absolute necessity of collecting together all the medico-technological knowledge available;
- —the fact that the results will not have a direct military application;
- —the traditional internationality of medical science.

Consequently, the situation arises whereby important exploratory basic research—which is not yet directly related to industrial production but is also too large in scope to be any longer purely a task for university institutes—is largely left undone, whereas highly product-orientated research is conducted secretly. The result is that on the whole a great disservice is done to the cause of biomedical engineering and—what is really the point—to the sick or disabled person, especially, as has already been pointed out, in the case of a minority of gravely afflicted patients.

In Europe, a remedy might be to set up a European organisation, on the lines of the American *National Institute of Health (NIH),* which, with international backing, would be in a better position to carry out unrestricted research of its own for the benefit of all users and producers (in the member

Fig. 5: *Prince of Lagash, detail, around 2200 BC.*

countries at any rate) and to award research contracts. The danger of a slackening of effort in the course of time, even on the part of this organisation's research staff, could be largely averted through a close linking of the research teams with the groups of patients to whose problems it is planned to apply the results of the work. There is in any case no place in this field for researchers who do not feel impelled to work responsibly as a consequence of any sort of real contact with the people seeking help.

Guiding principles

On what can we base our decision when, in a given practical case, we have to strike out along one of the roads that biomedical engineering opens up?

As has been said, biomedical engineers need an image of man that must be founded on the sum of knowledge of the essential factors of human life. This knowledge is without doubt interdisciplinary in a different sense from biomedical engineering itself. Consequently, it would be helpful if groups of responsible people who are inspired by a love for the needy and are drawn from various walks of life (such as psychologists, sociologists, philosophers, theologians, physicians, engineers and laymen) were now to reflect really profoundly—without having to cast anxious glances over their shoulder at the general public or at various pressure groups—on the problems typified by those mentioned below. This should be done on a far larger scale than has hitherto been the case from time to time either as a result of private initiative or at the behest of other interests such as television.

Here, then, are some of the problems to which thought should be given:

1) *How does one really help a sick or disabled person in his particular situation?*
2) *What constitutes morbid excesses of biomedical engineering which do not spring from an understanding of the patient's real needs?*
3) *Under what circumstances is it unjustifiable to prolong life artificially?*
4) *How is it possible to evoke and support a responsible and patient-orientated approach on the part of engineers, doctors, institutes, industrial companies and the authorities responsible for promotion at a national or international level?*

It simply is not possible, nor perhaps is it even a sensible aim, to restore every patient to a more or less normal state of health; in view of the limited possibilities of biomedical engineering and the unique nature of the patient's situation, all biomedical engineers can do is to strive to provide the *optimum* aid in a particular case.

Yet, what is "optimum"? Probably the maximum augmentation of the particular person's feeling of happiness in life, which, however, can always mean the individual joy based on his own highly personal response to life, and not some schematically defined sense of happiness.

One of the problems is that *the optimum aid to living is not susceptible of an all-embracing definition, but is closely bound up with the character of the patient.* Such reflection therefore demands a very large measure of identification with the person in need of help, a sort of elder-brother relationship, as in all cases of genuine aid by one human being to another. This personal commitment can neither be learnt nor bought, since this is a question of our attitude as human beings.

On the other hand, personal contact with the "cases" will certainly enable ideas of a more general nature to take shape; such ideas will then serve as guidelines to the overall pattern and not merely to the details.

Besides, owing to a keener nose for wrong tracks in development (wrong because they lead away from man instead of towards him), they will help to guard from the outset against the manipulation of the sick or handicapped person and thus finally contribute to his release from the prison of his impaired feeling for life. In such an activity one may be absolutely confident of continually finding new landmarks, since this is a living process. In this way, moreover, we can undoubtedly learn a great deal more about the vital needs of healthy people, e.g. as regards the situation that frequently arises today of a close symbiosis between man and a complex machine (computer, process control, fast means of transport, safety devices, etc.).

Properly understood, biomedical engineering is the joint expression by doctors and engineers of their love for their fellow men in need of help. Hence it is a mirror of what is probably the most meaningful and certainly the most satisfying of all human activities. There should consequently be no need to bring up the question of its necessity, its acceptability or its worthiness for advancement.

Perhaps the basic meaning of the Greek word θεραπέυω (therapéuo), "I serve", will be able to sustain us in our reflection.

EUSPA 10-12

Ispra's contribution to reactor safety[1]

Far too many people, especially the man in the street, think that reactors are a great technical and scientific achievement, but much too dangerous to live with. This article shows how many exacting studies are continuously carried on to make sure that even the remotest accident will never have a chance to occur or, should such an event present itself, that it can be totally controlled.

JACK RANDLES

STATED IN THE simplest terms, the basic objective of a reactor safety research programme is to provide the nuclear business with the technical knowledge required to design and build power reactors with a negligible probability of serious maloperation and with systems which reliably limit the danger to the environment of hypothetically possible accident conditions. Safety research is therefore aimed at obtaining information on those specific properties of reactor components, structures and materials which would be involved significantly in maloperations or would influence the evolution of accident situations.

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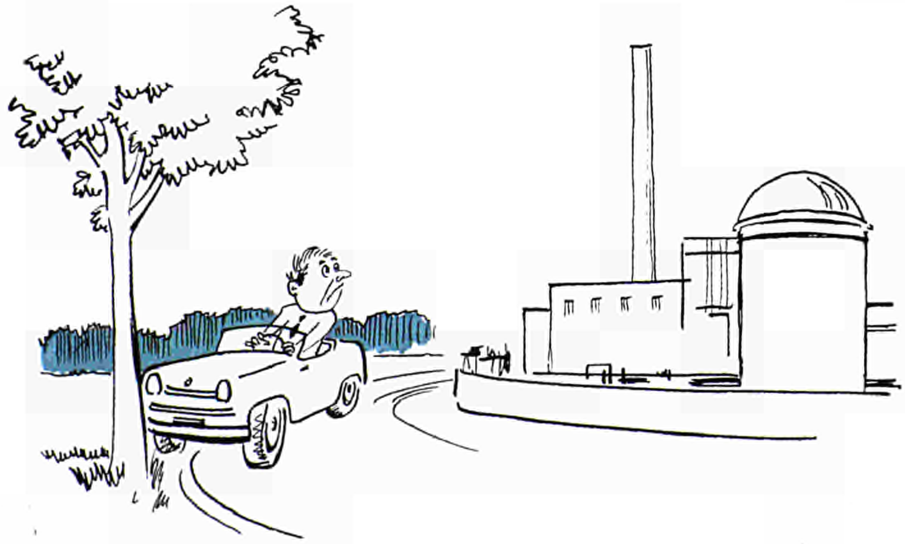

Of particular importance, requiring the most exploratory effort, are the laws governing the thermal, hydraulic, mechanical, chemical and neutronic behaviour of reactor systems and subsystems. It is in this area where activity at Ispra is mostly concentrated.

Such research cannot itself ensure the safety of reactors but must be a supporting service to industry in its effort to guarantee the safety and operational reliability of its designs, and to the state authorities charged with the responsibility of judging the safety of reactors and granting licenses for their construction. It is from this position, the "support to national industries and licensing authorities" viewpoint, that Ispra has increasingly developed its safety orientated research in recent years.

The major stimulus to this trend has, of course, come from the great paralysis at the political level of the Community over the question of a Euratom research programme. This problem is closely related to the fact that it is private industry rather than the national (still less international) centres which will ultimately play the dominant role in nuclear technology. The nuclear programme at Ispra is thus being compelled to become more and more a "support" or "public service" activity. For this reason, many collaborative connections have been established with external bodies to assist them in the solution of certain difficult safety problems encountered in the course of reactor development. As a result, a more valuable use has been made of the resources available at Ispra than might otherwise have been possible. A high proportion of the research presented in this article has arisen in this way. However, the article is certainly *not* a comprehensive survey of the work and facilities at Ispra devoted to reactor safety problems. The intention

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[1] This article was written with the assistance of E. BURCK, G. FRIZ, B. HENRY, H. HOLTBECKER, W. HUFSCHMIDT, H. KOTTOWSKI, W. RIEBOLD, C. RINALDINI, G. VOLTA.

is only to describe and explain some of the more recent or "dramatic" studies in the field.

Research in support of fast reactor safety

The fundamental property of all fast reactors, which underlies the thinking on their safety, is the fact that they contain so much fissile material that a compaction of the core—or a part of it—could in principle raise the reactivity above prompt critical and cause an uncontrollable nuclear excursion and dangerous energy release. Since a chain of events (see below) leading to this catastrophic result has a chance of occurring (remotely) only if the core cooling system goes seriously wrong, a large area of safety research is directed towards the study of possible coolant failures and their immediate consequences.

In the gas or steam cooled fast reactor, which necessarily has a highly pressurised primary circuit, the principal initiating mechanism of coolant failure would be primary circuit rupture and depressurisation. In the sodium cooled system *(LMFBR)*, however, the primary circuit is not highly pressurised and a serious coolant failure could only be initiated by such accidents as a blockage of a subassembly, pump failure, fuel element distorsion etc.

For several years, much work at Ispra has been devoted to the study of problems arising from such types of coolant failure in *LMFBR* systems. The phenomena of sodium superheating, flash boiling and rapid ejection from heated channels followed by the condensation of the vapour and re-entry into the channel has received particular attention, as these phenomena determine the residual cooling which remains after a failure in a subassembly and the pressure pulses which may have to be resisted by the subassembly structures (not to mention the reactivity input due to a positive void coefficient).

A problem of very great concern at present to *LMFBR* designers is to know what happens if the above mentioned residual cooling is insufficient to prevent the melting of the Uranium Dioxide (UO_2) fuel and the re-entry of the sodium (Na) leads to an intimate mixture of hot molten UO_2 (around 2 800° C) with Na (around 600° C). Such a mixing will almost certainly involve very rapid heat transfer and the explosive ejection of the Na, with the possibility of damage to neighbouring subassemblies and the propagation of the coolant failure conditions to other parts of the core.

Very briefly, the complete postulated chain of events of which the above processes are a part is as follows:

a) blockage of a subassembly, reduced Na coolant flow;

b) boiling and expulsion of Na coolant from the subassembly;

c) partial melting of UO_2 fuel due to depressed heat removal;

d) re-entry of Na, vigorous Na/UO_2 mixing, dispersion of UO_2 into small fragments;

e) rapid transfer of heat stored in UO_2 to Na with (2nd) violent ejection of Na from the subassembly;

f) damage and blocking in neighbouring subassemblies ;

g) repetition of the cycle until widespread core melting and prompt criticality (due to core slumping and compaction);

h) uncontrolled nuclear excursion, explosive core destruction;

i) dynamic loading of reactor containment.

The rest of this chapter on fast reactor safety will describe research at Ispra on the UO_2/Na interaction [processes (*d*) and (*e*)] and the problem of containing the mechanical energy released if events proceed unchecked [process (*i*)]. The UO_2/Na interaction is important not only explicitly in processes (*d*) and (*e*) but also implicitly in process (*h*). A part of the heat deposited in the UO_2 fuel during a prompt critical excursion will inevitably pass into and vaporise the coolant—if any remains in the core at that stage—and thereby generate additional mechanical energy for stressing the container [process (*i*)].

Direct contact interaction between hot molten uranium dioxide and sodium

Work on this problem has been in preparation for about three years, during which two experimental installations have been designed and built. One of them has a channel geometry, to simulate a single subassembly, and the other a tank geometry, to simulate the core and containment structures. These set-ups provide the environment for the duplication of the processes (*d*) and (*e*) above in conditions where all the important variables can be measured accurately and inter-related by means of theoretical models of the thermo-hydrodynamic phenomena occurring. Both systems are now approaching the exploitation stage and research will be aimed at direct support for the Benelux-German 300 MW (*e*) fast reactor project *SNR* which contributes towards the costs.

The channel experiment. In Fig. 1, the basic essentials of an experiment in the channel system are shown. A specimen (1-50 gm) of molten UO_2 at about 2 800° C is prepared (using direct electrical heating) in an oven which is also designed as a chamber for the containment of the UO_2/Na interaction. A diaphragm supporting a column of liquid Na (at about 600° C) in a long channel is then broken and the column drops onto the UO_2 specimen (Fig. 1 A). On impact, violent fragmentation of the UO_2 and Na/UO_2 mixing occurs and, because of the large surface contact area thus created, the heat transfer into the Na is extremely fast. This then causes rapid thermal expansion and vapour formation in the Na in the interacting chamber and the ejection of the Na liquid column in the channel (Fig. 1 B). The velocity of this ejection and the pressure in the interacting chamber, at the mid-point and top of the channel, are measured as a function of the time.

The factor having the largest influence on the above processes, in particular the amplitude and duration of the pressure burst, is the total UO_2/Na contact area formed due to fragmentation. This area will be estimated after each experiment by opening the oven and examining the UO_2 debris. If the contact area can be determined in this way for a sufficiently wide range of conditions, it is hoped to uncover the main factors which control it.

One of the major aims of research is to establish calculation methods which—given the degree of UO_2 fragmentation (contact area), the relevant thermal and physical constants of the system and the initial Na and UO_2 temperatures—will predict correctly the observed pressure pulse and ejection velocity. Such methods will contribute to the stock of theoretical tools for fast reactor safety design and analysis.

Some such work on the theoretical side has already been done; simplified equations of heat balance, heat transfer and fluid column motion have been derived and solved jointly by a numerical method using the Ispra IBM 360/65 computer. This theory has not yet been adequately checked by experiment and is expected to require improvement as tests continue and better information is obtained.

The tank experiment. Fig. 2 depicts schematically the basic sequence of events in an experiment in the tank system. A crucible containing molten UO_2 (up to 4 Kgm at about 2 800° C) is dropped (Fig. 2.1) from an oven above the tank through a tube and a system of quick operating valves which keep the tank sealed. On arrival in the tank, the crucible is automatically caught and overturned and the UO_2 is spilled (Fig. 2.2) into a pool of liquid Na (at about 600° C). The region above the Na pool is filled with argon cover

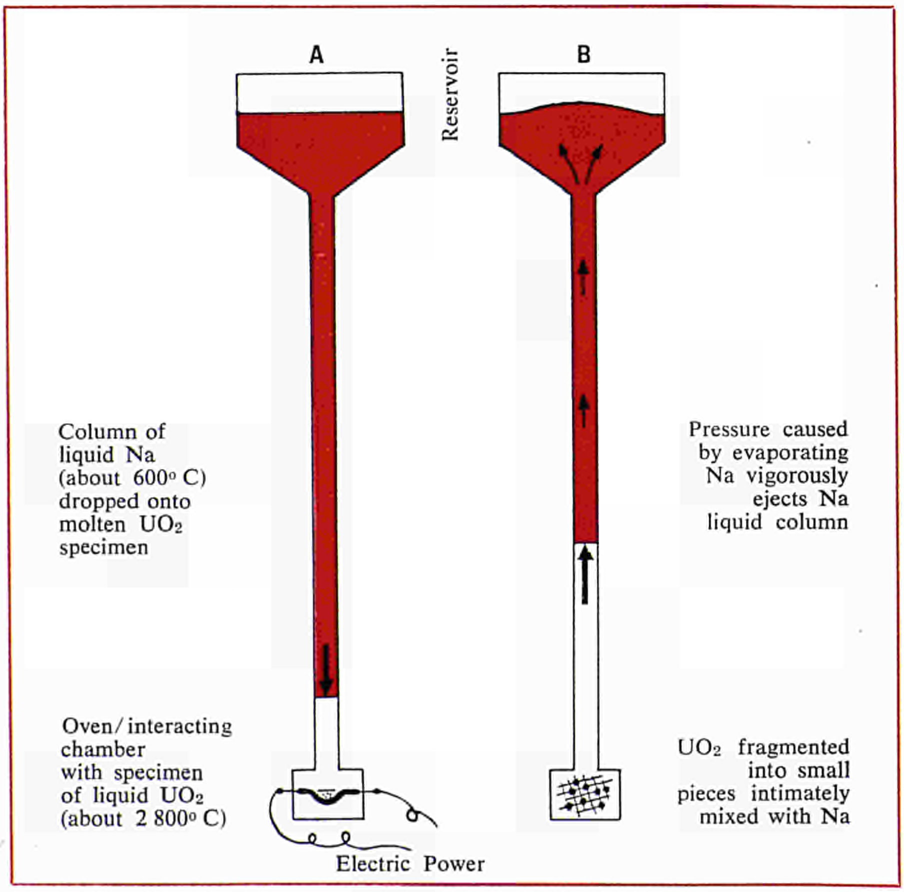


Fig. 1: *Schematic representation of a UO_2/Na interaction experiment in the channel system.*

gas and submerged in the pool is a model of typical fast reactor core structures. Into the subchannels of this model the molten UO_2 falls, breaks into small fragments, transfers heat rapidly to the Na and induces the sort of flow field indicated (Fig. 2.3). The accompanying pressure burst is measured at many positions on the tank wall and it is planned to observe the rapidly varying configuration of UO_2, Na liquid, Na vapour and cover gas by means of high speed X-ray photography.

As in the channel experiment, the all-important heat transfer surface created during the interaction will be determined from an examination of the UO_2 fragments extracted from the tank after each test. It is of particular importance to see if the very divergent conditions in the two experiments cause differing UO_2 fragment sizes and UO_2/Na contact areas. If, with luck, the difference is small, then we can hope that this very important but complicated process of UO_2 dispersion in Na may be amenable to theoretical prediction.

In the meantime, theoretical analysis must remain as described above for the channel experiment, that is, the magnitude of the contact area must be regarded as given and the calculation of the thermohydraulic processes continued from there. On this basis, a very tentative mathematical description of the tank experiment has been derived by assuming that the argon cover gas and Na vapour form a single bubble with the UO_2 fragments hovering in the bottom of it. Simplified equations describing heat transfer in this configuration have been derived and solved numerically on the IBM 360/65, but again the results of this procedure must await comparison with experiment before any confidence can be placed in them.

Dynamic loading of the containment of a fast reactor due to an accidental prompt critical excursion

Despite the extremely low probability that a failure such as a loss of cooling [event (*a*) in the hypothetical fault chain] will lead to violent core destruction [events (*h*) and (*i*)], such a catastrophe is nevertheless studied to provide the basis for the design of completely safe containment systems. For this reason, a prompt critical excursion, leading to core disassembly (*h*) and dynamic loading of the container (*i*), is called a "design basis accident" or "*DBA*".

The magnitude of the energy release caused by a *DBA* is estimated by the well known Bethe-Tait method which, given the disturbance (reactivity input) due for example to widespread fuel melting [event (*g*)], calculates the reactor power and core material movement provoked by the resulting high pressures. These pressures arise because the power burst in a prompt critical excursion is so fast that the fission energy deposited in the fuel (UO_2) has no time to escape and so causes rapid thermal expansion and vaporisation of the UO_2. The displacement of core material by high internal pressures serves to quench the excursion because it shifts the fuel into a less critical configuration. However, the main quenching ("shut-down") mechanism in a typical *LMFBR* is the loss of reactivity due to the fuel temperature rise— the famous "Doppler feedback". The combination of these two effects within the Bethe-Tait theory determines the answer it gives for the total heat produced by the excursion. A further calculation then has to be made to estimate how much of this heat may be converted into *mechanical work* (including the effect of the UO_2/Na interaction discussed before) to be constrained by the containment structure.

Having thus got a theoretical estimate of the mechanical energy which the containment must be designed to withstand, the question arises: how can we demonstrate that the containment actually *can* withstand it?

Generally, the answer to this question is provided by carrying out explosive tests in reduced scale models. With their flexibility of parameter variation and the support of realistic calculation codes, it is felt that such tests can give reliable information on the behaviour of real systems. Ispra has worked on the simulation of catastrophic accidents for many years and the present effort in connection with fast reactors is made in close collaboration with the projects *SNR* (Benelux-German) and *PEC* (Italian *CNEN*).

In order to simulate the computed mechanical energy release, TNT, dynamite and recently also slow deflagration explosives have been used. The latter were developed by *Belgo-Nucléaire* and tested in a quarry to establish the magnitude and timescale of the energy release. The chemical reaction has to be adjusted to produce the same amount of mechanical energy—released in the same time—as in the computed nuclear excursion.

When a new charge is found to reasonably duplicate the hypothetical nuclear excursion, the charge can be detonated in models of the reactor system and its containment and the response of these components studied in detail. For the results to be meaningful, the model must be constructed according to certain scaling laws. In the present state of the art, these laws assert that if the pressure, velocity, stress and strain in the real system are to be reproduced in a model where all the linear dimensions are a fraction λ (< 1) of those of the real system, then the model must change:

—displacement and timescale: by a factor λ;

—inertia: by a factor λ^2;

—mass, volume, momentum and energy: by a factor λ^3;

—acceleration and strain rate: by a factor $1/\lambda$.

These conditions for the retention of the same pressure and strain history as would occur in the real system are valid only if the same materials are used, and if the dynamic properties of these materials do not depend on the speed of deformation. If the scale of the model is very small ($\lambda \gtrsim 1/10$), the change in the strain-rate (factor $1/\lambda$) becomes large enough to cause the well known change, for example, in the elastic limit of the materials and thereby to violate the second restriction. Such problems, though not dealt with here, are a subject of special study at Ispra.

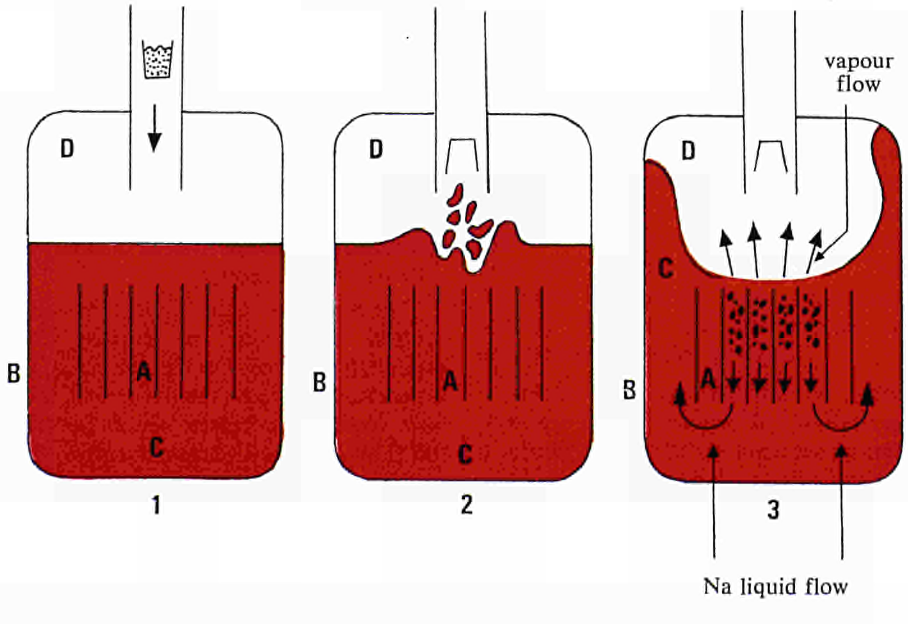
The above described modelling techniques for the study of the containment of destructive nuclear excursions are currently being applied at Ispra to the two proposed reactors *PEC* and *SNR*. To illustrate this work, Fig. 3 shows schematically a vessel whose main dimensions are $\lambda = 1/12$ of those of the *SNR* reactor vessel. Tests in this model serve not only to reveal the stresses to be expected during explosive excursions, but also to evaluate further the characteristics of the slow deflagration charge and to check such safety devices as an inner skirt and a perforated plate held in the sodium pool (simulated by water) in such a way as to reduce the impact on the roof. Fig. 3 also shows typical pressure traces measured for a charge corresponding

Fig. 2: *Schematic representation of a UO_2/Na interaction experiment in the tank system.*

Crucible containing molten UO_2 dropped from oven via quick acting valve system

Cruicble overturned and held by a spilling device —molten UO_2 falls into liquid Na pool

UO_2 fragmented—heat transferred to Na in model of core structures



A: Model of core structures
B: Model of reactor tank
C: Liquid Na
D: Argon cover gas

to an energy release of 1 000 Mega-Joules in the real 1/1 scale vessel. From the pressure traces we see that the largest pressure pulses occur on the roof of the vessel. The probable reason for this is the "waterhammer" effect caused by the rapid acceleration of a plug of water above the charge and its impact on the roof. A satisfactory detailed interpretation of the three pulses observed at position P_3 in terms of this waterhammer process has not yet been accomplished owing to some remaining uncertainties in the characteristics of the charge and its detonator. However, it appears very likely that the basic mechanism underlying at least one of the pulses is the "bouncing" of the water plug between the high pressure gases released by the charge and the compressed cover gas above the pool. Considerably more theoretical work is required to obtain an acceptable diagnosis of such phenomena and thereby improve the tools available for containment design.

Research in support of water reactor safety

Unlike fast reactors, water cooled reactors do not contain sufficient fissile material to make a prompt critical configuration of any type whatever. On the other hand, in order to be able to operate with a sufficiently high coolant temperature for reasons of plant efficiency, the primary circuit has to be highly pressurised, often in excess of 60 atmospheres. Thus, a point of major concern for the safety of water reactors arises from the possibility—though remote—of a rupture of the primary circuit and a consequent depressurisation of the system leading to a loss of core cooling.

The problems to be studied in connection with such an accident are essentially twofold. On the one hand, it is necessary to know the dynamical and heat transfer processes which govern the flow rates and temperatures in the system during depressurisation; for example, one needs to know the behaviour of the fuel cladding temperature during blowdown to assess if burn-out and fission product release are likely. On the other hand, it is necessary to investigate the problems of emergency core cooling with a view to designing systems for the removal of the decay heat from the fuel in post-blowdown conditions (after the normal coolant has been ejected). Research at Ispra is involved in both of these aspects and, to a large degree, has been started in response to problems posed by *Siemens AG*, Erlangen.

Depressurisation studies

A rupture in a system filled with hot water at a high pressure causes a rapid outflow through the rupture and an immediate formation of vapour within the system by the well-known process of flash evaporation (boiling due to a release of pressure). If this occurs in the primary circuit of a water cooled reactor, the normal cooling conditions change completely within a few seconds or even fractions of a second.

At the moment of occurrence of a rupture the reactor will be shut down because the sudden loss of pressure in the primary circuit generates a scram signal. The negative void coefficient of water reactors supports this process. Thus, one might deduce at first that depressurisation presents no serious danger. However this is not true because the heat stored in the fuel elements is of the order of some full-power-seconds. To give an idea of what this means, 5 full power seconds in a 500 MW reactor equals about 600 million calories. In addition to the stored heat, there is also the decay heat released after the scram, which gives a power input to the core of about 5 % full power. Since core cooling during primary circuit depressurisation is poor, there is a danger that this heat will melt the fuel cladding (burn-out) and cause the release of highly radioactive materials into the reactor containment through the rupture.

To be sure that this danger can be avoided, a detailed knowledge of the thermohydraulic behaviour of the coolant during primary circuit blowdown is necessary.

An experimental programme aimed at contributing to this knowledge has been underway at Ispra for some years,

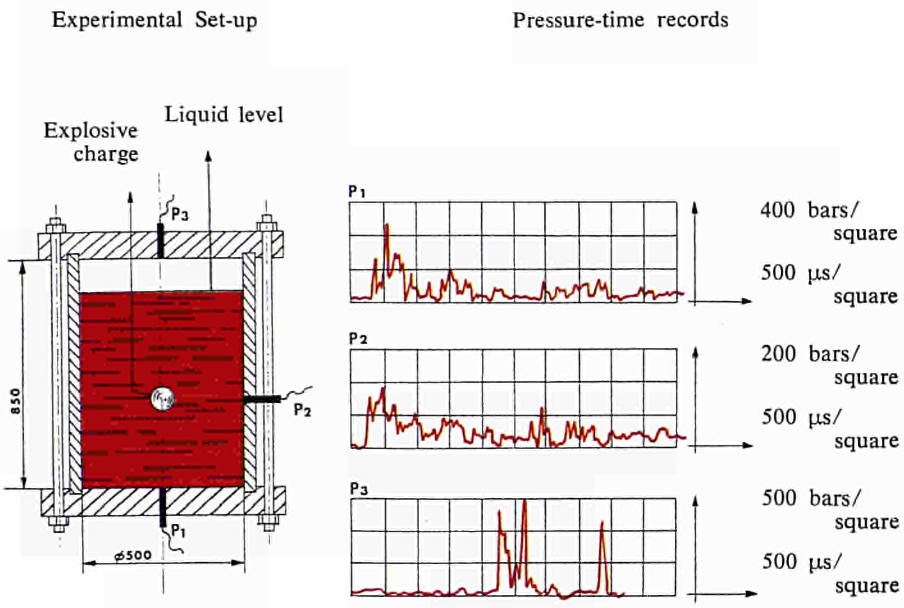


Fig. 3: *Schematic diagram of a 1/12 scale model of the* SNR *pressure vessel and typical pressure traces corresponding roughly to a* DBA.

during which close contact has been maintained with interested nuclear industries to ensure correct orientation of the work. Two test loops have been built to study respectively the heat transfer and dynamical aspects of depressurisation.

The loop designed for the *heat transfer* studies has a test section with the heated length and hydraulic diameter of a real reactor subchannel. The inlet and outlet plenums of the real core are represented in the loop by appropriate volumes of coolant beyond the bottom and top of the test section. The rupture is simulated by a quick opening valve which releases the coolant into the atmosphere. The effect of the position of rupture in the primary circuit is being investigated by placing this valve in different parts of the loop. Reactor power during depressurisation is simulated by suitably varied direct electrical heating. The nature of this variation is very important since it must reproduce reasonably the behaviour of the heat flux from a real fuel element in depressurisation conditions. However, this heat flux is not known in advance, and its simulation has to be achieved by an interplay of theory and experiment. First an experiment is performed with a given heat flux, e.g. equal to that calculated for a real fuel element under the assumption of a constant cladding surface temperature. The variation of the test section temperature corresponding to this heat flux is then measured throughout the depressurisation transient. This observed temperature variation is substituted for the cladding surface temperature in another calculation on the real fuel element and a "corrected" heat flux is evaluated. A second experiment is then performed with this heat flux to obtain a new test section (cladding) temperature variation and from this, using the theory for a third time, a second "corrected" heat flux is computed. This iterative procedure is repeated until the test section temperature and heat flux are both consistent with the behaviour for the cladding of a real fuel element as predicted by the theory. In this way the need for a large expenditure on an experiment using a more realistic representation of a fuel element is avoided.

In the other installation built for the study of the *dynamical* aspects of depressurisation, detailed measurements are made of the transient pressure distribution and flow rate inside the loop and the momentum of the free jet blown out from the rupture (again simulated by a quick opening valve). The experiments yield information on the amplitude and speed of waves excited in the system by the pressure release at the rupture, the time required to attain quasistationary outflow conditions, the behaviour of the flowrate and the mechanical forces exerted by the free jet.

In both installations the objective is not only to provide practical information on the events following a rupture in the primary circuit of a water reactor, but also to supply the data necessary to test the established blowdown calculation methods. Lacking a detailed knowledge of some of the physical conditions occurring during depressurisation (in particular the degree of departure from thermal equilibrium in the flashing two phase mixture), these methods have had to make certain assumptions which require experimental assessment. That such an assessment is a clear area of common interest to industries and licensing authorities is the major stimulus for undertaking the work at Ispra.

Studies associated with emergency core cooling systems

The depressurisation studies are concerned with the first five to ten seconds after a failure of the primary circuit of a water reactor. After this period the whole reactor core is voided and the emergency core cooling systems should begin to operate to transfer the decay heat out of the fuel elements. Two problems connected with emergency cooling systems are the subject of experimental studies at Ispra.

Measurement of heat flux by radiation in a 37 rod cluster. In the limit of a serious failure of an emergency core cooling system, the only mechanism for the removal of the decay heat from the fuel is radiation (and a little conduction) through the vapour environment. This investigation is pursued in order to assess the sufficiency of this mechanism in a typical fuel bundle in a pressure tube reactor in which the heat is absorbed into the surrounding calandria tube and moderator.

The experiments are performed with a full scale model cluster of 37 rods made of 11.9 mm outer diameter Zircalloy tubes located by means of spacers in a Zircalloy calandria tube of 110 mm inner diameter. The outer side of the calandria tube is surrounded by an insulating gap bounded by a water cooled Zircalloy foil. The decay heat of the reactor is simulated by an electrical heating device in 36 of the rods, the central rod being unheated because of its role as a mechanical support.

Two different test series are made. In the first, the temperature of the heated rods is kept constant and the different heating powers in three zones (inner 6 rods; middle 12 rods; outer 18 rods) are measured. In the second test series the heating power to each rod is kept constant and the different rod temperatures in the zones are measured. All the tests are made both in an air atmosphere of 1 bar and a vapour atmosphere of about 2 bars, the calandria tube cooling water temperature being in the range 30 to 60° C.

The situation is typified by the results for the first test series in which, for a uniform rod temperature of about 800° C, the mean heat flux from the rod surfaces is about 0.9 Watts/cm^2 in air and 1.2 Watts/cm^2 in the vapour atmosphere. These measured heat fluxes are not sufficient to extract the decay heat from the fuel element rod cluster, which gives about 5 Watts/cm^2. The only way to increase the heat flux by radiation up to this requested value would be to increase the rod temperatures up to about 1 300° C. This, however, is not possible because of the Zirconium/water reaction. Even at the lower temperature (800° C) of the tests using the vapour atmosphere in the cluster, the Zr/H_2O reaction ($Zr + 2H_2O \rightarrow ZrO_2 + 2H$) produced, during less than 5 hours of operation, enough hydrogen to cause (if ignited) extensive damage.

It seems, therefore, in the event of a primary circuit rupture accompanied by a failure of the emergency cooling system, that very little benefit can be expected from radiative cooling of the fuel.

Thermal stresses caused in the wall of a reactor pressure vessel due to the onset of emergency cooling. The problem of the transient temperature distribution and the resulting thermal stresses in the thick wall of a reactor pressure vessel is of great importance when the vessel, at its usual temperature of about 300° C, is flooded with water at about 60° C from the emergency cooling system. The resulting thermal stresses in the wall should not exceed the limits required to guarantee the integrity of the pressure vessel.

To measure the varying temperature distribution in the wall and thereby compute the stresses and heat transfer coefficient (which it is thought will provide a basis for a more general stress calculation method), the following experimental facility is used. A mild steel block of 2 meters height, 30 cm width and 20 cm thickness plated with stainless steel of 0.6 cm thickness, is mounted in a flooding chamber in such a way that only the stainless steel plate is wetted, the other side of the block being always dry. This block, representing a part of the reactor pressure vessel (the wetted stainless steel plate being the inside), is provided at different places on the wetted side by four tight fitting plugs of 3 cm diameter and 5 cm length (of which 4.4 cm is mild steel and 0.6 cm stainless steel to correspond exactly with the rest of the block). Ten thermocouples are embedded at various distances along the axis of each plug and from these the transient temperature distribution in the block during flooding is obtained. A radiation heating plate in the centre of the flooding chamber enables the pre-heating of the block to 300° C before the ingress of the flooding water, which can either submerge the block from below or be run in from above.

The temperature distribution is measured during flooding under various initial conditions, namely, initial block temperatures T_o (before flooding) in the range 150 to 300° C and water inlet temperatures T_b in the range 30 to 90°. The temperature transients obtained from the four sets of ten thermocouples are displayed visually by means of a fast response light beam recorder. As might be expected, the temperature in the first few millimeters of the plated block decreases very rapidly, especially if T_o-T_b is large (when rates of 20 000° C/sec are typical), while the temperature further inside the block changes much more slowly. Detailed analysis of the temperature traces yields not only the information required for a direct computation of the stresses, but also a good estimate of the heat flux and heat transfer coefficient at the block/water interface. This extra information serves to check more generally applicable stress calculation methods than that based directly on the temperature measurements.

At the beginning of the cooling process, heat transfer occurs by film boiling because the block surface is more than 100° C above the boiling point of water. After about one or two seconds, the surface temperature is low enough to allow the much better heat transfer conditions of nucleate boiling. By this time, however, the rate of change of temperature in the block is not so large. As the block cools further, boiling ceases and the remainder of the heat transfer occurs by natural convection.

Using the experimental results, the first rough calculations show that whereas the thermal stresses in the mild steel wall of the vessel do not exceed the elastic limit of the material, those occurring in the stainless steel plating are likely to cause plastic deformation and to bring about a failure of the mild steel/stainless steel junction.

Research on general aspects of reactor safety

This article has so far dealt with research arising entirely from the problems posed by specific reactor types. Now we shall present research whose methodology is more widely applicable to the analysis or prevention of reactor accident conditions or to the improvement of operational reliability.

Reactor dynamics

For some years now, large high power reactors have been under development and are planned for integration into the European electricity grid during the 1970's and 80's. To be sure that no costly failures will occur in these systems, the dynamic analysis of their response to all possible disturbances must be suitably thorough. In large cores, detailed spatial effects can occur which have a strong influence on such safety factors as the margin against fuel element burn-out. Hence in order to reliably exclude all damage in large cores as a result of power transients, and at the same time to operate them at the high specific powers demanded by economics, the analysis of the transients must include a reasonable allowance for all the important space dependent phenomena.

Basically, there are two aspects to spatial reactor dynamics. On the one hand, there is the problem of evaluating the time dependent distribution of power in the core from the equations of neutron diffusion, when the coefficients of these equations are in general functions of:

1) the local temperatures;
2) the local coolant void fraction (if boiling occurs);
3) the local Xenon concentration;
4) the local absorber rod positions.

On the other hand, there is the problem of relating these four physical variables—themselves space dependent quantities—to the power, using a suitable mathematical representation of:

a) the thermo-hydrodynamic laws of the system [for the evaluation of 1) and 2)];
b) the laws of formation and decay of Xenon [for 3)];
c) the laws of absorber rod movement engineered into the control system [for 4)].

The first of these aspects, dealing with power variations, is often referred to as the "neutronic" part. The second aspect, which deals with the changes in the system caused by power variations and the effect these changes have on the neutronics, is generally called the "feedback" part.

To a large extent, the "neutronic" and "feedback" aspects can be separated for purposes of mathematical analysis and computer programming. The result is then a set of "neutronic" and "feedback" programme modules which can be coupled via the temperature/void/Xenon/absorber-rod-position dependence of the coefficients of the neutron diffusion equations to make a "spatial reactor dynamics model". In constructing such a model, one is rarely interested in calculating the influence of all four of the above mentioned feedback mechanisms simultaneously but, depending on the particular reactor and problem under study, only one or two at a time. For example, the calculation of the self-regulation of rapid power transients (1-10 sec timescale) in a boiling water reactor would need to incorporate only the temperature (fuel and coolant) and steam void feedbacks. The same problem for a gas cooled reactor would require even less—the temperature feedback. On the other hand, the problem of the reaction of the control system and power distribution to variations of Xenon poisoning (timescale of some hours) would require essentially Xenon and absorber-rod-position feedbacks. Thus, it is very important to develop spatial reactor dynamics calculation methods in the form of a "computer programme series" in which the neutronics part is coupled with various subroutines embodying the different combinations of feedback effects corresponding to the different reactors and reactor transients of interest.

Several groups around the world are engaged in this large area of activity and effort at Ispra has lead to the *COSTANZA* series of computer programs. The development of this series was originally started for the analysis of power transients in light water reactors. For this purpose a general one dimensional (axial) neutronic code was written and coupled, as described above, to a code giving the time dependent temperature and steam void distributions along a typical water cooled fuel channel. This code, called *FRANCESCA,* is based on a currently accepted simplified theory of two phase flow which it is hoped to check experimentally in the future Ispra research programme.

From this starting point, the *COSTANZA* code series has undergone steady expansion. The neutronics part can now be treated in either one or two spatial dimensions and up to two energy groups. With this can be coupled subroutines giving feedback due to the thermohydraulic processes accompanying: 1) a single phase coolant (for pressurised water and gas cooled reactors) and 2) a two phase coolant (for any reactor in which coolant boiling occurs during transients). There are also subroutines giving the feedback due to Xenon poisoning and control rod movements. The power transients driven by this feedback also evoke, as an incidental secondary effect, certain temperature (and possibly void) changes. These changes, which in Xenon transients occur so slowly that they can be evaluated by simple static calculations, do not contribute essentially to the overall process.

It is emphasised that the development of this series of programs was not motivated only by academic interest, but to a large degree was the result of specific requests for practical calculations from firms in the nuclear business. In many cases contracts have been arranged in which these firms have partly paid for the work done.

On this basis, recent work on the *COSTANZA* series includes the development of versions suitable for application to high temperature gas cooled reactors with pebble bed cores and cores with prismatic fuel elements. Work is also underway to determine the modifications needed in both the neutronic and temperature/void feedback routines to treat fast reactor dynamics which involves, on the one hand, a hard neutron spectrum (perhaps requiring several energy groups) and, on the other, the peculiarities of liquid metal cooling (perhaps requiring a different treatment of the boiling process than that applied to water).

As a result of the continuing interest from reactor designers, this work on the *COSTANZA* series seems fully justified.

Reliability: A tool for safer design and rational hazard assessment

Man has to live with uncertainty in all spheres, but scientific man needs to *measure* his uncertainty. To this end, the theories of probability, information and systems analysis have been combined in engineering to give birth to "Reliability Theory". This relatively new discipline has the aim of evaluating the probability that a device will perform its required function during a given time in given operating conditions. The device can be a simple component or a complex system. It can have more than one function (e.g. a primary circuit pump serves both to circulate the coolant and contain it). What new element has Reliability brought into engineering practice and safety assessment?

Let us consider a very simple example: a stressed structural member. The traditional method of assessing the safety of such a member is to assume certain average material properties and compute the stress L at all points within it. If the stress which causes "failure" (a definition of which is unnecessary here) is, on the average, F, then the ratio $S = F/L$ is referred to as the "safety factor" of the member. If $S > 1$ everywhere, then the member was said to be "safe". In the Reliability approach, however, it is recognised that the material properties and failure limit F are by nature uncertain, the values for one specimen being slightly different from those of another. Thus, the quantities L and F are treated statistically. The question is not then: "what is the safety factor S?", but "what is the probability that $L > F$?". Engineering safety design becomes a problem of ensuring acceptably low failure probabilities.

This is the basic spirit of the reliability approach. When applied to complex systems there are essentially two lines to follow. First, it is necessary to determine the possible failure modes of each component of the system and to evaluate the probability of these failures as a function of the parameters describing the manner and conditions of operation. Second, knowing these probabilities, the network of components which make up the system has to be considered with a view to evaluating the effect of a disturbance in the operation of a part of the system (e.g. primary circuit pump failure), the response of the various components as they become affected by this disturbance and the identification of possible chains of failure (with overall probabilities) leading to catastrophic results (see the chapter on fast reactor safety). The sum of all such failure chains is called the "fault tree".

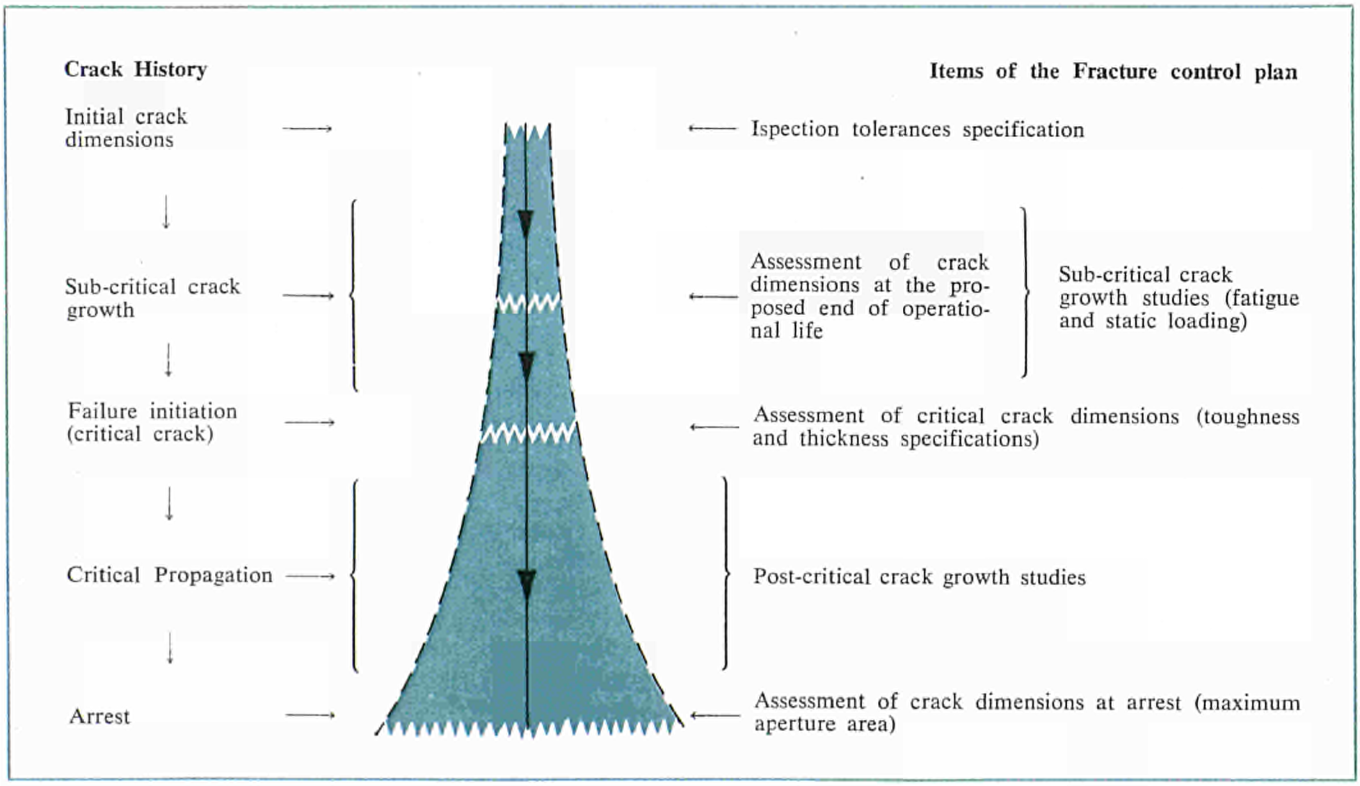
Experience in the pursuit of both of the above lines has been acquired at Ispra. In the first line, the main effort has been on the collection of data and developement of calculation methods for the determination of the failure probability of specific components in specific systems. This work has naturally been done in close collaboration with the operators of running plants, in particular the in-pile boiling water fuel testing loop *CART* of the *ESSOR* reactor. The essential problem in this field is that of deducing a *probability* function from a statistically small set of data. Its solution rests on the *assumption* of likely functions (component failure models) and the assessment of these functions by comparison with the operational data. In the second line, the component reliability information thus generalised has been assembled into a "fault tree" analysis of a pump failure accident in the *CART* loop. Other systems have also been examined in this way but not yet with comparable thoroughness.

Because of the large potential value of this type of approach to reactor safety analysis, it is aimed to establish further ties with reactor-system operators and other reliability specialist teams. The large task of data handling and analysis, of calculation methods development and application demands close collaboration, and an avoidance of duplication.

Early failure detection: Techniques to reveal malfunctions before they become dangerous

In many ways, a complex plant is like a living organism: the various malfunctions produce characteristic symptoms—and skillful fault diagnosis can yield a cure and prevent a catastrophic breakdown. Because of the high cost (for repair and lost operation time) and possible danger to people if such a breakdown occurs in a reactor, there are very strong incentives to investigate incipient failure signals in detail with a view to developing devices and techniques able to recognise them in normal operating conditions. By this

Fig. 4: *Crack propagation history and fracture control plan.*



means, control action can be taken to avoid further deterioration and allow repairs to be done with a minimum of inconvenience.

The main problem obstructing this objective is that of finding unambiguous signals of malfunction. Ideally, the signals should have a unique and well pronounced form—should be a "fingerprint" or "signature"—for each type of malfunction. The present state of the art is far from this ideal, however, and much more basic research is necessary. Among the phenomena to be studied as possible early failure warning signals are:

—neutron flux variations (neutron noise) caused by abnormal structural vibrations or coolant vapour bubbles;

—low frequency vibrations due to the abnormal shaking of heavy parts (broken bearings, fuel elements etc.);

—acoustic and/or ultrasonic noise accompanying abnormal vapour bubble formation and collapse, friction or crack formation and propagation.

In addition to such emitted spontaneous signals, "probing" methods of detection using ultra-sound, X-rays etc. have to be considered.

At Ispra, considerable experience relevant to these problems has been acquired. Neutron noise analysis has been an area of intense study for some years and a lot of first class equipment is now available for the work. Techniques for the analysis of low frequency (random) vibrations have been systematically exploited for the study of wear in fuel element bundles and are now being used in a more general way for vibration analysis in water reactors. With regard to acoustic emission processes, the shock waves generated by the collapse of vapour bubbles during abnormal incipient boiling has been investigated by both visual *(Schlieren)* and ultrasonic detection techniques and, as a result, a device for incipient boiling detection has been patented. Basic studies of the ultrasonic waves emitted by friction and fracture processes are underway. On the side of probing techniques, practical experience has been gained in the use of ultrasonic probing for fault detection in reactor vessels. The main concern in this field is to provide users with information on the effect of irradiation on the signal generators and detectors.

Like "reliability", early failure detection is a growing field on which reactor safety will increasingly depend. Thus, there is a strong motive for Ispra to continue and expand the above described activity. However, it is recognised that, as new ideas for early failure detection appear, they have to be submitted to in-pile tests and that the research has therefore to be pursued in close connection with the designers and users.

Fracture mechanics and pipe rupture studies

During the last ten years, the relatively new subject of fracture mechanics has been intensively developed in the United States and Britain and successfully applied to fracture control in many spheres: ships, pipelines, aircraft, pressure vessels, etc. The object of fracture mechanics is to predict the conditions leading to catastrophic failure of structures. This prediction is made in a *quantitative* way by the application of a tested relationship between failure stress, defeat geometry and material fracture "toughness". Such a relationship, an entirely new tool provided by fracture mechanics, constitutes a very large advance on the traditional fracture control methods based on toughness testing such as the well-known Charpy test. These methods were only qualitative or, at best, comparative, while the concepts of fracture mechanics can be used to design and check structures so as to *avoid* the combinations of initial crack dimensions, material toughness and stress which would cause the cracks to become unstable during the lifetime of the system. The set of procedures to be followed (during design and inspection) on the basis of fracture mechanics to guarantee this avoidance has been called the *fracture control plan* (see Fig. 4).

The work performed so far at Ispra in this field has been concerned with the application of the *COD* (crack opening, displacement) criterion for fracture control in Zr — 2.5 % Nb pressure tubes in heavy water reactors. This criterion asserts that a crack becomes unstable if the displacement at its tip, i.e. its "opening", reaches some critical value. Hence, the failure conditions of a structure in its operational environment—in this case, subjected to hydriding and irradiation embrittlement—can be ascertained by measuring the *COD* value for small hydrided and/or irradiated samples.

It is planned now to extend such rupture studies to the steel vessel and primary circuit of *LMFBR* systems. In such systems, because of the particular combination of wall thickness (stress field) and toughness (corresponding to the grade and temperature of the steel), the conditions are essentially those of "plane stress". The brittle fracture hazard may be excluded and the chief failure mode assumed to be fatigue and corrosion enhanced crack growth (taking account of the liquid metal environment). As a consequence this will be the main item in the planned studies. Communication with reactor industry is good and the study will be conducted with the aim of specifying possible methods of design of fracture safe structures as well as providing immediately needed data.

In closing, we would like to draw attention again to the fact that nearly all of the research described in this article has been stimulated by and derives its greatest value from contacts with reactor industries. If a significant improvement is to be made in reactor safety research at Ispra in the future, such contacts will have to be expanded and coordinated systematically.

For this purpose, it is believed that the Commission of the European Communities should sponsor the creation of a *"Consultative committee in matters of reactor safety"* along the lines already done for fast reactors, water reactors etc. Through this committee, the national industries and licensing authorities could promptly make known their feelings on the work underway at Ispra and bring attention to new problems which they consider best attacked on a Community basis.

EUSPA 10-13

Hydrogen, master-key to the energy market

An analysis of the potential uses of hydrogen shows that practically the whole of the energy market can be served by this "clean" energy medium.

CESARE MARCHETTI

AN EARLIER ARTICLE[1] described chemical processes for producing hydrogen using nuclear heat and pointed out that this hydrogen could be employed in order to penetrate the energy market. The ways and means of breaking into the market are discussed in further detail in the present article.

How to utilise atomic energy outside the electricity-generating field has been a gnawing problem in nuclear circles for many years for the obvious reason that electric power satisfies only about a quarter of the world's primary energy requirements. One solution after another has been proposed, but always of a sectoral nature—reactors to produce steam for paper mills or chemical plants, reactors for seawater desalination, reactors for bringing sensible heat to iron production processes, chemical reactors for synthetising nitrogen oxides, and so forth.

It is sheer illusion to imagine that the energy market can be conquered by such a piecemeal approach, first because the development of a purpose-built reactor is an extremely costly undertaking, usually not warranted by the size of the sector, and secondly because it is the very big reactors that are economical, and giant industrial plants account for a relatively small proportion of total energy consumption.

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For these reasons a search began some five or six years ago for a solution based on a more convincing philosophy. Obviously the model to copy was the electricity system; what we had to find was an "intermediate" energy agent that would be:

1) easily producible in large-scale plants,
2) easily transported, and
3) as flexible to use.

The last condition is crucial and is the hardest to fulfil. In point of fact we found only one solution, and the other people who have studied this problem independently, in Europe and the United States, have reached the same conclusions. The intermediate is hydrogen, and the raw material to produce it is obviously water. The fact that Nature herself chose hydrogen as first intermediate in the photosynthetic process to "hitch" the biosphere to the sun only adds a touch of magic to this answer.

As regards condition (1), if (2) and (3) are fulfilled there is no size problem. Chemical processes capable of breaking down water and producing hydrogen and oxygen were described in the previous article. The size of the plant depends solely on the optimum economic size for the reactor and on the market open to hydrogen once the system is firmly established.

For the first production plants the problem is somewhat different, and we shall return to it later; the essential fact is that there are already numerous ammonia and fuel-hydrogenating plants, each capable of using the hydrogen output associated with a reactor of economic dimensions (2 000-3 000 MWth).

Transporting hydrogen

Let us now look at condition (2). The first objection raised in any discussion of the transportation of large quantities of hydrogen is that air/hydrogen mixtures are explosive.

This is true, but it is equally true that methane/air and hydrocarbon/air mixtures are highly explosive and cause considerable death and destruction every year, yet this does not slow down the growth of consumption of these fuels, even at the expense of other types, such as coal, which are far less explosive-prone but dearer and less easy to handle.

Incidentally, when the first motor-cars appeared the danger represented by the various dozens of litres of petrol in their tanks was regarded as so prohibitive that in England they had to be preceded by a man on foot waving a red flag—a precaution which would certainly be more useful today, though for other reasons.

The fact is that the question must be tackled with a healthy sense of the hazards involved, and the answer found through empiricism and progress. We are therefore very pleased to exhibit Fig. 1, which shows a network of hydrogen ducts linking various firms in Germany, which has large-bore pipes and an overall length of 204 kilometres.

Similar networks exist in the United States, notably in Texas, as a part of more complex systems for carrying chemical intermediates between refineries and petro-chemical works.

As to retail distribution, the town of Basilea distributes "detoxicated" gas (i.e. without carbon monoxide) which contains about 80 % hydrogen.

These examples are not meant to suggest that the problem should be

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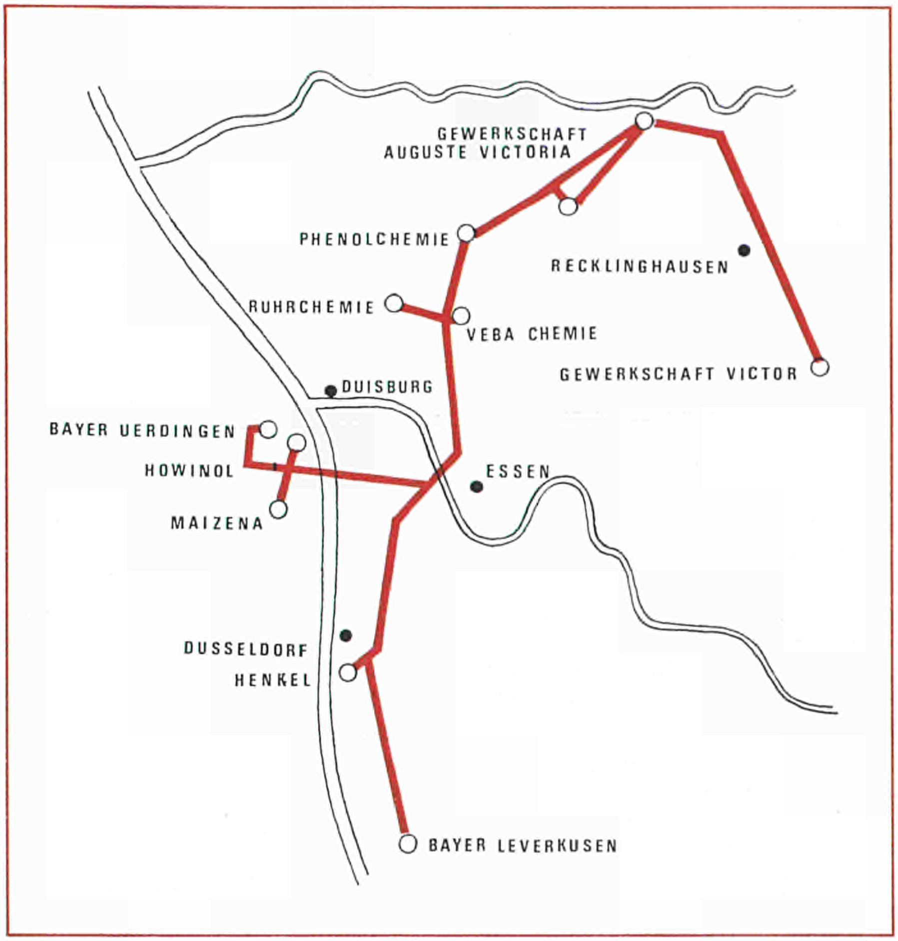
[1] euro-spectra, Vol. IX, No. 2, p. 46.

Fig. 1: *a) The coloured line shows the commercial distribution line for hydrogen from the* Chemische Werke Hüls AG, *Germany. The total length is 204 kilometres. b) Oxygen distribution network in the north-eastern sector of the Community.*



treated lightly, but simply that we must consider it realistically, without being led astray by schoolboy memories of Volta's alarming pistol.

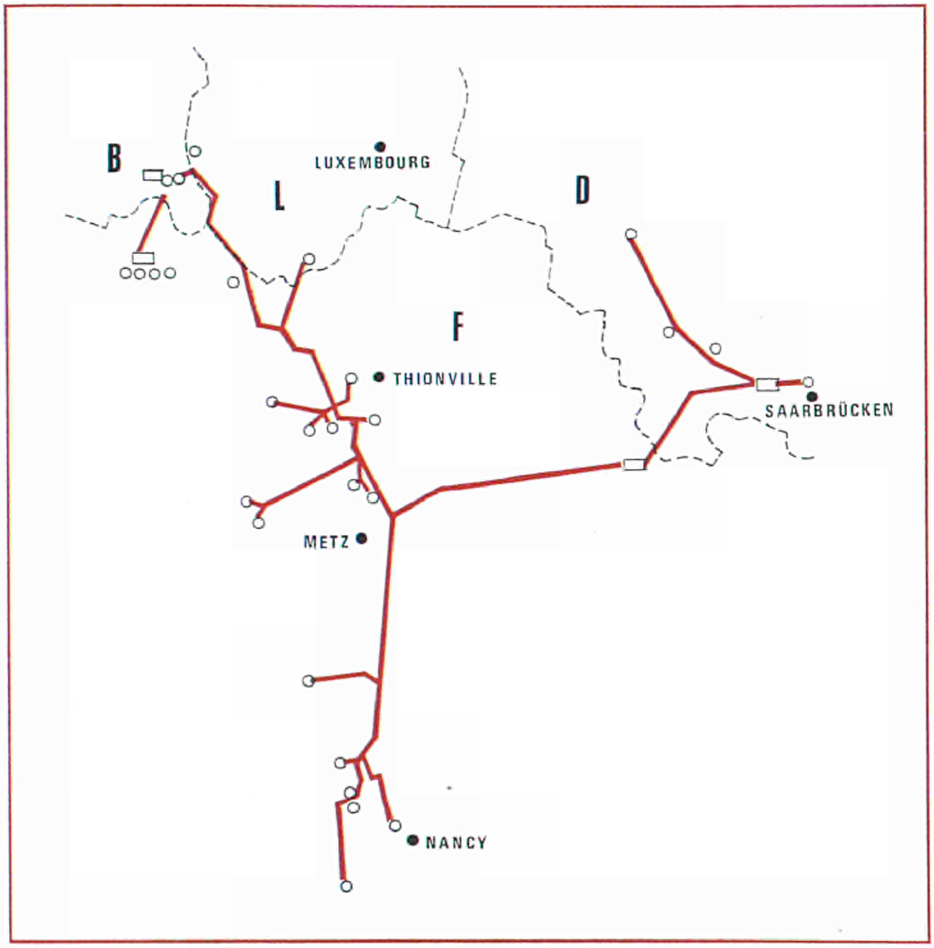
After all, the world produces some 200 thousand million Nm³ of hydrogen a year (1970) (see Table I) and consumes it in plants that are often highly complex. Perhaps all that is needed is to make a little extra effort and pool the experience acquired.

If it is accepted that hydrogen can be piped in a similar manner to methane, let us see what this transport costs.

Hydrogen has the disadvantage that its molecule is lighter and less energetic than that of methane; in other words, roughly three times the volume is needed to carry the same amount of energy. On the other hand it flows more readily, and given the same pressure gradient and pipe dimensions its speed is about thre times as great. A methane duct adapted to carry hydrogen would therefore transport the same amount of energy but would need three times more powerful pumps, and the pumping, which has to be done at every 150-200 km of gas-duct, accounts for about 30 % of methane transport costs.

In absolute value these costs are very low, about an order of magnitude below those for electric power, and this fact has very interesting consequences, as we shall see (Figs. 2 and 3).

The first is that for long distances it may already be more practical today to convert electricity into hydrogen at the power station, transport it by gas-duct, and use it for thermal purposes such as domestic uses in place of electricity (Ref. 1) (see again Fig. 2,



where the cut-off of the hydrogen transport cost for zero distance represents the cost of converting electricity into hydrogen). Another idea receiving serious attention in the electricity distribution field (London Electricity Board) is the use of fuel cells to back up the grid locally (Ref. 2). The two lines of thought will probably meet in the end, spurred on by competition from the gas distributors, who are contemplating supplying fuel cells for consumers to make their own electricity at home, using the gas supply, of course. In this connection, a gas distributors' association in the United States is providing fifty million dollars to finance a research project for the industrial development of methane/air fuel cells and has opened, at Farmington, Connecticut, the first house with natural gas plus fuel cells (Ref. 3).

These rather disconnected bits of information are only given to show that the ease and simplicity of transportation offered by fuel gases, their cheapness and their clean combustion products are slowly conquering the conventional forms of fuel and constitute a technological trend into which an energy system based on hydrogen will be able to fit perfectly, alternating elegantly with the electrical system.

Air/hydrogen cells can be used to assist the electric system at peak periods and as a standby for essential purposes if the electricity supply fails (Ref. 1).

A very useful property for an energy intermediate, and one which electricity does not possess, is ease of storage. For gases, the distribution lines themselves serve, through a system of pressures, as a very big reserve, but suitable geological structures can also be used for gas storage at extremely low cost (Ref. 15). This is very important for an energy system anchored to hydrogen. Besides, the installations can store and transport hydrogen in the form of liquid hydrogen, easily decomposable hydrides, or highly hydrogenated compounds such as ammonia and methanol. We shall discuss this further on, when speaking of its use as a motor fuel.

The fact that hydrogen can be transported cheaply has another consequence, increasingly important as the energy demand rises: it means that the primary energy sources, i.e. nuclear reactors, can be sited far away from the consumer areas.

The twofold need, to preserve the environment and to find enough cooling water, make such decentralisation necessary. The vast energy plants of the future can be sited close to the sea, or perhaps even in remote recesses of the Alps where they can use clean water in their cooling towers and discharge the heat without harming the ecology and microclimate of the inhabited areas.

Let us now look at condition (3), flexibility of use, which is of capital importance. In listing the various types of utilisation we have tried to estimate the time needed to penetrate the market in question, which depends on the development of particular techniques, on economic questions and on the slow growth rate of the technology involved.

Chemical uses

This heading essentially comprises ammonia production and the hydrogenation of fuels, i.e. the principal uses of hydrogen at the present time. Table I shows the world consumption figures for 1970. The forecasts could be considerably influenced by anti-pollution legislation setting very low ceilings for the sulphur content in liquid fuels. The usual desulphurising process is based on hydrogenation and even today, if it were applied to lower the sulphur content to 0.5-1 %, for instance, the hydrogen consumption would be of the same order as

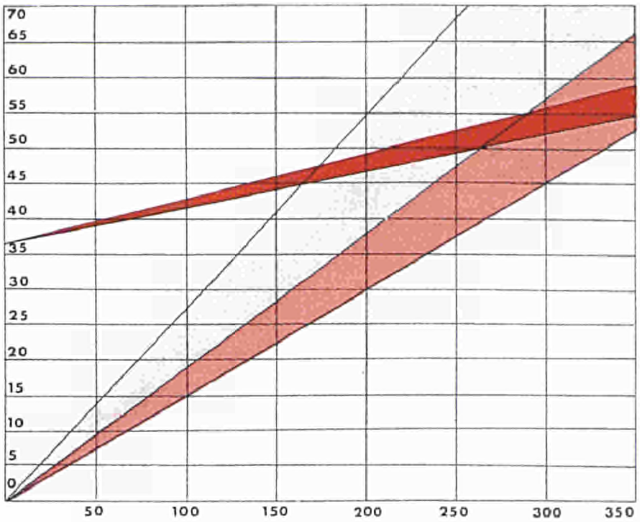


Fig. 2: *Relative costs (in US cents/Mcal/km) of energy transport by electric cables and by hydrogen-ducts.*

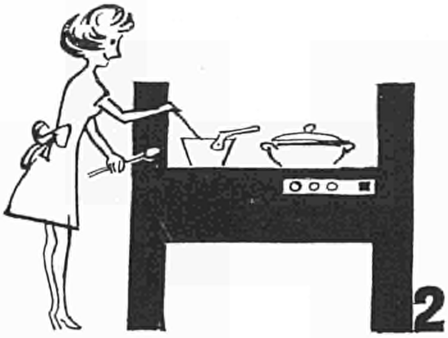
today's production—about 100 000-200 000 million Nm^3 a year.

The two interesting features of these uses are:

1) the huge scale of the new plants (Ref. 16), which would allow reactors of optimum capacity (of the order of 2 000 MWth) to be employed to produce the necessary hydrogen by *Mark I* processes (see previous article in "euro-spectra");
2) the fairly high price that these users pay for hydrogen.

These two factors provide the opportunity for a process using nuclear heat to produce hydrogen to establish itself without waiting for a distribution network and without having to cope straightaway with the much fiercer competition of the energy market.

It goes without saying that the one technical condition for the use of hydrogen in these plants is a sufficient degree of purity.



Metallurgical uses

This heading essentially comprises the reduction of iron ores to produce sponge iron, by the overall reaction

$$Fe_2O_3 + 3\ H_2 \rightarrow 2\ Fe + 3\ H_2O$$

Various processes exist [e.g., H-Iron (Ref. 17), HyL (Ref. 18), Purofer (Refs. 21, 22)] for producing iron by this reaction, and numerous plants have also been built (Ref. 19), most of them fairly small.

The perfection of blast furnace technology, the size of the capital investment and the scale economy still achievable today make it very difficult for new processes to gain a foothold, even if they are more profitable on paper or at the pilot plant level. But the rising trend of metallurgical coke prices, the introduction of anti-pollution measures and the exhausted development potential of the blast furnace process will be powerful incentives to turn to other processes, of which those based on hydrogen (perhaps mixed with CO) appear the most promising. The amount of hydrogen needed to produce one kg of iron is roughly one cubic metre. Graph I shows the iron output in the world and the Community, with the hydrogen "equivalent". Fig. 4 shows a diagram of one of the reduction processes (H-Iron) where pure hydrogen is used.

Here, too, the plant dimensions are well suited to reactor sizes. For example, a steel output of a million tons a year would need a 1 000 MWth reactor to produce the necessary hydrogen. Another reason for seeking systems that use nuclear energy in one way or another to reduce iron ores is the reliability of the energy supply. This is probably the factor that has prompted the Japanese to study the matter more thoroughly.

Domestic uses

These can be summed up as cooking and heating. They account for a substantial fraction of the energy market (around 20 %) and are a major source of pollution owing to unsuitability and poor maintenance of the appliances. A perfect fuel like hydrogen would contribute a great deal to the clean air drive. Methane is already very good; the spreading and branching of the methane distribution network now going on throughout the Community (Fig. 5) will practically solve the pollution problem. But the methane reserves are not unlimited, and supplies if imported are not always controllable, so that to have a fluid fuel that can be distributed in the same network and does not depend on the Community's reserves and the policies of the producer countries would be a first-class guarantee as regards both supply and the investment capital tied up in the network.

The switch from methane to hydrogen would raise two problems for users—the burners would have to be changed and safety standards would have to be adjusted. As already said, these standards ought to be made simple, efficient and uniform with the standards for other fuels. The change-over might be made more flexible by a transitional phase in which the hydrogen would be mixed with methane for distribution (Ref. 1).

As to the penetrability of this market, it is more a political than an economic matter. It is true that it will be hard for hydrogen from nuclear or

Table I: *Hydrogen consumption in 1970, as evaluated by the* Bataafse Internationale Petroleum Maatschappij NV (BIPM) *(extracted from "Chemical Age").*

PRODUCTION (in 10^9 Nm^3/year)			USES (in 10^9 Nm^3/year)		
USA and Canada	about	80	Ammonia	about	100
Western Europe	"	40 *	Methanol synthesis	"	15
Eastern Europe	"	40	Other chemicals	"	10
Other countries	"	130	Hydrogenation, hydro-cracking, hydro-desulphurisation	"	48
			Fuel	"	10
World total	"	*200*	World total	"	*200*

* For the Community, it is expected that consumption in 1980 will be about 100 000 million Nm^3.

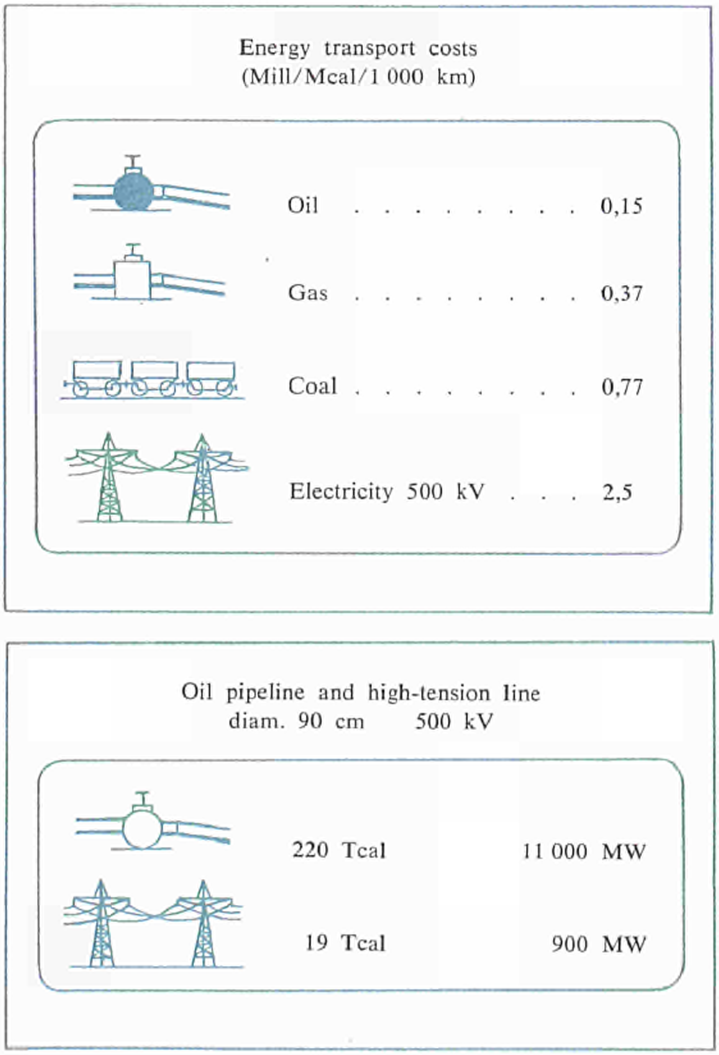
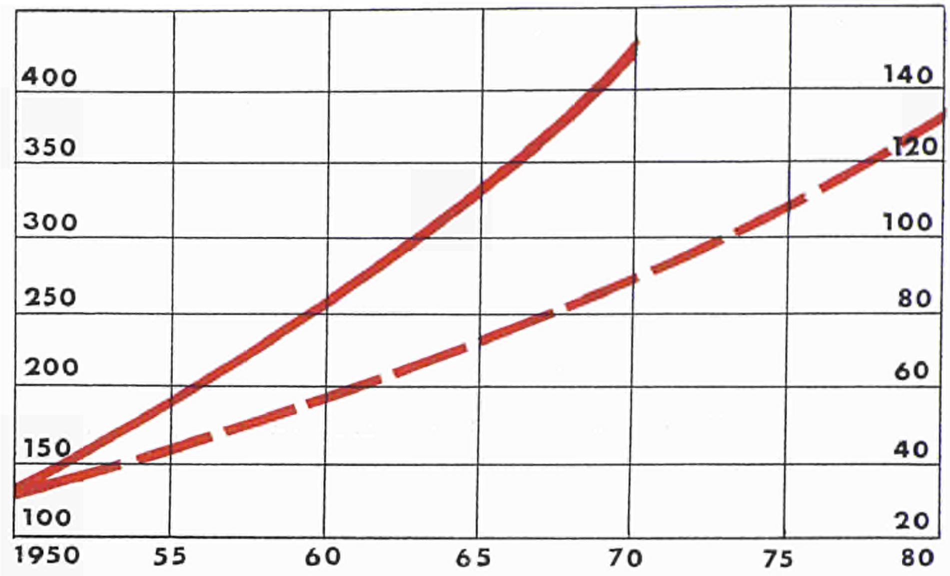


Fig. 3: *Energy transport by various systems: comparative costs and capacities.*



Graph I: *The continuous line shows the world steel production curve (in* 10^6 *metric tons) up to 1970; the dotted line shows the production curve in the European Community. The hydrogen consumption is given in* 10^6 m^3 *(Data from the EEC Statistics Office).*

other sources to beat methane in respect of cost per unit energy, but the price paid by the small user is so swollen with distribution costs and taxes that the basic cost difference is hardly noticeable and may be outweighed by the attraction of a reliable supply.

Thermal uses in industry

There is no need to say much in this connection, for as soon as there is a network to distribute hydrogen at prices competitive with coal and oil products, industrial firms will naturally change over to this energy source, as they changed from liquid fuels to methane.

This is a very wide market, but hard to penetrate until the economics are right.

A foothold could be gained, even if further progress were very slow, by underground gasification of coal. In this case a Mark I type of process would naturally be allied with the gasification process, to produce cheap oxygen, and the hydrogen can be used to "methanise" at any rate some of the CO produced.

It is probable that underground gasification will come back into favour in America through the desire to exploit the extensive deposits of bituminous shale without incurring too much trouble with the environmental protectionists, and this may provide an easy way in.

Motor vehicles

The mind naturally turns first to motor-cars, and people all over the world are busily trying to devise a reasonable car fuelled with hydrogen or simple derivatives of hydrogen such as ammonia or hydrazine.

The obvious advantage of using hydrogen is that there would be no noisome hydrocarbon emissions, a prime source of pollution, and no carbon monoxide.

The product of hydrogen combustion is water. Very hot flames, causing the oxygen and nitrogen in the air to combine, can also lead to the forming of nitrous oxide, however; this, of course, should be avoided, although it is not very harmful if there are no hydrocarbons in the air.

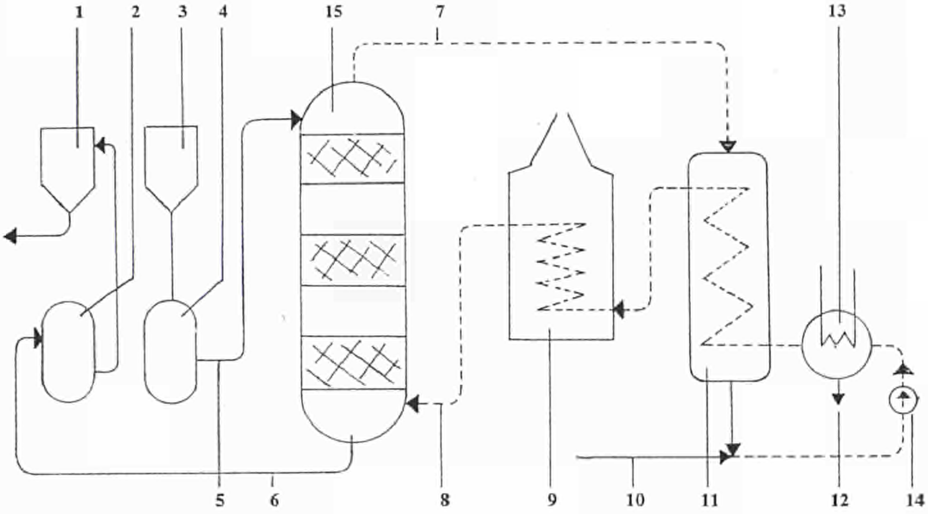
The three most promising lines seem to be the following:

a) *direct-injection engine:* being studied at *Oklahoma State University* under contract to the *National Air Pollution Control Administration* (Ref. 4). It is a standard engine which has been adapted (Fig. 6). It works very well; its power has been stepped up by use of hydrogen and it produces very small amounts of nitrogen oxides. Since direct-injection is a system based on a well-known technique, it is the one which would least modify the car as we know it.

b) *Stirling engine:* mainly studied by *Philips* at Eindhoven (Ref. 5). This is an external combustion engine, of high thermal efficiency (about 40 %, with up to 60 % potential), silent and having attractive mechanical characteristics. The speed, and consequently the specific power, are limited at present by heat exchange problems. It is a little heavier and dearer than a diesel engine of equivalent power.

The external combustion system allows the use of flameless catalytic burners which reduce the production of nitrogen oxides to zero. Hence this engine would be absolutely non-polluting, both chemically and acoustically.

c) *Electric motor with fuel cells:* under study by *Union Carbide* and *General Motors* (Ref. 6) in particular, who have actually produced running prototypes. By combining fuel cells, booster batteries and an electric motor it is possible to build quite lively cars, in spite of their weight, owing to the very high boost provided by the dc electric motor. The overall efficiency is good, about 50 %. Although the hydrogen/air fuel cells have proved their quality in space, they are not yet cheap, simple or rugged enough to be put into the hands of car drivers, and this is why the system stands third on the list.



1) H-iron storage; 2) dump hopper; 3) ore storage; 4) charge hopper; 5) ore; 6) iron powder; 7) wet H_2; 8) dry hot H_2; 9) heater; 10) H_2 make up; 11) cooler reheater; 12) water; 13) dryer; 14) pump; 15) Fluidised bed reducer.

Fig. 4: *Schematic diagram of an "H-Iron" plant for iron-ore reduction with hydrogen.*

In all three cases there remains the problem of how to carry enough fuel without too much weight and too many complications.

It should be mentioned in passing that the arguments about weight and range seem to take undue account of drivers' preferences, which are certainly very important but could perhaps be exchanged for other preferences, so that the technical problems would be easier to solve.

The most obvious way of carrying gaseous fuel about is in cylinders. In Italy there are more than 40 000 vehicles using methane. The gas cylinders are fixed and are refuelled at the filling station in the same way as with petrol. The cylinders are heavy, however, and hydrogen has a lower calorific power per cubic metre than methane. A possible answer might be to make them of carbon fibre and resins, which have a weight-to-strength ratio about one-tenth that of steel.

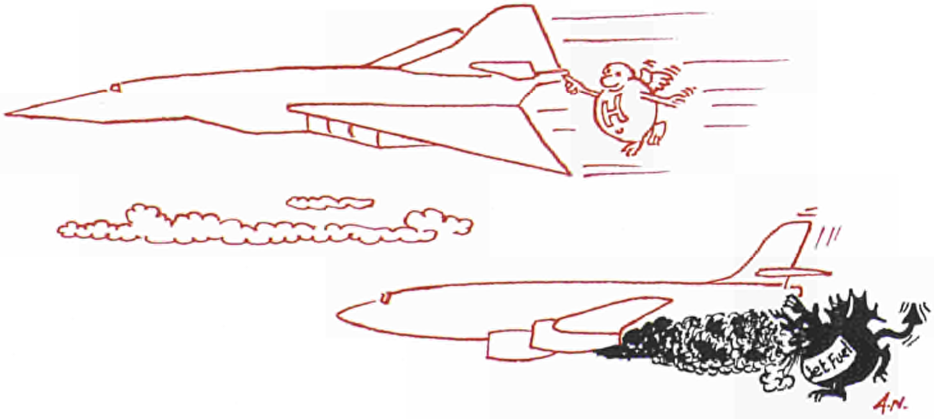
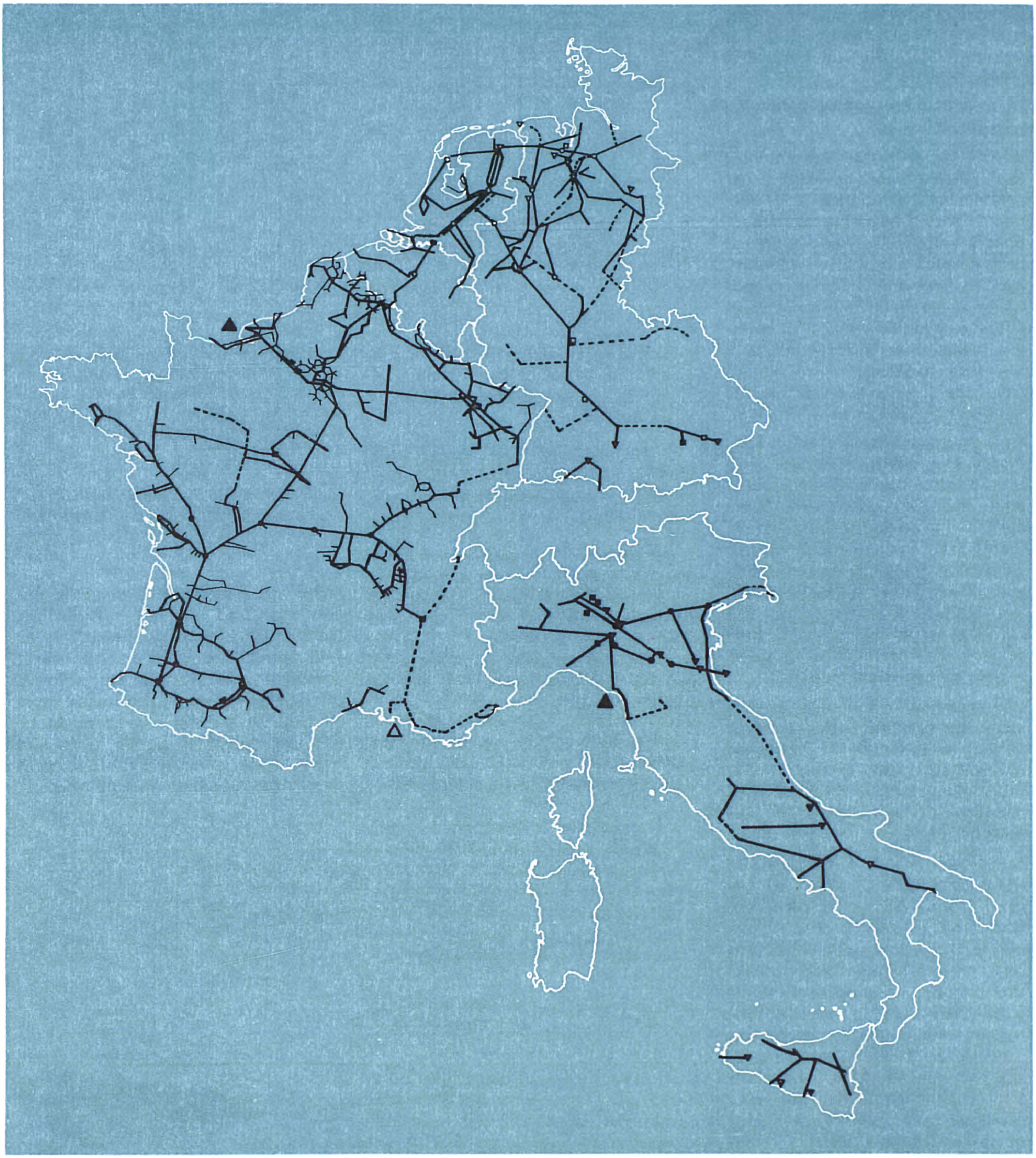
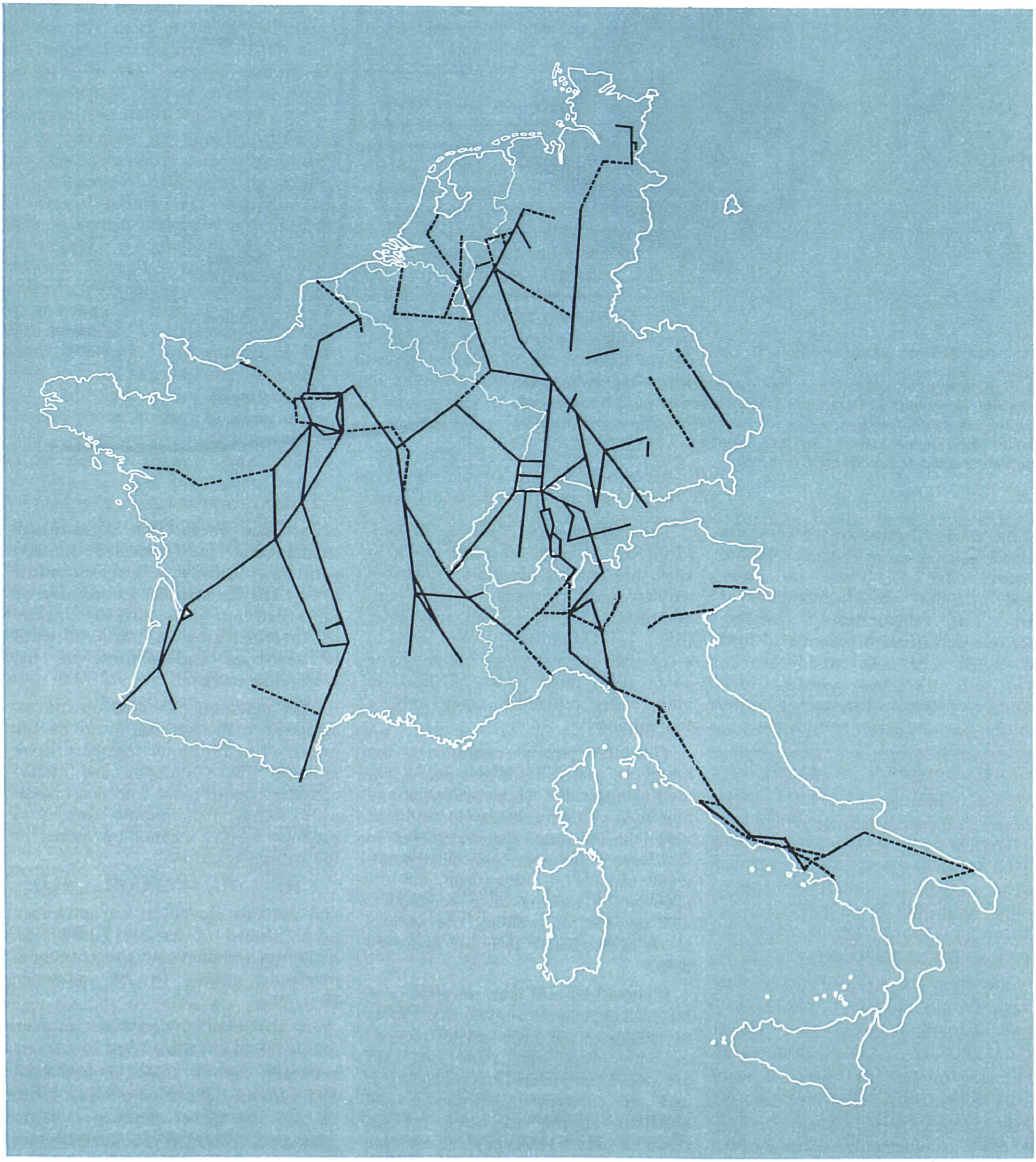
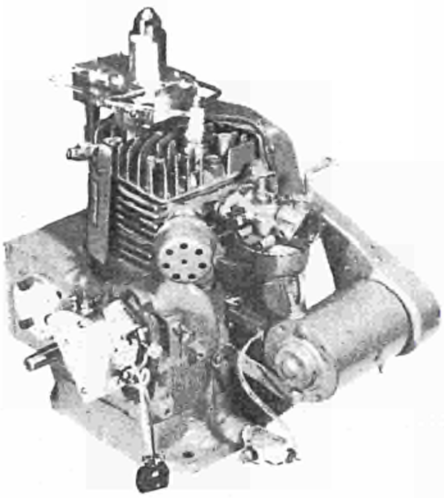


Fig. 5: *Maps showing networks of (A) natural gas distribution and (B) high-tension lines, in the European Community (EEC Statistics Office, 1969 Year-Book).*







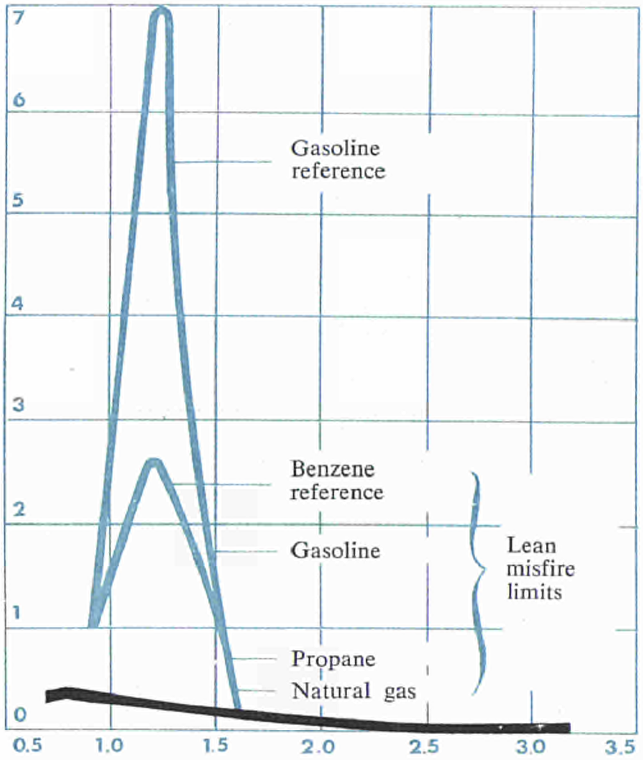


Fig. 6: *a) Internal-combustion engine converted to hydrogen-injection operation, developed at* Oklahoma State University ; *b) Characteristics of nitrogen oxide emission, using various fuels and various mixture proportions (engine running at full throttle). The emission of the hydrogen engine is represented in black.*

The *Philips* research workers are proposing a far more elegant solution, however (Ref. 5). There are many metal hydrides which decompose at fairly low temperatures, releasing hydrogen at sufficient pressure to feed the engine. The tank would thus be filled with this metal powder which absorbs or releases hydrogen according to the pressure present. With the compound proposed by the *Philips* team—Ni_5La, the hydride of which has a hydrogen pressure of several atmospheres at temperatures close to ambient temperature—a stored energy density (kcal/kg) is obtained which, though about 15-20 times lower than that of petrol, could still be acceptable for cars for use in towns, but is out of the question for long journeys.

Solutions (*a*) and (*b*) nevertheless leave the way open to a mixed system, with non-polluting hydrogen in towns and hydrocarbons for long journeys. This compromise has been achieved very successfully in methane vehicles, where the switchover from one fuel to the other is practically instantaneous.

The *Brookhaven National Laboratory* (Ref. 7), with the same object in view, has studied magnesium hydrides which release hydrogen at higher temperatures (250-300° C) but are lighter (Fig. 7). Optimized, these lead to a car with normal range but weighing about 10 % more under full load. In both cases refuelling takes only a few minutes.

The other possible course is to use liquid or easily liquefiable hydrogenated compounds such as hydrazine and ammonia. These substances would fit well into the long-term system (*c*), in that there are already fuel cells theoretically capable of using them, but the problem of making them economical and suitable for ordinary use appears to be even greater than for hydrogen cells.

It should be said that, since the need for such expensive catalysts as platinum or palladium has been greatly reduced or done away with, these fuel cells are rather complicated but reproducible and are constructed of plastics and materials capable of being brought down in price. Thus they are the type of product whose cost is essentially technological and tends to decrease with time, usually at an exponential rate. Their commercial future may be far ahead but it is assured, because the marginal uses will enable them to be developed and matured for the large-scale market.

This reasoning is based on the assumption that hydrogen is to be the primary fuel for motor transport. If we abandon this assumption and merely consider how to break into that market as it stands, the simplest way is to produce methyl alcohol by means of the overall reaction

$$3\,H_2 + CO_2 \rightleftarrows H_3COH + H_2O$$

and use this alcohol as an anti-knock agent instead of tetraethyl lead. The quantities required and the economics involved appear to be attractive (Ref. 8).

In the case of public transport, where the lines follow fixed routes and servicing can be fairly sophisticated, hydrogen can be carried in liquid form. In that case there would be a weight gain, since hydrogen is about 2.5 times lighter than petrol or diesel oil [cf. the *General Motors "Electrovan"* (Ref. 6)]. This, however, is a far from likely outlet, in the short term at any rate, since public transport companies are permanently short of funds and cling to antiquated technology. Yet they can be listed in the potential market if major external factors such as anti-pollution laws come into force.

The lightness of liquid hydrogen, and the assurance with which the *NASA* handled hundreds of thousands of tons of it, are very appealing to military aircraft designers, and the *US Air Force* is gradually becoming tempted. To give a specific example, a Boeing 707 carries roughly 80 tons of fuel and 20 tons of useful load. With hydrogen, even allowing for the different structure and volume of the tanks, it could carry 60 tons of useful load, thus trebling the aircraft's productivity (tons km/h). It is an enormous step forward, and design studies for aircraft fuelled with liquid hydrogen (Fig. 8) have been going on at *NASA* for the last ten years (Refs. 9, 10, 11). The resulting hydrogen requirement would be so great that most of the international airports could afford to have a nuclear reactor and water-decomposing plant. In other words, the system could be developed as a closed system, independent of local hydrogen distribution networks.

These potential uses, too, are only cited on the clear understanding that they are trends still in the course of development—but trends which can be catalysed by the arrival of a new cheap hydrogen source on the market, and which form a very encouraging context and reason for our studies on the production of hydrogen by means of nuclear heat.

Foodstuffs

Under this heading we do not propose to describe the hydrogenation of vegetable oils to make margarine, an operation which only takes insignificant amounts of hydrogen, but a far more ambitious, long-term project, namely, the *production of primary proteins.*

About a century ago yeasts capable of nourishing themselves on hydrogen and mineral substances were discovered in the soil. They form a genus of wide variety, *Hydrogenomonas,* existing in all soils, and particularly in old towns where the numerous leaks in the gas distribution system provide them with abundant free food at the town's expense.

These yeasts are able to store the energy from the hydrogen with extraordinary efficiency, in the form of proteins, fats and vitamins admirably suitable for animal feed. Here, then, is a prospect of being able to create a food source independent of agriculture (and of oil deposits) and linked only to nuclear reactors, by a process rather similar to the beer-brewing process. This is a most useful prospect for the Community, which imports large quantities of proteins in the form of meat and animal feedstuffs, and it is worth developing up to the industrial level, if only as a means of ensuring supplies.

The study of these yeasts and their large-scale culture has received a considerable boost from the possibility that they might be employed on long space missions (e.g., the mission to Mars, which should take a year) to produce food for astronauts by using the carbon dioxide and mineral salts produced by their metabolism, plus the electricity obtained from solar cells to produce hydrogen (and oxygen) by electrolysis. A study conducted by the *Battelle Memorial Institute,* Columbus, Ohio (Ref. 12) and at *RIAS,* Baltimore (Ref. 13) indicates a weight of 90 kg for the whole of the intricate contraption that would feed the three astronauts, or the equivalent in weight of the food and oxygen that would have to be carried to survive 20-30 days.

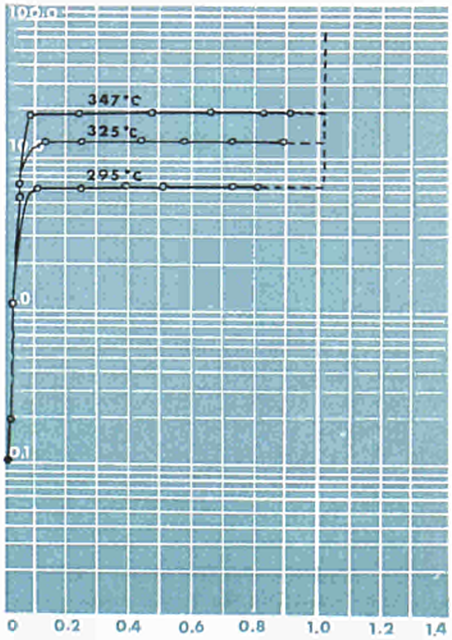
Similar studies, but with more academic ends in view, are being done at the *University of Göttingen* (Ref. 14).

Conclusions

The theories reviewed above and more especially the studies relating to them show that:

Fig. 7: *Pressure curve for hydrogen released from hydrogen-magnesium compounds, at various temperatures: abscissa values: percentage of hydrogen in the alloy; ordinate values: pressure of the released hydrogen.*

1) Practically all the energy needed for a technological society can be supplied in the form of electricity and of hydrogen carried through capillary distribution networks;
2) The natural trend of technological evolution lies in this direction;



3) The fact that hydrogen can be carried over long distances, in underground pipelines, and that it is transformable and interchangeable with electric power, together with the absence of harmful or unwanted end products, make this the perfect solution from the point of view of protecting and conserving the environment;

4) Because nuclear reactors can be used to produce hydrogen, its cost is essentially technological [2].

Thus the fears of the conservationists can be allayed, and the human race can go on growing for some time yet, if they have the sense to make the proper use of the facilities technology can provide for them. But politics is a far more complicated sphere than technology, and such a simple, logical state of affairs as the one we have outlined must be regarded realistically as a target for the next fifty years.

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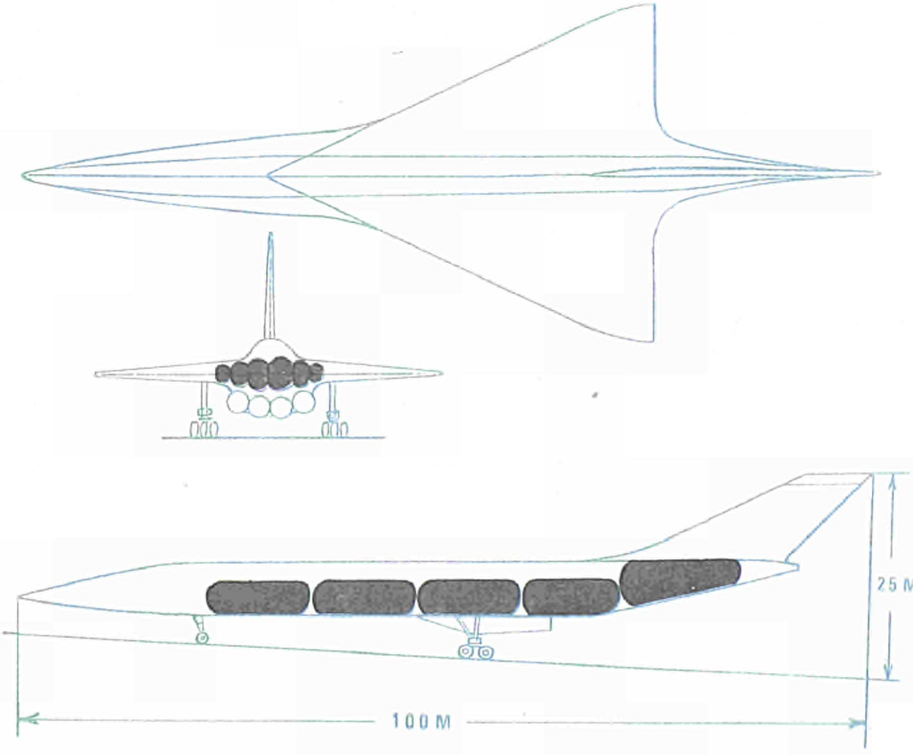

Fig. 8: *Diagram of hypersonic aircraft (Mach 4-8) fuelled with liquid hydrogen. The five tanks are shown in black.*

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[2] The cost of the nuclear fuel consumed is already very low and will become negligible with the advent of breeder reactors, not to mention fusion. Hence it will tend to go down, whereas the price of conventional fuels tends to rise in line with a general law valid for all minerals.

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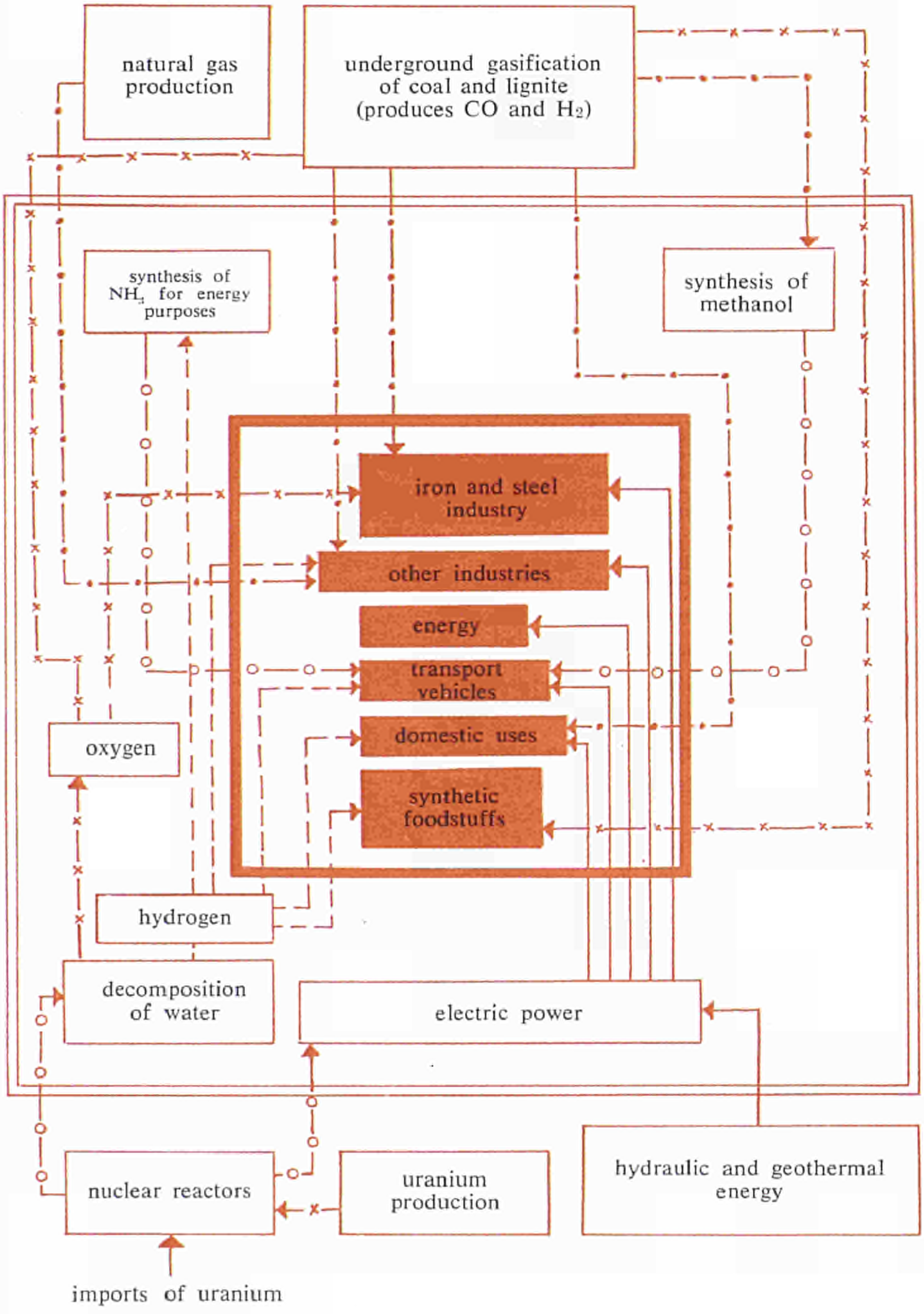

Fig. 9: *Diagram of the Community's total energy balance (production and consumption) as it might be if nuclear power replaced oil as the primary energy source. Nuclear reactors would produce electricity and break down water into hydrogen and oxygen; the hydrogen would serve as fuel in fixed installations and as a basic material for synthesis, and the oxygen for steelmaking and underground gasification of coal (Refs. 20, 23). The fuels for mobile vehicles would be synthesized with the coal gasification products (methanol), or directly from hydrogen (ammonia).*

—o—o—o— *Fuel for transport*
— — — — *Hydrogen*
—·—·—·— *Coal gasification products (CO, H_2) and natural gas*
———— *Electricity*
—x—x—x— *Non-energetic gas*

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