Engineering with Nuclear Explosives near Populated Areas - A Survey from the Technological and Economic Viewpoint

K. Parker
AWRE, Aldermaston, U.K.

Summary

Current experience with underground firings of nuclear explosives and of large charges of conventional explosives is largely confined to sparsely populated areas such as the Nevada and Sahara deserts and parts of Siberia. On the other hand many of the commercial applications proposed for nuclear explosives are directly relevant to industrialized areas, where consumptions of energy and natural resources are high, as are population densities. In many of these areas there is a need to increase the efficiency with which natural gas, oil and electrical power are supplied and to make safe disposal of fluid wastes; completely contained nuclear explosions could be a useful tool in achieving some or all of these aims.

Whilst radioactivity and air blast hazards are likely to rule out nuclear cratering operations near densely populated areas, the prospects for carrying out completely contained explosions are much better, providing seismic damage is kept within reasonable bounds. In large areas of Western Europe and on the eastern, southern and western seaboards of the United States this might be achieved by using nuclear explosions beneath the seabed at a reasonable distance from the nearest coastline, always provided the relevant political issues can be resolved.

Stimulation and storage of North Sea natural gas, construction of off-shore oil storage and storage of electrical energy are areas where engineering with nuclear explosives merits more detailed investigation and some of the relevant technical problems are discussed.

1. Introduction

In the past fifteen years considerable progress has been made towards demonstrating the use of nuclear explosives as a feasible, safe and economic technique in civil, mining and petroleum engineering. The United States Plowshare programme has led to an improved understanding of the effects and potentialities of nuclear explosives important in their peaceful application. The Soviet Union has also gained considerable experience in this field [1] and has indicated its willingness to provide a peaceful nuclear explosive service under article V of the Non-Proliferation Treaty [2]. Again the Russians have discussed and carried out civil engineering works involving detonation of large charges of conventional explosives [3]. Whilst both the United States and the USSR have large populations, their territories are large and their population distributions uneven so that areas can fairly easily be found in which to carry out nuclear explosive engineering experiments and projects.

Once it becomes apparent that an engineering technique is feasible, safe and economic under particular circumstances it is natural to ask what are the ultimate limits on its use. By analogy, open cast mining is a proved technique but its application in urban areas would be uneconomic,whilst methods used to demolish buildings must be varied on safety grounds according to the nature of the surroundings. Many of the possible engineering applications of nuclear explosives relate to economic activities which are concentrated in heavily-populated, industrialised areas. Oil storage is often required near major ports. Gas storage is generally most important near to consumers. For these reasons it is no academic question to examine the possibility of engineering with nuclear explosives near populated areas.

If one looks at maps showing population density such as are shown in figures 1 and 2 one readily confirms that the Nevada, Sahara and Australian deserts are low density areas as is Novaya Zemlya. On the other hand there are well-known areas of high population density such as the eastern United States seaboard, Japan, the United Kingdom and much of the coast lands bordering the North Sea and the Mediterranean Sea. These are areas of high economic activity where much of the world's consumption of energy and natural resources takes place and where any remaining minerals of commercial importance are won only with increasing difficulty. Engineering techniques involving nuclear explosives could be useful in these areas providing they are both safe and economic.

Section 2 of the paper considers possible applications of nuclear explosive engineering near populated areas from a West European viewpoint. There follows in section 3 a discussion of how the hazards of nuclear explosives might be minimized or avoided so as to make such application possible. Specific examples of possible projects are referred to in section 4 and the paper concludes in section 5 with a discussion of outstanding technical problems and possible future developments.

2. Possible Uses of Nuclear Explosives near Populated Areas

General

From a West European viewpoint the applications of nuclear explosives which first merit detailed examination appear to be those concerned with improving the economics of fuel and energy supply. The exploitation of mineral and water resources may also be assisted by the use of nuclear explosives but there are probably more problems to be overcome in these areas.

Oil Storage

Over the past fifteen years natural gas and uranium have taken their places alongside coal and oil to give a four-fuel economy in many parts of Western Europe. Following the Middle East crisis of 1956 there has been considerable diversification in the sources of imported oil but in the absence of substantial indigenous production (17.3 million tons in 1968 out of a world annual production of over 2,000 million tons) a healthy stock level is always a useful safeguard against any interruption of supplies. It has been argued [4] that commercial stock levels in European countries, typically at two or three month demand level, should be at least doubled. This implies the provision of some 80 million tons of oil storage in Western Europe. Nuclear chimneys either on land or beneath the seabed might provide a sizable fraction of any such large increase in storage capacity. But there is another reason for providing oil storage beneath the seabed. The continual increase in tanker sizes is giving rise to a need for special berthing facilities. At Bantry Bay in south-west Ireland an off-shore terminal has been provided at a cost of about $24 million [5] which provides storage for nearly a million tons of crude oil

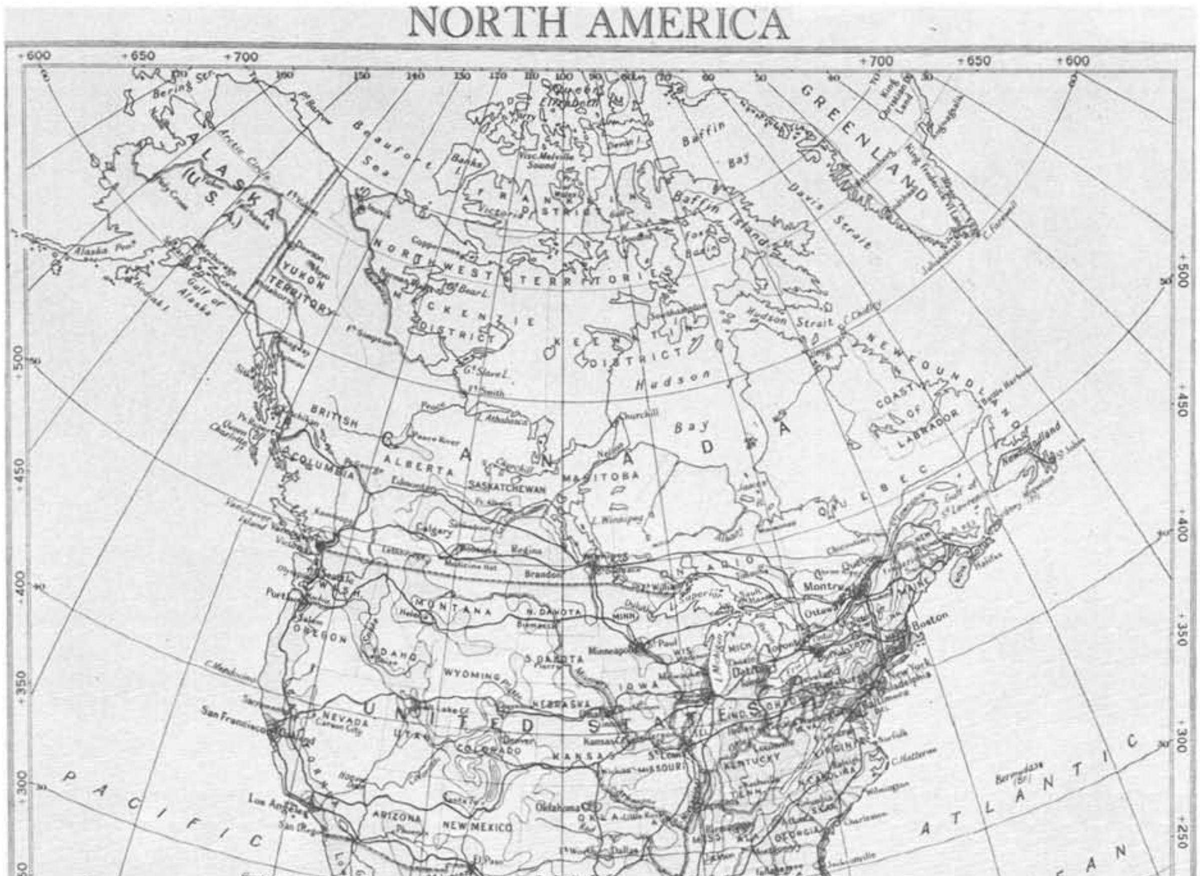

Figure 1 Population densities in North America

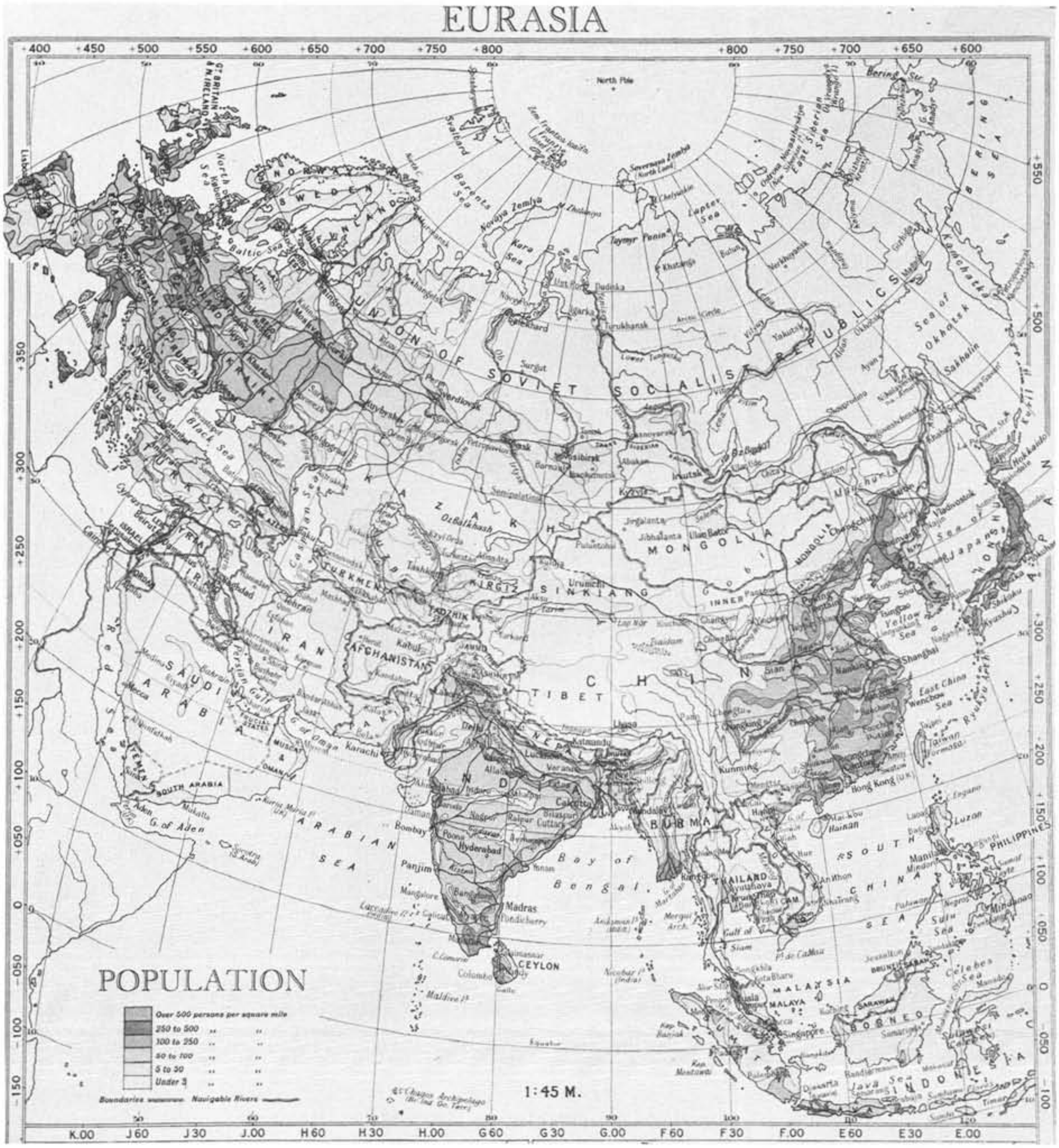

Figure 2 Population densities in Eurasia

in 12 tanks each 262 ft. in diameter by 64 ft. high [6]. This handles tankers of 300,000 dwt. and allows trans-shipment to smaller tankers for onward transport to several European refineries. At Milford Haven, an excellent natural harbour in west Wales developed primarily for tanker traffic, it has become necessary to spend about $28 million in dredging and navigational aids in order to allow regular entry by tankers of 250,000 tons [7]. Fully laden tankers with a draught of 63 ft. will then be able to enter and berth on every tide throughout the year. However if tankers of 750,000 tons or even a million tons are built then it may be necessary to cater for fully laden draughts of 95 ft. Figure 3 is a map of the European Continental shelf showing the 17 fathom (102 ft.) line. This shows that the English Channel and the southern North Sea might be excluded to such large tankers and has led the Mersey Docks and Harbour Board [8] to study the possibility of building a terminal ten miles or more off the North Wales coast. Such a project would probably cost over a hundred million dollars and, for efficient operation, it would be advantageous to provide on-the-spot flow storage for a million tons of oil or more. Other large oil terminals are planned for a position 12 miles off the coast near the French/Belgian border [9] and off Heligoland [10]. A third possible need for substantial oil storage-again beneath the seabed might arise should oil be discovered on the Continental Shelf. Although the major finds in the North Sea have been the gas fields in the United Kingdom sector, it is reported that oil has been found near the boundary of the Norwegian and United Kingdom sectors [11] although it is not yet known whether recovery would prove economic at a point 150 miles off-shore. It could be that here, and for any other fields that may be discovered, recovery will be most economically achieved by direct transfer to tankers using suitable mooring near the drilling platforms, rather than by laying seabed pipelines. In this case buffer storage could prove advantageous in maintaining steady production during periods of bad weather when tankers were prevented from loading.

Oil Stimulation

A further future use of nuclear explosives in relation to West Europe's oil supplies might be in stimulating tight fields. As long as indigenous production remains small this might be considered worthwhile under conditions where it might be uneconomic in the United States or other major producing areas, although there do not appear to be any promising areas at the moment. The current emphasis on gas rather than oil stimulation experiments in the United States appears to stem partly from concern at the declining level of natural gas reserves available by conventional techniques and partly from the existence of fewer unworked tight oil fields (the value of oil in place having justified greater use of conventional stimulation techniques).

Gas Stimulation

Turning to natural gas one immediately asks what are the prospects of employing nuclear stimulation in the North Sea fields. Certainly the North Sea explorations have revealed areas where gas occurs in tight formations and could perhaps be extracted by nuclear stimulation. But the economic situation is currently almost the opposite of that in the United States; the proved reserve to annual production ratio is rising strongly and gas is tending to displace other fuels. However, if the nuclear stimulation technique is proved in the United States, or elsewhere, it may eventually be employed on the European Continental Shelf. An application of nuclear stimulation which might be tried somewhat earlier could be the stimulation to improve the overall economics of working the proved productive fields shown in figure 3. Exploitation usually involves the drilling of twelve to fifteen production wells from a single platform [12] at a cost of 10-20 million dollars. It may be worth examining whether

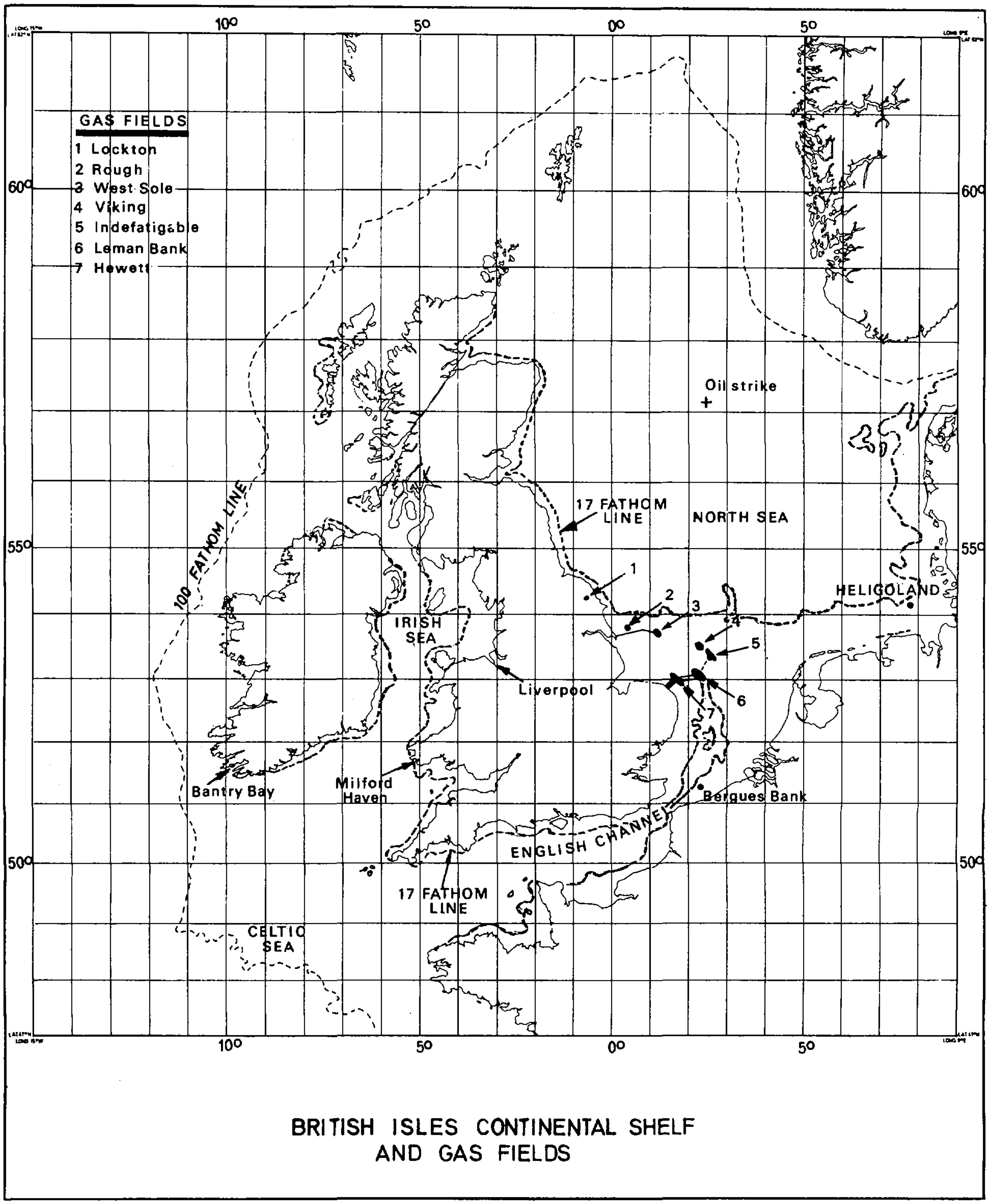

Figure 3 The European Continental Shelf

a single stimulated well can achieve the same production rate at a lower total cost. The gas from such a well could be burnt in a specially designed power station or used to provide total energy systems for large industrial concerns; in either case any radiation could be dealt with under closely controllable conditions.

Gas Storage

In the present decade a substantial high pressure gas pipeline system has developed in Western Europe and further growth can be expected. Figure 4 shows the current position. Even before the discovery of natural gas in the North Sea, the United Kingdom Gas Council had begun to develop such a pipeline grid to distribute natural gas transported in liquid form from Algeria to Canvey Island in the Thames Estuary. The system has been extended and further developments are planned (figure 5). The total mileage of high pressure transmission pipeline - about 2,500 miles should be in use by 1973 [13] - is very small compared with that in North America - about 250,000 miles - but it is still desirable on grounds of supply security and peak-shaving economics to provide storage, particularly near the extremities of the grid in South-West England, North-West England, Wales and Scotland. The eventual pipeline mileage in continental Europe is likely to be much higher. By the end of 1968 over 15,000 miles of pipeline were in use in Europe [13], mainly as a result of developing the Slochteren field in the Netherlands. The network is likely to undergo considerable extensions particularly if, as seems likely, Russian gas is piped to Austria, Italy and other West European countries, and the provision of stand-by storage will probably become increasingly necessary. Although storage in aquifers, disused coal mines and salt cavities is possible there are certainly not the same number of depleted oil and gas fields available for storage as in the United States. In any case nuclear cavity storage has the advantage of high deliverability. Liquefied natural gas may be stored to provide peak-shaving facilities. Although a competitor to nuclear cavity storage this method in itself requires sophisticated storage facilities which may in certain circumstances be provided using nuclear explosives.

Shale Oil Production

Deposits of shale oil occur in France, Germany, Italy, Scotland, Spain and Sweden. In the absence of indigenous oil supplies there are strong incentives to exploit these resources. However the economics are so unfavourable that shale oil production has been very small except during the 1939-1945 war. In many cases deposits are very thin and are unlikely to be an attractive proposition for extraction techniques involving nuclear fracturing.

Stored Energy in National Electricity Systems

The efficiency of the production and distribution of electricity in densely populated areas depends strongly on the effect of the peak load problem and electrical engineers are constantly seeking means of disposing of surplus off-peak cheap electricity in energy storage devices [14]. Probably the water pumped storage scheme is the best known but if the two storage reservoirs are both above ground then the number of topographically suitable sites may be limited. This problem could be lessened by constructing the lower reservoir below ground. An alternative storage scheme involves the compression of air into underground tunnels or cavities during off-peak periods. At peak periods this air is used to burn oil fuel in a gas turbine thus generating additional power; the net output of the turbine can be increased by a factor of about 3 with a reduction in generation costs. Without discussing the overall economics of these and other energy storage methods it can be seen that the construction of underground cavities using nuclear explosives could be helpful in exploiting the two systems mentioned, particularly by reducing construction costs.

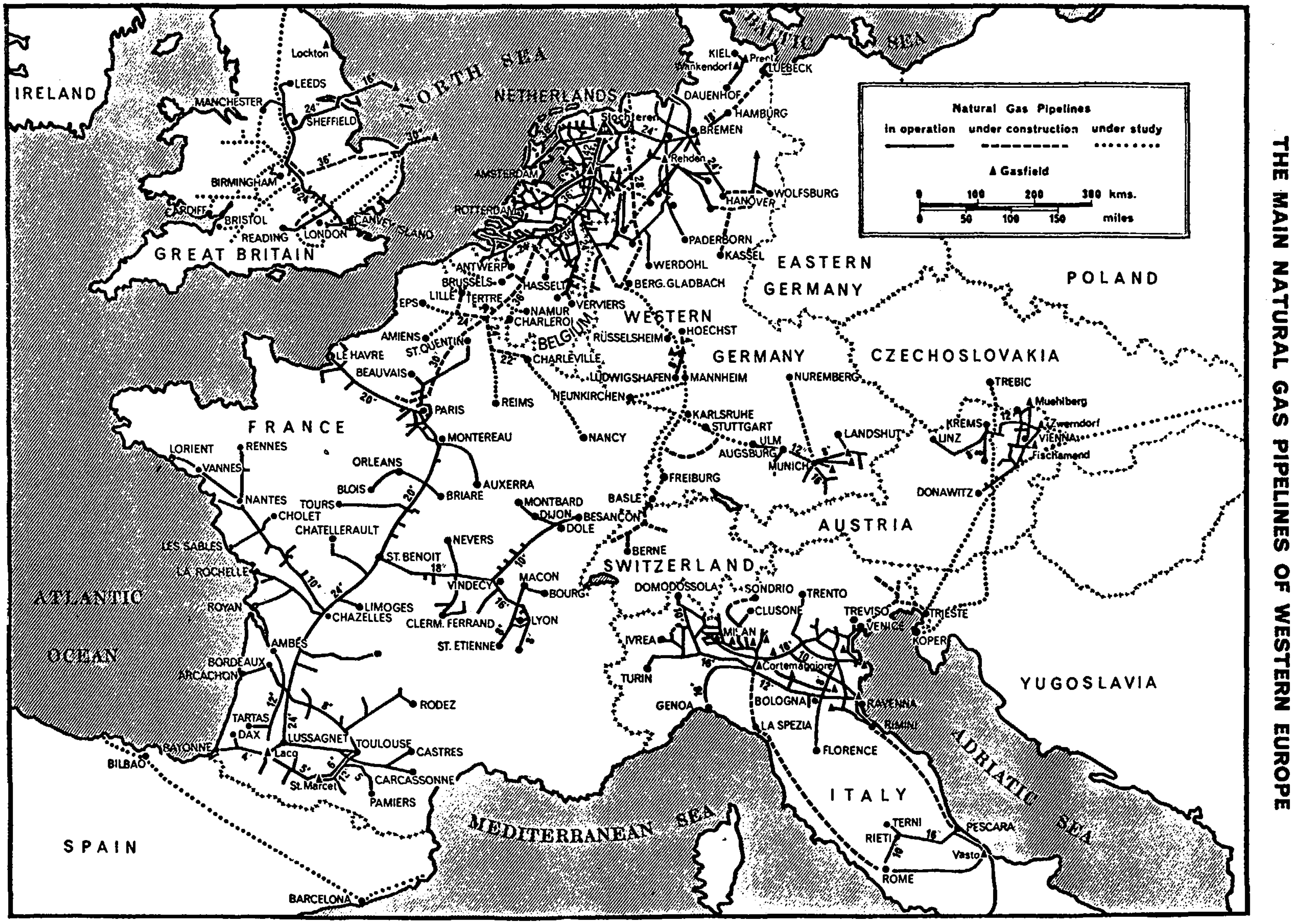

Figure 4 Gas pipelines in Western Europe

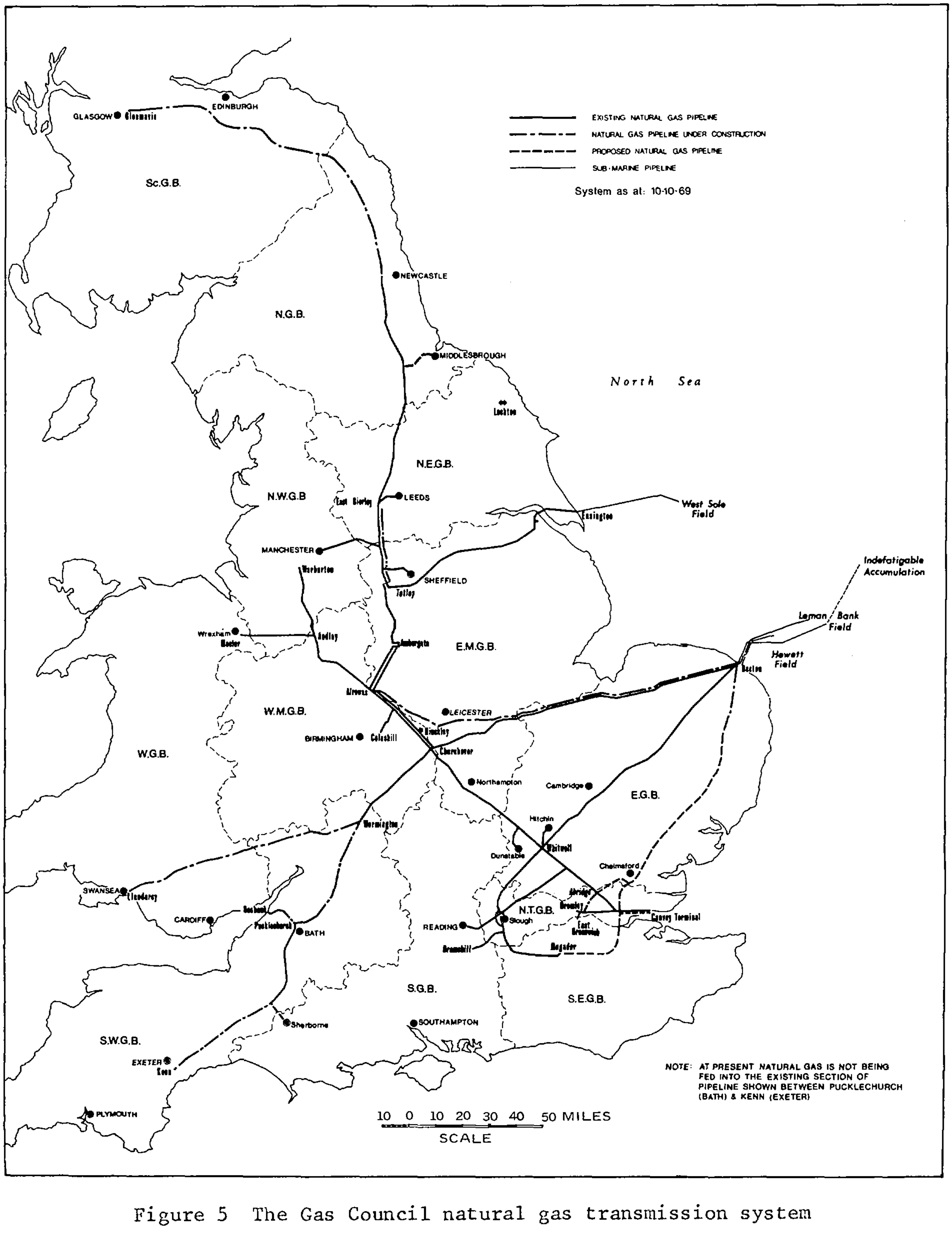

Figure 5 The Gas Council natural gas transmission system

Waste Disposal

Again the problems of waste disposal will be greater in densely populated areas. It is to be expected that nuclear chimneys will be considered as a means of storing radioactive waste arising from nuclear power generation and as a facility in the treatment of sewage and industrial effluents.

Mineral Exploitation

For their size the British Isles were well endowed by Nature with mineral resources but, of course, the inevitable result of early industrialisation has been early exhaustion of the best deposits of many ores, particularly those containing lead, copper and tin of which the United Kingdom was once the world's leading producer. The intensive prospecting of the Continental Shelf for gas and oil raises the obvious question of whether other useful minerals can be recovered from beneath the seabed. Off the north coast of Cornwall tin lodes are known to extend under the seabed as do coal seams in Cumberland and Durham. There is already a large underwater sand and gravel industry meeting about 10% of the United Kingdom demand. The economic geology of the Continental Shelf around Britain has been reviewed by Dunham [15]. Because of the additional costs of exploration and of drilling and tunnelling beneath the seabed there will be strong economic incentives to reduce the costs of overburden removal and rock breaking and crushing and the use of nuclear explosives for this purpose is bound to receive consideration. On the other hand the use of nuclear explosives in mining on land near populated areas seem less likely. Quite apart from the inherent problems in their use, increasing objections on amenity grounds are likely to preclude large-scale mining near densely populated areas.

Figure 6 summarises the possible uses of nuclear explosives near populated areas.

3. Eliminating the Hazards of Nuclear Explosives

The principal hazards which could arise in the commercial application of nuclear explosives are airblast, radioactivity and ground motion. Leaving aside very large completely contained explosions, which will be economically unacceptable in populated areas because of seismic damage considerations, airblast would only be a problem with cratering explosions used in certain mining operations and in civil engineering projects. Similarly, it would only be in cratering explosions that radioactivity would be released into the atmosphere at the time of the explosion. None would be released in a contained explosion, providing that precautions were taken to prevent venting up the emplacement hole. On present experience, as reviewed by Rapp [16] and by Germain and Kahn [17] it appears that containment can be assured. The probability of seepage of radioactive gases to the surface following the shot is very small as is the quantity of radioactivity involved. The remaining radioactive hazards in a contained shot would be those arising in the development and use of the cavity or chimney and those arising from radionuclide migration in ground water. Seismic damage resulting from ground motion is a common hazard of all underground explosions, nuclear or conventional.

Clearly the use of cratering explosions near densely populated areas would raise very considerable problems in relation to these three main hazards. But in practice the need for such cratering explosions is likely to arise in lightly populated areas, not because the hazards are thereby lessened, although of course they are, but simply because these are the areas where harbours are needed, where overburden must be removed and new roads, railways and dams constructed in order to develop new sources of minerals and power. Most densely populated areas are already well equipped with good means of communication and most mineral resources have already been worked or are being worked by conventional methods.

- Oil storage
  - Buffer storage
  - Offshore terminals
  - Offshore fields
- Gas storage
  - On land
  - Beneath the seabed
- Oil stimulation
- Gas stimulation
  - Exploitation of tight fields
  - Quicker, cheaper development of production fields
- Energy storage
  - Pumped water storage
  - Compressed air storage
- Waste disposal
  - Radioactive waste
  - Sewage
  - Industrial effluent
- Extraction of seabed minerals
  - Cratering explosions
  - Contained explosions

Figure 6 Possible uses of nuclear explosives near populated areas

Turning to completely contained explosions the picture is different. For a suitably designed device of up to 100 kton yield, say, suitably emplaced in a carefully chosen geological structure the potentially mobile radioactivity produced should be small. Contamination of ground water by fission products should then be negligible [18, 19] and the chimney could be purged to reduce radioactivity to an acceptable level. Tritium - from thermonuclear reactions and from neutron reactions with surrounding rock - is likely to be the most troublesome radionuclide. In gas and oil stimulation work and in the development of water resources [18] it may be necessary to use all-fission devices. This may be necessary in all contained shots if tritium proves to be troublesome to remove from storage cavities by purging or presents a contamination hazard to ground water [18, 19]. Given the demand, the economic penalty, if any, of using all-fission devices should not be large.

With the elimination of air blast and the reduction of radioactivity to acceptable levels, seismic damage caused by ground motion remains as the crucial hazard of the contained nuclear explosion. An immediate reaction is that seismic damage precludes the use of nuclear explosions near populated areas. Of course this is true as far as explosions beneath the centre of, say, London or Las Vegas are concerned but even in densely populated countries there are considerable areas of lightly populated land. About an eighth of England and Wales has a population density less than 100 per square mile which implies a building density of something like 30 per square mile; in Scotland sparsely populated areas are more common. It appears from the Rulison shot [20] that explosions of up to about 50 kton could be carried out within 5 to 7 miles of sizable centres of population without causing unacceptable seismic damage. Naturally the costs of strengthening buildings, temporarily evacuating homes and meeting justified compensation claims must be considered in the overall assessment of any scheme and may impose unacceptable economic penalties but there appear to be no insuperable short or long term safety problems associated with shots of up to 100 ktons.

The economic penalties of seismic damage may indeed be sufficient to preclude many nuclear explosive engineering projects near populated areas but often a simple remedy would be to hand - site the project beneath the sea bed at a sufficient distance from shore. As already shown the off-shore oil terminals are often a considerable distance from shore because of navigation problems. Nuclear explosions beneath the seabed at terminals sites should then pose few seismic damage problems. Tsunamis - or seismic sea waves - will need to be considered but around Western Europe at least their effects, if any, should be small compared with those from typical stormy weather [21].

A final hazard which must be mentioned is earthquakes and aftershocks related to nuclear explosions [22]. For contained explosions of up to 100 kilotons seismic tremors outside the chimney growth area are most unlikely, particularly in the many regions of low natural seismic activity such as the Eastern United States and Northern Europe.

It seems that the safety problems associated with contained nuclear explosions of up to about 100 kton yield are sufficiently limited and sufficiently well understood as to make their use in engineering works near populated areas possible. The close proximity of the sea to many densely populated areas provides the key for a successful solution to the principal problem of seismic damage, providing the overall economics of any engineering scheme are not adversely affected.

4. Nuclear Explosive Engineering in and around Western Europe

Having suggested that nuclear explosive engineering can be both useful and practicable near densely populated areas it is natural to ask what are the immediate prospects for this technology. Some of the broad possibilities in and around Western Europe are brought out in the discussion of section 2 but it seems worthwhile to consider a few aspects in more detail.

For safety reasons the cratering explosion has already been seen to be a doubtful starter near densely populated areas. An important exception is the cratering explosion on the seabed with its possible application to mineral exploitation on the Continental Shelf. Here the seismic damage and blast hazards can be overcome by going a sufficient distance from the shore but there are obvious problems concerned with sea waves, the base surge and radioactivity in seawater - problems which have been discussed very briefly by Tomblin et al of AWRE [23]. Another application of the less than fully contained under-seabed nuclear explosion might be the removal of navigation hazards but much as it may be desired to remove such notorious hazards as the Seven Stones Rocks (scene of the grounding of the Torrey Canyon) it is unlikely that such sites will be sufficiently far from land to permit the use of uncontained nuclear explosions. The main application of cratering explosions then is likely to be in exploiting the mineral resources of the Continental Shelf; they may be used as a complement or alternative to the completely contained explosion. In both cases the rate of application is likely to be governed by economics and by the speed with which other branches of underwater technology develop.

The storage of oil in nuclear excavated chimneys seems most likely to be developed first in connection with large tanker terminals. Figure 7 is an artist's impression of a possible design for the Mersey Docks and Harbour Board's Liverpool Bay oil terminal. The island, 3,800 feet long, situated 11 miles off the coast, would be capable of berthing million ton tankers 1800 feet long by 283 feet with a draught of 95 feet. Two submarine pipelines would connect the island to a point on the coast about 14 miles away from where a main pipeline would run to oil refineries in North West England. In this design the base of the island provides storage for $1\frac{1}{4}$ million tons of oil. Using nuclear explosives it would be possible to provide additional storage beneath the seabed at the island itself or - at a later date - 2 or 3 miles away, connected to the existing storage by additional pipeline. In a possible alternative scheme tankers would tie up to a single buoy mooring [24] and all the storage would be provided beneath the seabed. An important economic factor in favour of off-shore storage linked with tanker terminals is that the pipeline must be provided as part of the overall scheme. Off-shore buffer storage filled from land would be considerably more expensive.

As far as the gas industry is concerned the main North Sea fields are 15-50 miles off shore (figure 3) - sufficiently far from the shore to allow for gas stimulation shots being undertaken without risk of seismic damage to shore installations. The same is likely to hold true in the Irish and Celtic Seas where a period of intensive prospecting is now being followed by the first drilling. The storage of gas may also be feasible and economic in nuclear chimneys either beneath the seabed or on land. A study of conditions in the United Kingdom suggests that, apart from seismic damage costs, which must vary from site to site, on-land storage costs should be very much in line with those given in the feasibility report for Ketch [25].

5. The Future

At a time when Gasbuggy and Rulison are the only reported applications of nuclear explosive engineering which can be considered as being of a commercial or near-commercial nature it cannot be claimed that the application of nuclear explosives in engineering projects near to densely populated areas is imminent. Nevertheless there is sufficient evidence of potential use to justify a continuing appraisal of the possibilities as nuclear explosive engineering

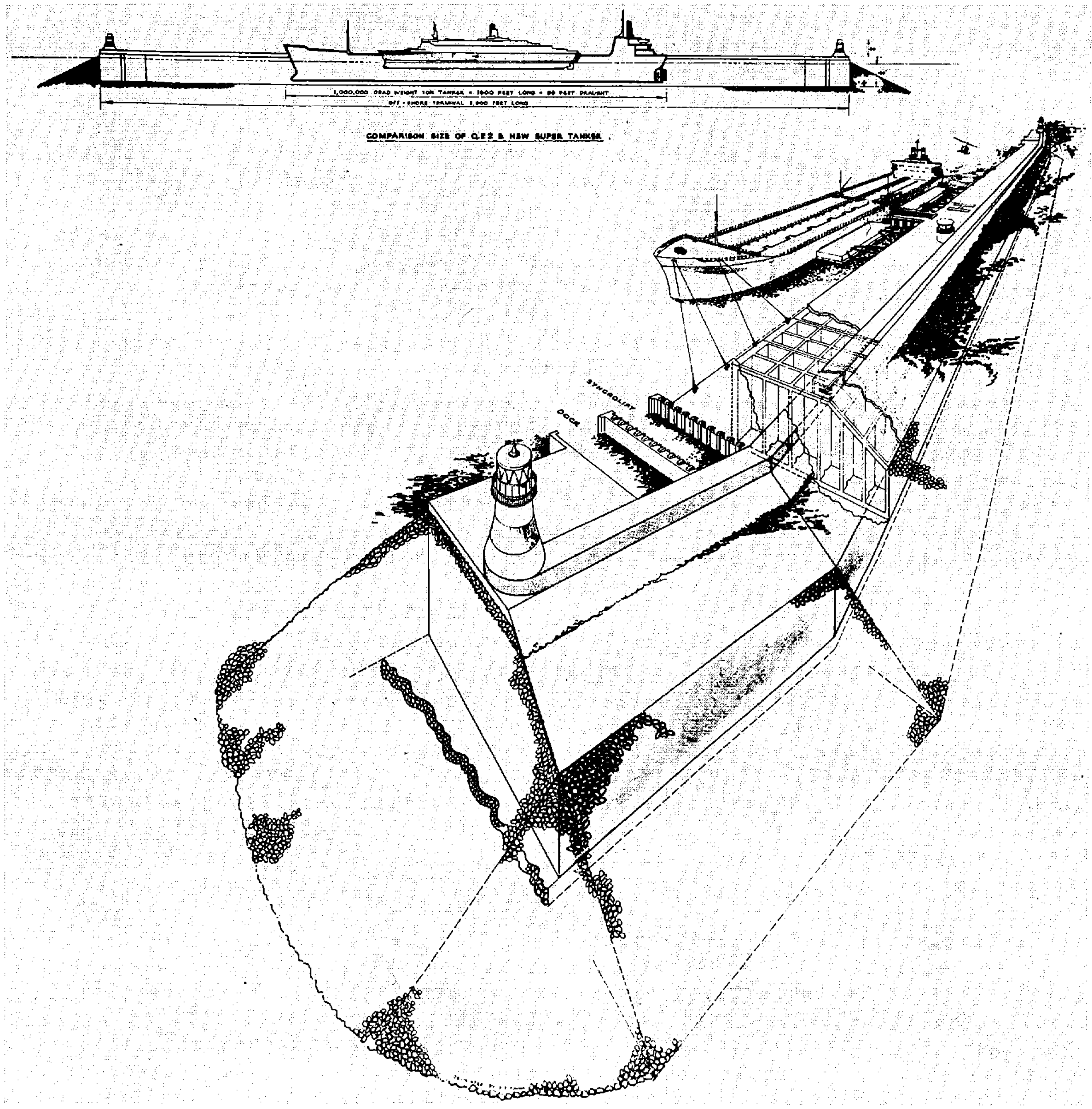

Figure 7 Artistic impression of a million ton tanker terminal

develops. The substantial American and Russian development programmes appear likely to answer many of the technical problems now facing us. Of primary economic importance is the seismic damage problem.

Figure 8 illustrates how seismic damage effects can vary with geology. Using the pseudo absolute acceleration (PSAA) or building response as a criterion for seismic damage one finds variations of 200-250% in response depending whether buildings are situated on hard rock (favourable) or alluvium (unfavourable). In practice a variety of site conditions will probably be found. When these variations are converted into costs of investigating claims and paying justified claims the uncertainties can be very great. In Table 1 are the results of a calculation of seismic damage costs using the procedure recommended by the United States Army Engineers' Nuclear Cratering Group [26] for a hypothetical population and building distribution in a densely populated area around a 25 kton shot. Several conclusions can be drawn from these figures:

(i) The percentage variation in damage costs may be much greater between hardrock and alluvium sites than the percentage variation in pseudo-absolute accelerations (which is a constant 220% in this example).

(ii) Although the proportion of complaints and the cost of settling claims decreases with distance the major contribution to damage costs can easily come from many small claims at large distances.

(iii) In the case of a city (population 180,000) at 30 km the total compensation becomes very difficult to estimate.

(iv) Present estimates of seismic damage costs for a shot near densely populated areas could be uncertain by a factor of 5.

It may be argued that the assumptions made in deriving Table 1 are unrealistic. Certainly the first reports of the Rulison shot suggest that the assumptions may be pessimistic. Nevertheless there remains a great deal of uncertainty about the costs of seismic damage. If nuclear explosions are to be used near to populated areas a great deal more theoretical and experimental knowledge and practical experience will have to be acquired and thoroughly analysed so that realistic costs can be incorporated in economic assessments of particular projects. No amount of sophistication in device design, drilling techniques and the like will ensure the use of nuclear explosives near populated areas unless this problem is tackled and solved. It is salutary to remember the proportion of breakdowns in nuclear power stations which arise from failure in their (possibly less well tested and proved) conventional equipment.

Because of the seismic damage problem it is hardly possible to contemplate development experiments near populated areas; the use of nuclear explosions in such regions must be limited to proved applications which can be guaranteed safe and which are virtually certain to achieve their engineering objectives. An analogy can again be drawn with nuclear power stations - siting close to centres of population becomes more acceptable as design and operating experience develop. This need not mean that development shots are limited to the United States and Russia. They could be safely carried out in many other sparsely populated locations in other parts of the world.

Similar considerations apply to peaceful applications of nuclear explosives on or beneath the seabed. Here the pace of progress is strongly dependent on the development of undersea technology although, as compared with the effects of on land explosions, there is relatively little information available on underwater cratering, the generation of water waves by explosions and the disposal of

Table 1

Illustrative Estimates of Seismic Damage Costs for a 25 kton Nuclear Explosion

Damage zone, km	Average distance from shot point, km	Population	Number of buildings	Sites on hardrock			Sites on alluvium		
				Complaint factor (CF)	Damage factor (DF)	Cost, 000 dollars	Complaint factor (CF)	Damage factor (DF)	Cost, 000 dollars
0-2	1	0	0	1.0	1.0	Nil	1.0	1.0	Nil
2-4	3	50	15	0.50	0.79	59.25	0.80	1.0	120.00
4-6	5	300	100	0.19	0.47	89.30	0.70	0.39	273.00
6-8	7	600	200	0.098	0.26	50.96	0.50	0.21	210.00
8-10	9	900	300	0.059	0.15	26.55	0.37	0.13	144.30
10-15	12.5	6,000	2,000	-	0.059	118.00	0.18	0.068	244.80
15-20	17.5	24,000	8,000	-	0.016	128.00	0.080	-	640.00
20-25	22.5	42,000	14,000	-	0.005	70.00	0.034	-	476.00
30	30	180,000	60,000	-	0.0015	36.00	0.011	-	660.00
					Total cost	578.06		Total cost	2768.1

Zone I ($\leq$ 16 cm/sec^2) cost = Number of complaints × \$400

Zone II (16 to 100 cm/sec^2) cost = Number of complaints × \$1,000

Zone III ($\geq$ 100 cm/sec^2) cost = Number of complaints × damage factor (DF) × \$10,000.

Number of complaints = Number of buildings × complaints factor (CF)

Number of buildings ≃ Population × $^1/_3$. Average value of a building in zone III = \$10,000.

Values of CF, DF and PSAA versus distance from figure 8.

PSAA = 2 peak ground acceleration = 1,000 $W^{0.7}$ R^{-2} cm/sec^2, W = 25 ktons, R = distance from shot point in km.

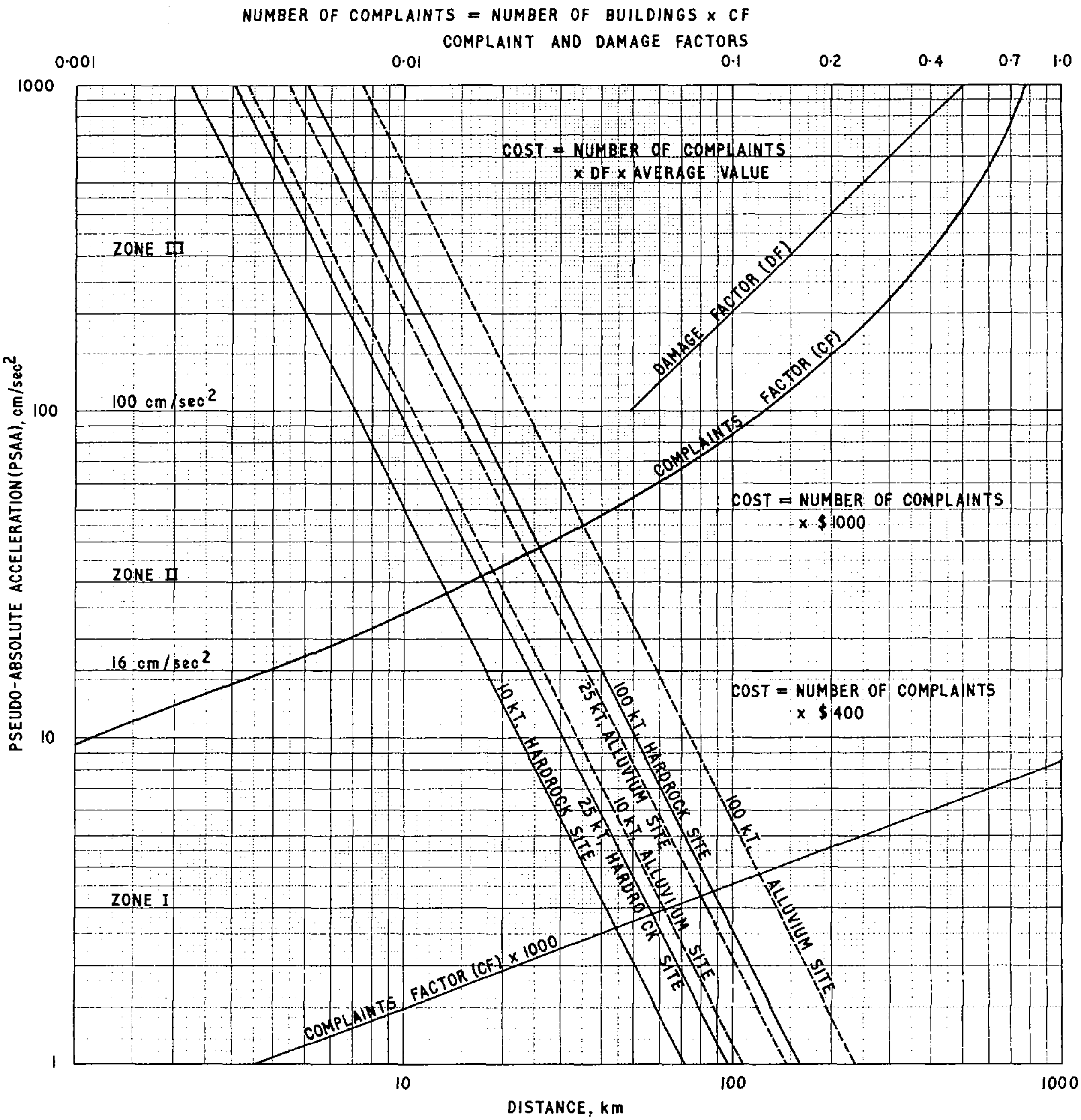

Figure 8 Variation of seismic damage with geology

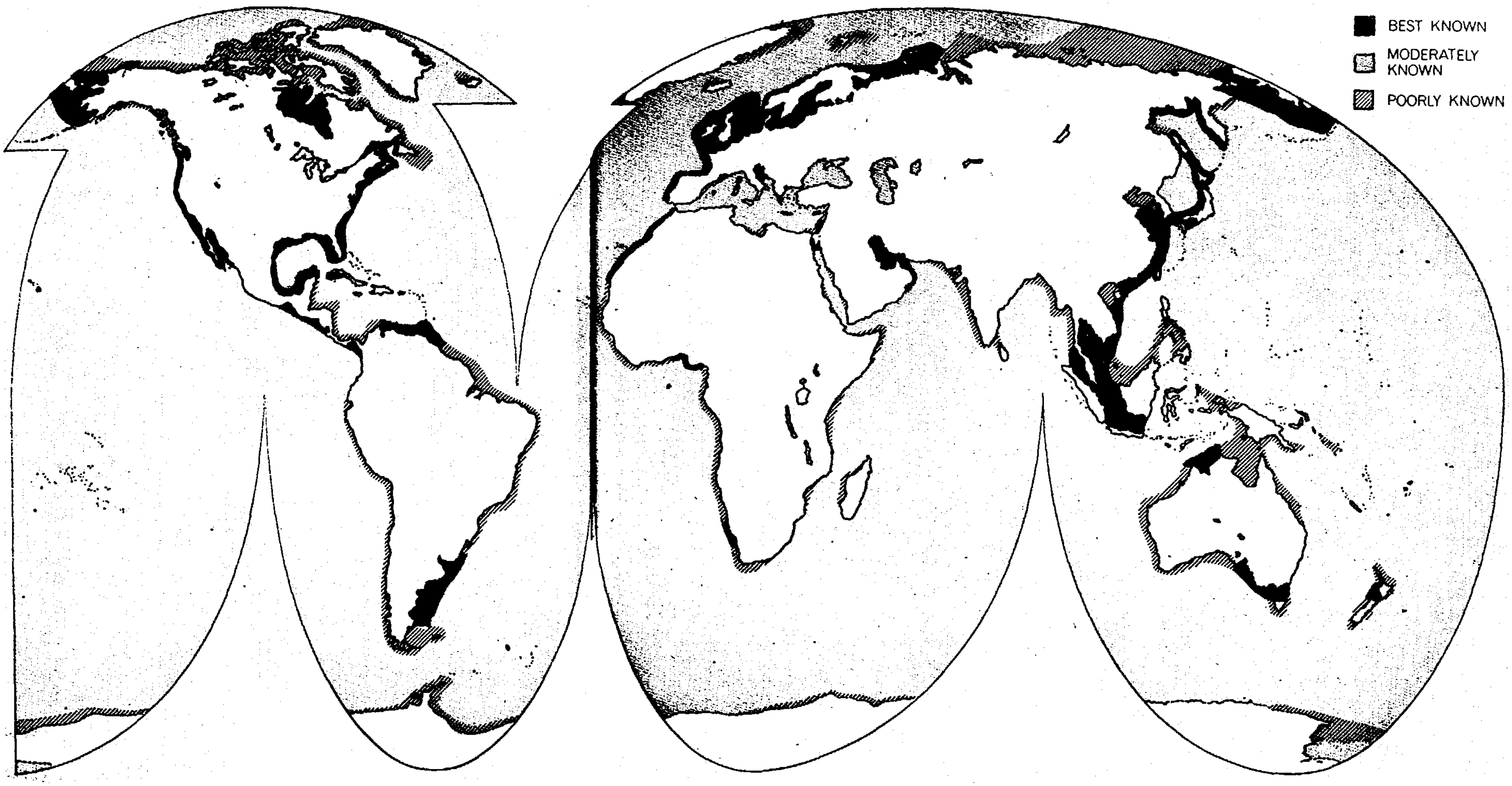

Figure 9 Continental shelves of the World.

any released radioactivity. Given the vast area of the world's continental shelves (figure 9) and their economic potential, the incentive for research in these fields is high.

To summarize, the use of nuclear explosives near populated areas may be practicable and further detailed studies of the technical problems involved are now justified. This is a necessary prelude to the assessment of the wider economic and political issues which must be undertaken before national policy decisions can be made. In the meantime it is desirable to bring to the attention of engineers both the potentialities and the limitations of the use of nuclear explosives in a variety of environments.

Acknowledgments

In preparing this paper I have consulted many individuals and organisations including my AWRE colleagues and staff of Associated Nuclear Services, the Central Electricity Generating Board, the Gas Council and the Mersey Docks and Harbour Board; but the views expressed and the conclusions reached are my own.

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