NAVGRA

THE NAVY AND VICKERS GEARING RESEARCH ASSOCIATION

BY

LIEUTENANT-COMMANDER B. J. McD. GOWANS, R.N.

The three principal suppliers of naval gearing, while commercially in competition, pool their research effort to improve gear quality.

INTRODUCTION AND HISTORY

During the Second World War the service reliability of main propulsion gears was felt to be inadequate. It was expected that reliability would be increased by the introduction of locked train gearing, but the Admiralty realized that greater standards of accuracy would be necessary to do this. After discussion with the firms concerned with manufacture of naval gearing, a contract was placed in 1946 with Vickers Armstrongs, with provision that sub-contracts should be placed with David Brown and Sons, Muir Machine Tools and Craven Brothers, to improve gear manufacturing techniques, evaluate new materials and processes, and develop surface hardening. Research was to be controlled by a Council and a series of Technical Committees and the research was to be carried out by the firms at their respective works. The group was called the Admiralty-Vickers Gearing Research Association (AVGRA) and was administered from Barrow-in-Furness by a Research Officer and a small staff.

Manufacturing accuracy rapidly increased through temperature controlled hobbing shops, better machine foundations and improvements in machine kinematics. Fatigue testing of materials sorted out suitable alloy steels for hardening and research into the carburizing process made surface hardening a possibility. AVGRA worked to fill the many gaps in gearing knowledge and helped to formulate the British Standards 1498 (Gear Hobbing) and 1807 (Gears for Turbines and Similar Drives). In 1959 and 1961 respectively, Pametrada (now replaced by the British Ship Research Association) and Associated Electrical Industries joined the group. After further research induction hardening and nitriding were introduced as surface hardening processes and full scale first and second reduction tests with these treatments were carried out.

Thus the major advantages seen in the Fleet by the 1960's were as follows:-

(*a*) The introduction of case hardening and more accurate manufacturing led to an increase in specific loading of gear teeth of over 400 per cent compared to 1945 standards. This led to a reduction of weight and space of over 50 per cent for a given horse power and configuration, and to an increase in permissible reduction ratio of 100 per cent. The complex reverse reduction gearboxes necessary for the Guided Missile destroyer and General Purpose frigate COSAG plants, were thus possible.

(*b*) There had been no failure by tooth breakage and the problem of scuffing had been virtually eliminated, in contrast to the war-time experience in the Royal Navy and to the problems experienced by other navies more recently.

(*c*) The accuracy of gear manufacture had been so improved that pitch and profile errors were one third of the 1945 standard. As noise is partly a function of errors, levels had reduced considerably.

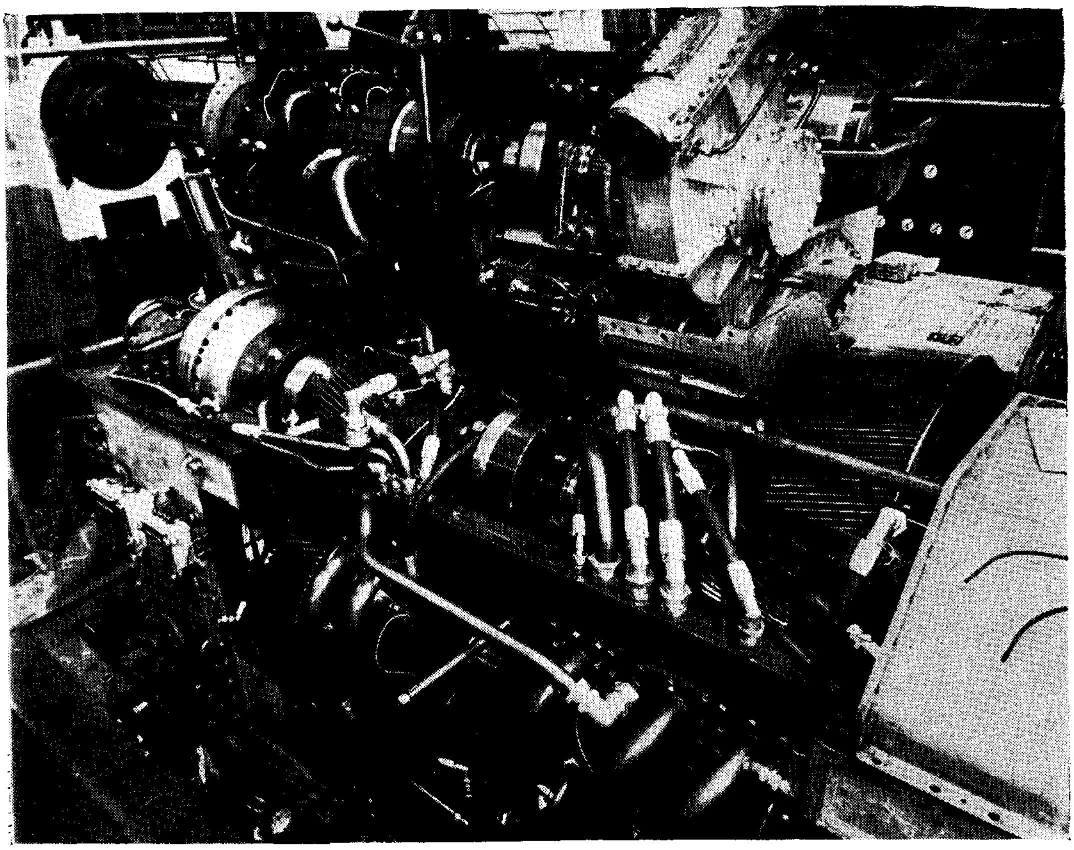

FIG. 1—TYPE 82 GEARBOX UNDER CONSTRUCTION
(*Courtesy GEC/AEI Ltd.*)

(*d*) The first induction hardened wheels had been installed in H.M.S. *Devonshire* and H.M.S. *Eskimo* and the first nitrided wheels in H.M.S. *Kent* and H.M.S. *Leander*. The success of these hardening processes allowed greater flexibility in manufacturing processes.

In the early 1960's AVGRA suffered a decline in activity, resulting from continuous work in a limited field. Little research was being generated and few advances were made.

The Council of AVGRA, as a natural development, approved a review of the management and progress. The investigation showed that:-

(*i*) The original requirements to improve gearing performance had in the main been met. New aims were necessary to provide the gears to fit the advanced propulsion machinery appearing.

(*ii*) The committees had over the years become large and unwieldy bodies so that little real progress was made at meetings. Much time was taken up in reporting progress of research projects and there was little liaison in parallel fields.

(*iii*) The noise research, which took much of the effort and resources, was undertaken in a predominantly practical way. Experiments were conducted in an *ad hoc* manner, often on unsuitable rigs. It was thought that a more fundamental approach was necessary.

(*iv*) The design rules were basically the same as in 1946 and there was a need to re-write them to incorporate the most up to date knowledge.

With these points in mind NAVGRA was revitalized in 1967—it was given new aims to take account of the considerable progress made in the first twenty

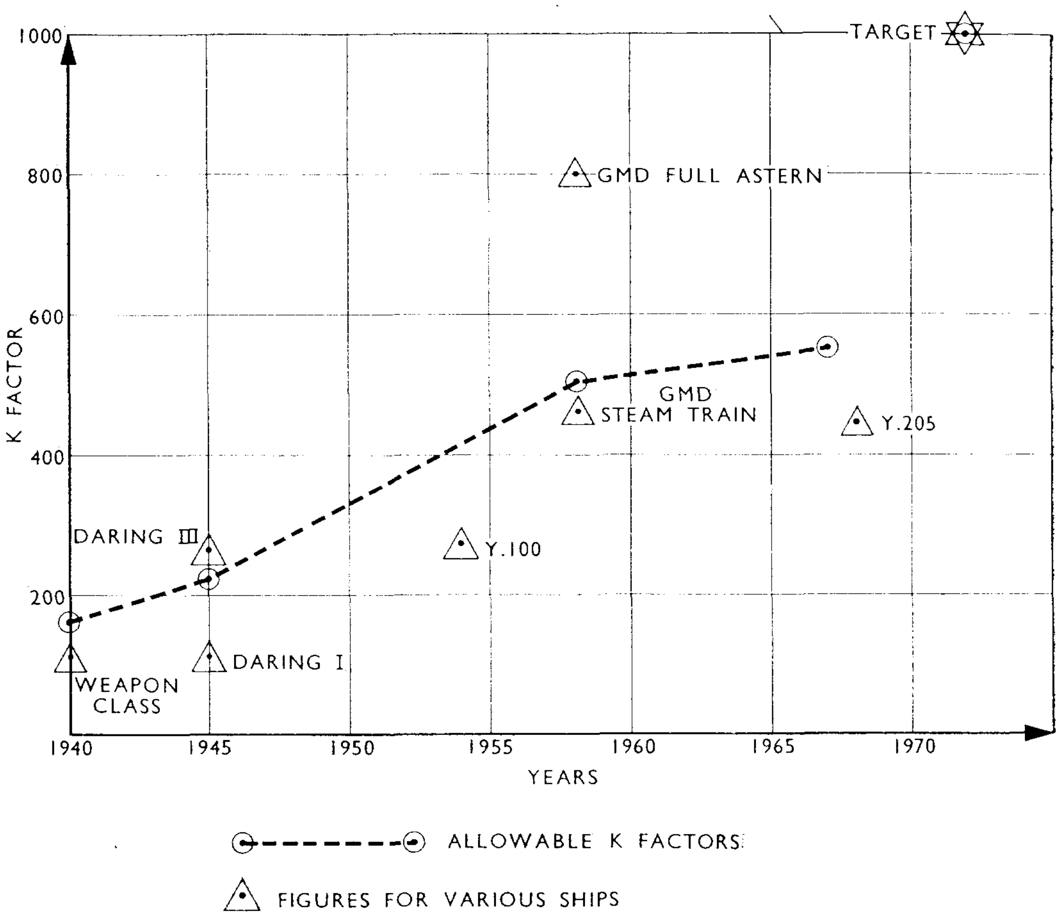

FIG. 2—INCREASE IN ALLOWABLE K VALUES OVER THE YEARS 1945–1972

$$\text{where } K = \frac{\text{Load/inch face width}}{\text{Pinion Diameter}} \left(\frac{1 + \text{Gear ratio}}{\text{Gear ratio}}\right)$$

(K is a comparative measure of the surface stress.)

years of NAVGRA's life and the future policy of the Ministry of Defence. The method of management was changed to incorporate the most up to date techniques available for controlling research.

THE NEW AIMS

The aims and requirements were redrafted in order to achieve the following by the end of 1972:

(*a*) The development of high duty gearboxes having service ratings equivalent to 1000K (i.e. double the 1967 capacity)

(*b*) Achievement of noise reduction targets as specified by the Navy Department

(*c*) The development of NAVGRA design rules correlating accuracy requirements to speed, load carrying capacity, and noise.

The Ministry of Defence was to accurately define its requirements and to indicate the lines of research it was willing to support. All research proposals were to be vetted to filter out anything irrelevant to the major aims.

THE NEW MANAGEMENT

Government and University research is often criticized for producing little of value, for not being cost effective and for not being commercially viable.

An alternative is for Government Departments to have a link with industrial research. NAVGRA is among the foremost of these links and is organized to provide answers for the Navy in an effective and rapid way by drawing on the resources of the Member Firms. Furthermore it has established personal contact and co-operation at all levels in the Firms and the Navy Department. In such a unique position its success is a credit to its organization and suggests that other fields than gearing would benefit from such an association.

The management structure is shown in FIG. 3. The Council lays down the policy for the research, monitors progress and provides financial control. The Technical Committee is responsible to the Council for carrying out the policy. It sets the requirements for the lower committees and gives them priorities within the financial allocation in order to meet the overall programme.

The Design Committee co-ordinates the work in the fields of material, dynamics, structures, lubrication, etc.

The Production Committee co-ordinates all the work required to update production methods, improve machines and introduce new metrology equipment.

The Design or Production Committees, through the Research Officer, can set up specialist panels to deal with technical problems. The saving in manpower is notable here; previously there had been four committees of 30 members each—now there are two committees each of six and temporary panels of about six.

The flexibility of this system has many advantages. The committees do not get bogged down with detail but may concentrate on co-ordination and advances. The panels consist of specialists in the field of study, and having definite objectives and finite life, quickly generate the research. The Research Officer is responsible for progress in the Firms thus providing the essential communications link.

As an example the problem of material selection and processing, which is of great complexity from the large number of variables involved, was handled rapidly and logically. The problem was discussed within the Design Committee who produced terms of reference and broad guide lines for the Materials Panel that was set up. This panel, consisting of the minimum number of specialists led by a member of the Design Committee, reviewed the situation, indicated areas of ignorance and proposed research to cover these areas, in just a year. Each Firm is represented on the panel, in this case by a stress engineer and metallurgist, so that the Firms detail research applicable to their own facilities, and provide costs and times for completion. These proposals are discussed within the panel and modified as necessary before being passed to the parent committee. The Design Committee critically examines the proposals for the technical content and may refer back or submit them on to the Technical Committee for further evaluation and allocation of priorities and finance.

When the proposals have Technical Committee approval the Panel is disbanded, and the resulting progress becomes the responsibility of the Research Officer. As results become available the panel may be reconvened. The results are analysed and sifted and passed back through to the Technical Committee for approval. In this way each piece of information is disseminated for use in the Firms—a feed back to the final product. The filtration, evaluation and analysis ensures the correct solution is available in the form required.

Getting answers is, however, only part of the story, for these must be available when they are required at a cost appropriate to their value. To achieve this the most modern management techniques must be employed.

Costs for each piece of research proposed by any one firm are subject to comment by the other firms who can suggest alternative methods if they feel the price is too high.

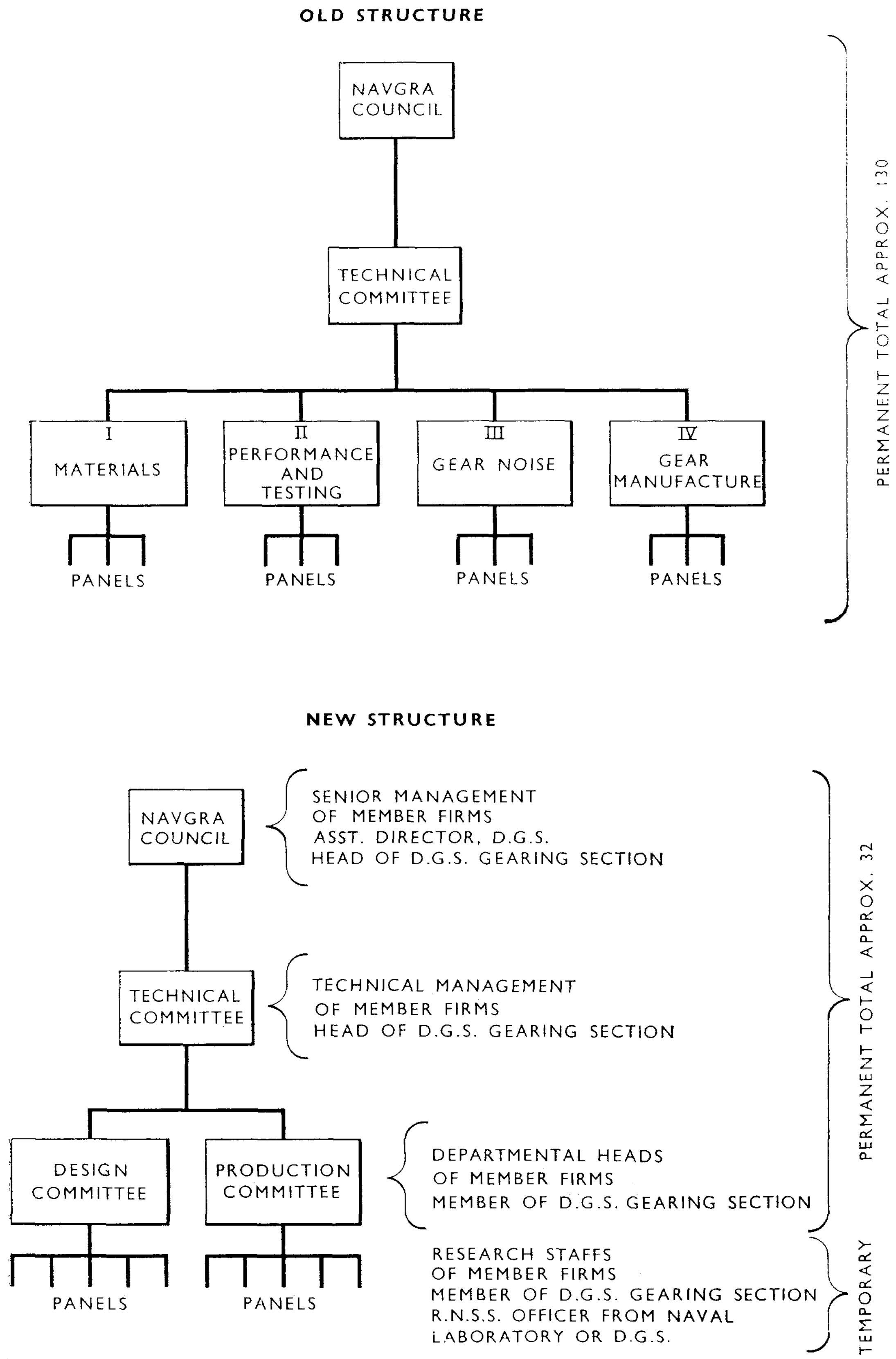

FIG. 3—COMMITTEE STRUCTURE OF NAVGRA—OLD AND NEW

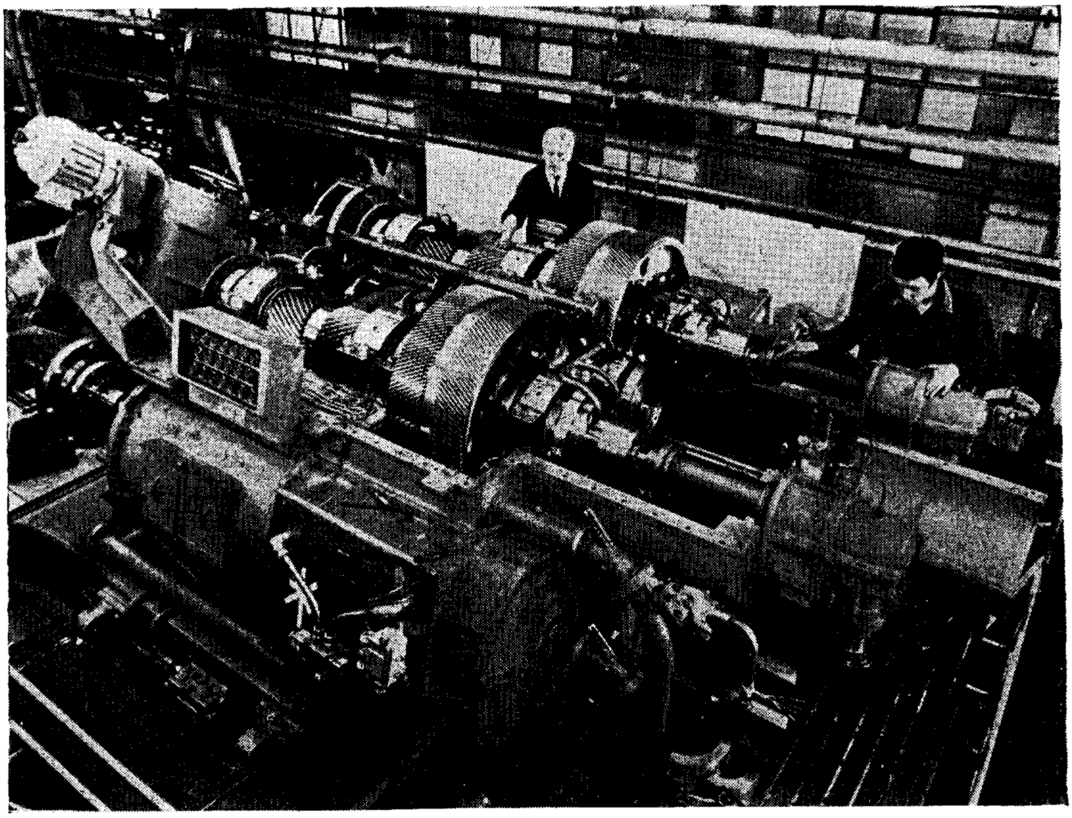

FIG. 4—H.M.S. 'EXMOUTH' GEARBOX DURING ASSEMBLY
(*Courtesy David Brown Gear Industries Ltd.*)

Detailed planning is done by the Research Officer and his staff based on priorities set by the Technical Committee. Critical path networks are set up for the whole research programme and for selected complex areas or research projects. This technique is essential if logical development is to be maintained. From the networks, bar charts are drawn for loading of test equipments, resources and finance.

At the planned start shown by the network schedule a contract is placed by the Research Officer on the selected firm (or firms if there is to be co-operation). This contract is a proper commercial document. The Research Officer holds regular review meetings with Member Firms to assess the state of progress. New research or extension of present work can be generated and this must be fed back for committee approval; the networks are then modified.

The management is the key to success of NAVGRA. It provides logical development, flexibility and good communications essential in control of a large volume of research, and it ensures that the Ministry of Defence gets value for money.

RESEARCH IN PROGRESS

Gearing involves many interrelated disciplines and so the research projects must be fully integrated. With limited resources this integration is no simple task. The policy is one of fundamental work in the required fields—each piece of work being checked by rig test work. The culmination is full-scale testing incorporating the results of all the work. The objective is the completion of all fundamental and test work and its evaluation prior to the testing of full-scale gears in 1972.

Materials and Heat Treatment

There is a specified material for each of the surface hardening processes, EN36 for carburizing, EN40 for nitriding, EN24 for induction hardening. Each material must be tested to find the effects on properties (core strength, case depth, hardness, etc.) of variables such as heat treatment (times, temperatures), grain size, composition, etc. There are a large number of properties and variables for each steel, so that this has generated an elaborate fatigue testing and surface testing optimization programme.

The effects of residual stresses introduced during the heat treatment process are, for the first time, being evaluated. These have a large effect on service properties and are being investigated theoretically by advanced finite element computer techniques. Practical confirmatory work being undertaken involves electrochemical and spark erosion machining.

Gear Dynamics

Little is known about the mechanism of gear teeth meshing dynamically. The knowledge of what happens under load is essential if the design is to be right. Correct design minimizes gear noise and thus reduces detection and sonar interference risk. The pioneering in this field was carried out at Cambridge and Sheffield Universities and NAVGRA takes note of such work as it formulates its research proposals.

The investigations are primarily concerned with the excitation in gearboxes to provide a theoretical and quantitative understanding of the mechanics of the excitation, the sources (tooth contact and rotational), the transmission, and the emission as both vibration and noise. The research into these fields is being handled by computer analysis techniques and parallel small scale practical tests. A simple rig will be built to verify the results. Results from existing gear noise test rigs will be utilized through the measurement of the rig impedance characteristics. Advanced instrumentation is being developed for measurement of transmission errors in both experimental and service environments. This should enable the prediction of vibration and noise emission from particular designs.

Structures

It is necessary that the gears mesh at all times as they are designed to do. The effects of torsion, ship movement and misalignment, all tend to worsen the meshing qualities and hence produce local overloading. A computer programme is being written which can select load paths and hence indicate how the load should be carried to minimize these effects. The programme is being written initially to optimize a manual design but later it is aimed to complete the whole design function. This will produce a design of gearcase containing no redundant material.

Lubrication

With correct material combinations and the general use of EP oils, scuffing is no problem at the present loads. As loads increase the scuffing barrier may once more be approached.

Lubrication research has been broken down into high-speed and low-speed regimes. In both cases the mechanism of lubrication as the tooth surfaces slide over one another is being investigated. From this the fundamental reasons for scuffing can be established and, with better knowledge of conditions under load, rules will be formulated to predict when scuffing could occur. To verify the theoretical work, disc machine experiments and full-scale testing are scheduled.

Bearings

As gearbox loads are increased the bearings and journals would get disproportionately large compared to the pinions, under the present rules. Research is therefore necessary to increase permissable loads on bearings without affecting their reliability. Some rig testing has shown that bearing loadings can be doubled given the right dynamic conditions. The results of other work should ensure that such conditions may be achieved.

There is some work in hand to provide a new design criterion. At present bearings are designed to an average pressure over the projected area. It is thought that a criterion of minimum film thickness with a temperature limit would be more satisfactory. A computer programme is being written to be used during the gear design process to calculate actual film thickness and temperature of the oil in the bearing under load.

Production

However good the design it will be useless if production cannot reproduce it in hardware; the design may be for decreased dynamic variation in loading but bad manufacture may re-introduce this and cause maldistribution of load.

It has been necessary to study the kinematics of the machine tools themselves. Much work is being done to decrease the inherent inaccuracies of the machines. Some large hobbing machines are producing to higher accuracy now than when they were new, due to improved master worms and decreased vibrations in the drives. Some research is being done to decrease the cutting forces and thereby increase the surface finish accuracy.

New metrology equipment is being developed to measure pitch and profile errors more accurately. Existing equipment is being evaluated to reduce the built-in errors in the equipment themselves.

Research has been initiated to consider the possibility of producing gears by a more fundamental method than cutting. This would lead to much improved load carrying capacities and increased fatigue life and should result in reducing the production costs.

Designs of various components are being studied to see that they are made in the best manner. As an example, the construction of main wheels may be optimized for each of the hardening processes.

The potential in this area has yet to be fully realized. New materials are appearing, such as carbon fibres, which will pose new production problems. It should be possible with low distortion hardening to reduce finishing processes and thus lower production times and costs. It is necessary to check that the accuracy standards that are set, which are very expensive to achieve, are really necessary.

As the present programme progresses, plans for work in the next five-year period are being formulated. These will embody future research and consolidation of the present state.

THE FACILITIES WITHIN NAVGRA

Each of the member firms maintains a large research department. In the main these departments undertake research aimed at commercial superiority over their competitors. The research facilities are first class, with modern and expensive instruments. Like the other divisions of each firm the research departments are managed to give value for money. All the NAVGRA research is injected into the research programme so that the same rules apply, the same research workers do the research and the same instruments may be used as in the companies own work. The Navy could not afford these facilities on its own and thus benefits greatly from this link with industrial research.

Y.102 Secondary Pinion—33 teeth, 1·2213-inch Transverse pitch. 12·829-inch P.C.D. 10° 43′ 33″ Helix angle.

	Permissable Errors	
	B.S. 1807: Part 1: 1952 Class A1	M.O.D.(N) Requirements 1968
Transverse Pitch		
Max. Cumulative Pitch Error	0·0011-inch	0·0006-inch
Single Pitch Error	0·00025-inch	0·0002-inch
Undulations	0·0002-inch	0·0002-inch
Profile	0·0009-inch Departure from nominal not to exceed 0·0009-inch	±0·0004-inch Departure from nominal not to exceed 0·0004-inch and mating profiles to be complementary within 0·0004-inch
Surface Texture	—	20 micro inch

FIG. 5—STANDARD OF ACCURACY OBTAINABLE IN 1968 COMPARED WITH ACCURACY REQUIRED IN 1952

The production facilities are among the most up-to-date in the world. Each firm produces its precision gears in air-conditioned, dust free, self-contained hobbing shops. The machines are checked by the National Engineering Laboratory and continual monitoring of accuracy has enabled planned maintenance schedules to be built up so that the highest accuracy of British Standards can be exceeded with certainty. The accuracy achievable is shown in FIG. 5 compared to BS 1807 for a GMD secondary pinion. Hobbing facilities are available up to 250 in. diameter.

Grinding is the normal finishing process for hardened naval gears as it is the most closely controllable process and in most cases would be the most economic. The member firms are equipped to grind up to 12 ft in diameter and face widths up to 40 inches may be handled. Tip, root and end relief, crowning and barrelling are also possible. The grinders are accepted and checked regularly for certification by the NEL.

With the NAVGRA firms in the world forefront of the hardening of marine gears they set up the necessary production facilities as soon as there was sufficient experience in the techniques.

(*a*) After initial work with pack carburizing, a self-contained gas carburizing plant was set up in 1958. This contains furnaces capable of 84 in. diameter and 20 in. length and 24 in. diameter and 60 in. length. Close control of carbon content is available with gas carburizing using propane/air mixture.

(*b*) An induction hardening machine was developed from a pre-war research unit with very satisfactory results. This machine is capable of hardening from 24 in. to 84 in. diameter up to 30 in. face width. The distortions from this method of heat treatment are much less than with carburizing and one member firm has an advanced machine producing industrial induction hardened gears.

Test Facility	*Location*	*Type of Test*	*Capacity*
Prime-mover drive to dynamometer	Barrow	Full-scale test bed trials of Diesel engines and/or geared Diesel engines.	Dynamometer capacity up to 32,000 shp at 105 rpm
	Wallsend	Full-scale test bed trials of geared steam turbine machinery.	Dynamometer capacity up to 60,000 shp.
	Huddersfield	Full-scale test bed trials of industrial gear units, electric motor driven.	Dynamometer capacity up to 4,000 shp.
	Manchester	Full-scale test bed trials of geared turbine machinery.	Dynamometer capacity up to 12,000 shp.
Power Circulator gear trials	Barrow	1st reduction destructive tests.	28,000 shp at 6,000 rpm of pinion.
		2nd reduction destructive tests.	24,000 shp at 1,500 rpm of pinion.
		Horizontal spindle gearbox proving trials.	40,000 shp.
		Vertical spindle gearbox proving trials.	15,000 shp.
	Huddersfield	Small scale gear tooth bending tests to destruction.	
		Small scale gear tooth pitting and scuffing tests.	
		Horizontal spindle gearbox proving trials and noise tests.	40,000 shp and 10,000 shp.
		Vertical spindle gear load tests.	10,000 shp.
	Manchester	18-inch centres gear load tests.	
		Horizontal spindle gearbox proving trials and noise tests.	Equivalent to 4,000 shp.
	Wallsend	10-inch centres noise tests.	

FIG. 6—TEST FACILITIES WITHIN NAVGRA

(*c*) The nitriding hardening process gives virtually no distortion compared to the two methods above thus eliminating the costly, time consuming finishing process. Member firms have the capacity for nitriding wheels up to 126 inches diameter.

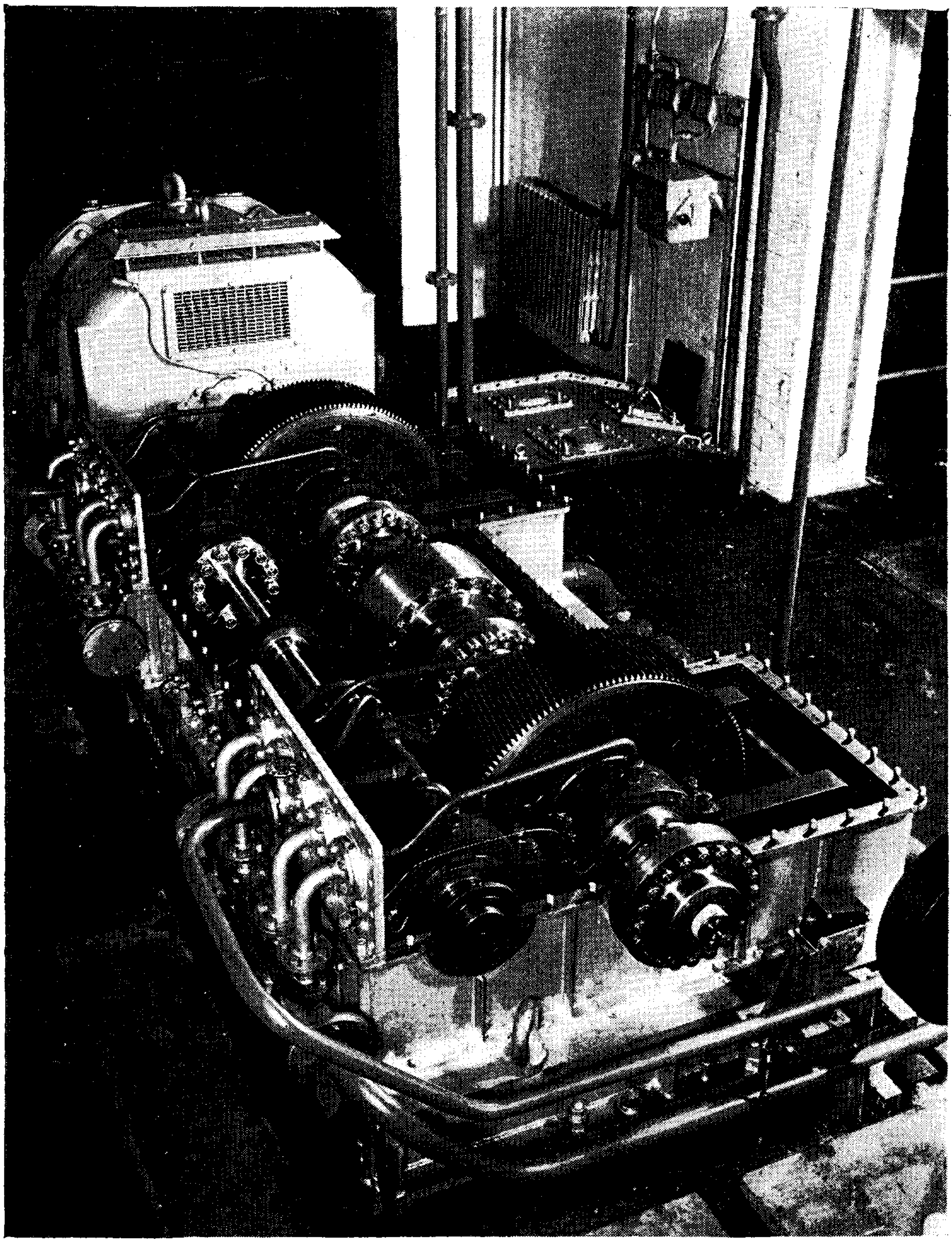

FIG. 7—18-INCH CENTRES GEAR LOAD AND NOISE TEST RIG

(*Courtesy EE/AEI*)

The NAVGRA policy is one of fundamental research, confirmed by small rig tests and ultimately full-scale testing to destruction. A number of test facilities are therefore necessary and some of these are shown in FIG. 6. The NAVGRA 1st and 2nd reduction test rigs will be used in 1972 for the testing at loads suitable to allow service ratings of 1000K.

Although the information gained from research is disseminated in the member firms through panel and committee membership, the NAVGRA office holds fully documented records and the staff are available to provide information and advice as necessary. There is also a bank of computer programmes available to the Member Firms.

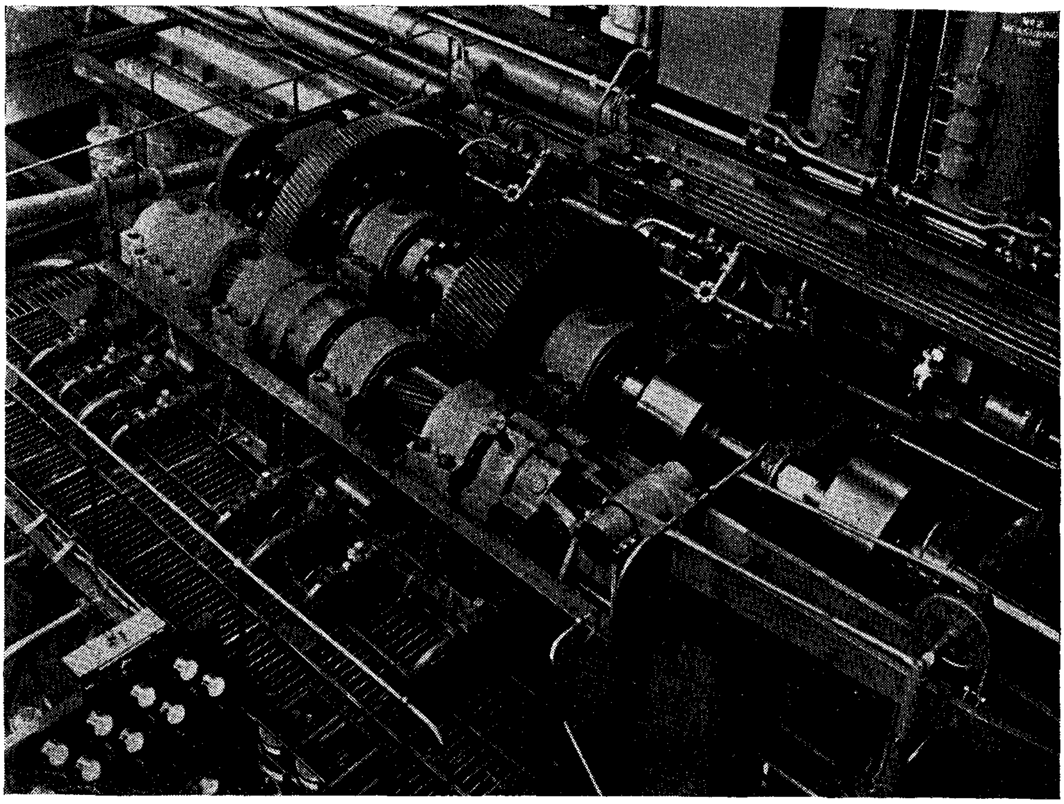

FIG. 8—SECOND REDUCTION TEST RIG CAPABLE OF CIRCULATING 24,000 HP AT 1,500 RPM OF PINION

(Courtesy Vickers Ltd.)

NAVGRA has liaison with a number of Universities, Government Laboratories, Industrial Research Associations and the British Standards Institution.

SUMMARY—THE GAINS TO THE NAVY

NAVGRA gives the Navy a stake in advanced industrial research in gearing, a most effective way of achieving the necessary progress. It has a modern management structure using up-to-date techniques. It has defined aims and a specified date for achieving them.

NAVGRA has incomparable resources on which to call. The member firms have a large group of engineers and scientists, mathematicians and metallurgists working on gearing research and development. NAVGRA is able to inject into this research the needs of the Navy, and to unite the firms in the ways of meeting these requirements.

The member firms are each capable of an equally superior level of design, although this does not mean that the designs from each firm are carbon copies. Each is able, with the same information, to approach a design its own way.

The manufacturing capability of each firm is of the best in the world, due in some part to NAVGRA research. The Ministry of Defence can be assured of the required high standard of accuracy whichever firm is selected for a contract.

By 1972, NAVGRA research will have established a service load limit equivalent to 1000K. This will allow great flexibility in design. It will be possible to design small, simple gearboxes, employing single reduction or single tandem trains, or to use lower shaft revs without increasing present gearbox size. The gears will be held properly in mesh, their dynamic loading will be known

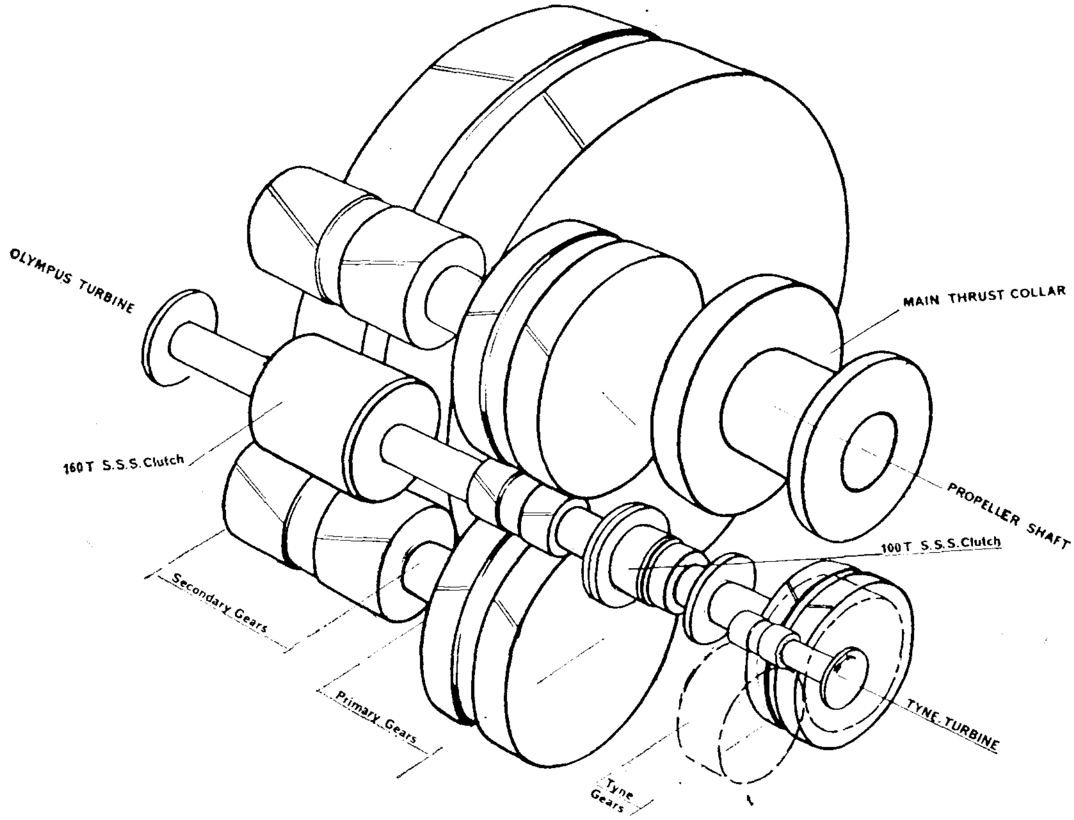

FIG. 9—TYPE 42 GEARBOX DESIGN
(*Courtesy David Brown Gear Industries Ltd.*)

and they will be correctly lubricated. They will have been manufactured to the necessary high accuracy in the most economic way.

By pooling their research the three member firms have made it possible for the Royal Navy to have the gears, among the most advanced in the world, which will be needed for the Fleet of the future.

Acknowledgements

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Bibliography

W. M. Brown—Production of Large Heat treated gears within the UK, *Marine Engineer and Naval Architect*, October, 1968.

Navy and Vickers Gearing Research Association—unpublished literature.