nation of low profits and high capital costs could lead to a situation where the trunk lines cannot survive without government subsidy. Already, fears are being expressed that the industry will not be able to raise the huge sums (some estimates have been as high as $27 billion) that must be spent before the end of this decade for new aircraft and ground equipment.

Heavy subsidization could lead to politically compelling demands for an increasingly large role for the government in airline management, with nationalization to be the eventual outcome. It is entirely conceivable of course that some form of nationalization would produce excellent results. The nationalized foreign airlines generally have a reputation of offering relatively limited and costly service, but circumstances in the United States might be much more favorable to air service to a mass market at reasonable fares.

Deregulation of the airlines would produce a major upheaval within the industry, and it is probably the alternative least likely ever to be adopted. Moreover, J. C. Constantz, chief of the CAB's economics analysis division, believes that deregulation would lead finally to an inadequate system dominated by a few big carriers. On the other hand, even at the CAB there are knowledgeable people who suspect that a deregulated system would work at least as well as the existing one.

A promising middle way that would avoid the uncertainties and pitfalls of nationalization and deregulation would be to modify the present regulatory system. The CAB could be directed by Congress to regulate airline schedules in such a manner as to ensure satisfactory load factors. The agency regards load factors of 60 to 65 percent as "reasonable," and even this may be conservative. Some students of the problem have concluded that the average load factor could be raised to 70 percent without substantially reducing the availability of service.

A truly efficient air service will of course be one that is planned as part of a well-integrated national network of intermodal transportation systems, with the air mode devoted primarily to long-haul service (at present, half of all domestic airplane hops are for distances under 260 miles). But the planning and development of such a system is a problem for the long term. Raising load factors for the existing domestic air service is a problem that cries out for early solution.—LUTHER J. CARTER

RESEARCH NEWS

Energy Storage (II): Developing Advanced Technologies

The concept of energy storage—storing energy generated when demand is low for use when it is needed later on—is rapidly coming of age (*Science*, 17 May, p. 785). Electric power utilities, faced with a demand for electricity which fluctuates with the time of day and season of the year, estimate that, by the end of the century, up to 25 percent of the total power generated during the day could be stored and subsequently used. One spokesman rated energy storage as the best technological and economic investment after advanced nuclear power. In addition to serving the needs of utilities, energy storage is needed for electric vehicles. While experiments with vehicles powered by storage batteries, one alternative to petroleum-fueled internal combustion engines, are well under way, advanced energy storage systems could make such vehicles much more useful than they are now. And energy storage will be essential to the development of presently unexploited energy sources, such as the sun, the wind, or the tides, which are intermittent in character.

A number of proposed storage technologies are emerging from the stage of preliminary feasibility studies and entering the stage of engineering study and prototype development. For example, energy can be stored in a magnetic field. In the familiar electromagnet, however, the resistance of the magnet windings results in power losses, and power must be constantly supplied in order to maintain the field. If the windings lacked resistance—that is, if they were superconducting—then once the desired magnetic field was obtained, it would require no further power, and the energy originally supplied to the magnet would be stored in the magnetic field. Later the stored energy (proportional to the square of the current) could be recovered by drawing off some of the current in the magnet. The storage efficiency (the fraction of stored energy that is recoverable) could be about 95 percent.

Such an idea for storing electrical energy has been advocated by researchers at the University of Wisconsin, Madison (*1*), and at the Los Alamos Scientific Laboratory, Los Alamos, New Mexico (*2*). Both groups have pointed out that storing energy for utilities via superconductors is economically thinkable only for large storage capacities, in the range 1,000 to 10,000 megawatt-hours (1 watt-hour equals 3600 joules). A typical magnet might be a solenoid with a radius of 50 meters and a height of 50 meters, and would probably be set in bedrock in order to contain the large forces on the conductors of such an immense magnet. Because of the relatively low energy density (measured in watt-hours per cubic meter) of superconducting magnetic storage, this type is inappropriate for vehicles.

Both the Madison and Los Alamos groups have made preliminary engineering and economic studies of the feasibility of storing energy in this way, and are hoping to build model systems from which to obtain data for extensive analysis. The Wisconsin group is aiming for a 10–megawatt-hour model (in the form of a solenoid) to be completed by 1980 or 1981. The solenoid would be made of niobium-titanium composite superconductors (*Science*, 25 January, p. 294) and would operate at 1.8°K with a field of 0.5 tesla. The Los Alamos researchers are planning first on a 30–kilowatt-hour model (in the shape of a torus), to be followed by a 10–megawatt-hour prototype later on. The largest superconducting magnets now operating (in terms of energy storage capacity, not magnetic field strength) are those used in bubble chambers, such as the big European bubble chamber (BEBC) magnet at CERN in Geneva. The BEBC magnet has a storage capacity of about 220 kilowatt-hours.

The large size of the superconducting magnetic storage plant means that there may be a need for extra power transmission lines, if large storage facilities are located far from the areas they serve. There could be superconducting storage facilities close to cities, however, since there is some flexibility in locating the storage site. Except for the possible influence of the magnetic field, which should be minimized by placing the storage unit underground, environmental effects ought to be small. The often expressed fear of what happens to the stored energy if the superconductor fails (goes normal) apparently can be assuaged if cryogenically stabilized superconductors are used. The term "cryogenically stabilized" means that even if the superconductor fails, the adjacent metal, usually copper or aluminum, can safely carry the current in the magnet. As was expressed by R. W. Boom of the University of Wisconsin, one builds an aluminum magnet, then short-circuits it with a superconductor. The heat that would be generated by the passage of the magnet current through the copper or aluminum in the event of failure of the superconductor can be dissipated via the structures supporting the magnet.

A number of questions still remain to be answered, however, and magnetic storage is rated by many as an exotic technology whose impact will not be felt for some time.

A proposal to store energy in rapidly rotating flywheels is eliciting much attention (*3*). The principle of the flywheel is thought to have been known for several thousand years, and the potter's wheel is the example given to support this contention. Flywheels are now being used in such diverse applications as automotive engines and synchrotrons.

The energy stored in a rotating flywheel is given by $W = \frac{1}{2} I \omega^2$, where W is the stored energy, I is the moment of inertia of the flywheel, and ω is the angular frequency (radians per second). Thus the stored energy can be increased both by increasing the mass of the flywheel and increasing its angular velocity, and, in principle, flywheels of any desired capacity could be built, if it were not for the limits implied by the finite strength of the flywheel material. When the stresses in the flywheel exceed its strength, the wheel will fail, with possibly catastrophic results. Up to now, most flywheels have been made of steel, but because of the fear of the results of large chunks of steel loosed from a failed flywheel, they have been operated at such low speeds that their usefulness has been limited. Even so, experiments with such flywheels to power trolleybuses in San Francisco and for braking and acceleration of subway cars in New York (regenerative braking) are under way.

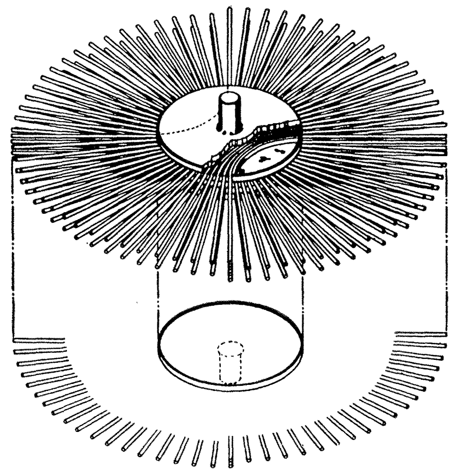

Fig. 1. Proposed superflywheel in the fanned circular brush configuration. The flywheel is not solid, but is made up of many long, thin fibers or rods. A flywheel 8 meters in diameter might be composed of rods less than 1.2 centimeters thick and weighing about 2.2 kilograms. [Source: David Rabenhorst, Johns Hopkins University]

The real future for flywheels, however, appears to depend on a new class of materials that have unidirectional mechanical properties (*4*). These materials often are made in the shape of long thin fibers or they are fibers embedded in a lower strength matrix. David Rabenhorst of Johns Hopkins University's Applied Physics Laboratory, Silver Spring, Maryland, has been an enthusiastic proponent of these superflywheels, as he terms them. A wide variety of materials, including steel wires, boron filaments, fiberglass, Kevlar (a new organic material from the DuPont Company), carbon fibers, bulk glass, and wood, could be used. Because of the relatively exotic nature of many of these materials, costs could be high. Future superflywheels might, however, become more competitive in cost through the use of low-cost ballast materials, according to Rabenhorst. (Ballast materials are used to add weight to the flywheel, but do not contribute any strength.)

Unlike previous flywheels, which have been solid disks, the likely configuration of the superflywheel would be either the fanned circular brush configuration (Fig. 1) or a multirim configuration in which the fibers are arranged in consecutive hoops of successively larger radii. Both configurations take advantage of the unidirectional properties of the fibers.

A utility peak power storage facility composed of superflywheels could offer a number of advantages, say flywheel proponents. Electric power generated during off-peak hours could be used to increase the rotational speed of the storage flywheel. During peak demand hours, energy could be withdrawn from the flywheel. Flywheels make little noise, emit no pollutants, and can be made with any desired storage capacity. They can therefore be put close to the load. The estimated storage efficiency of a flywheel system is 80 to 90 percent. Flywheels could also be a power source for automobiles and other vehicles. Vehicle-sized flywheels may be able to be recharged in a matter of minutes, whereas batteries require several hours; they are projected to achieve a much higher specific power (a few hundred watts per kilogram) than batteries, so that vehicle acceleration would be improved. However, flywheels probably will not be able to achieve the specific energy of advanced batteries, thus limiting vehicle range. Even so, it may be necessary to use a small flywheel in series with a battery to achieve the required specific power.

So far, no superflywheels have been built. Although some testing of materials has begun and flywheel development is under way at the Johns Hopkins laboratory, the ultimate costs, efficiencies, and engineering designs of flywheel systems are still theoretical. Hence, some observers suggest that widespread use of flywheels is still far in the future.

Hydrogen has received a good deal of attention in the context of the "hydrogen economy" in which, for example, hydrogen could be generated by electrolysis with the use of electricity generated by nuclear power plants; then the hydrogen could be stored or transported to appropriate sites via pipelines; and at the load site the hydrogen could be used directly as a fuel, or could be converted back to electricity via fuel cells or high temperature turbines (*Science*, 24 November 1972, p. 849). It is possible, however, to envisage a less grand scheme that would permit hydrogen to act as a storage medium both for utility load leveling applications and as a fuel for vehicles. Scientists at the Brookhaven National Laboratory, Upton, New York, are studying one such concept (*5*). Hydrogen can be stored with the use of metals. When pressurized hydrogen gas comes in contact with the metal surface, it readily diffuses into the metal and forms a metal hydride compound. Although a number of metals, usually alloys, have been and are being investigated, a 50 atom percent iron–50 atom percent titanium alloy appears to be the most attractive so far, primarily because of its lower cost. The hydride formation is exothermic, so the heat generated during the reaction must be carried away. Later, when hydrogen is desired, heat can be applied to the metal hydride, and hydrogen is evolved. The temperatures involved, both when the hydrogen is stored and when it is released from the hydride, are close to the ambient temperature. (Storage of hydrogen in liquefied form or compressed in storage tanks also has been proposed.)

Hydrogen stored as hydrides could be used in an electric power storage plant if the power generated during off-peak hours were used to electrolyze water into hydrogen and oxygen. During the peak-demand hours, the hydrogen could be recovered and used to power fuel cells. The Brookhaven workers will soon be designing just such a prototype storage facility, although how to reconvert the hydrogen to electrical power has not yet been decided. The present objective is to construct a 2–megawatt-hour prototype storage plant, with a 50– or 100–megawatt-hour facility being a later goal. Already a prototype hydrogen reservoir capable of storing 6.4 kilograms of hydrogen has been constructed at Brookhaven and will be undergoing testing by the Public Service Electric and Gas Company of New Jersey to study the feasibility of storing off-peak electrical energy.

One difficulty with hydrogen for storing electrical energy is that the overall efficiency of systems based on available fuel cells is only about 40 percent. Fuel cells are also expensive and short-lived (*Science*, 22 December 1972, p. 1273). Improvements in fuel cells operating on pure hydrogen are projected to permit system efficiencies of the order of 65 percent, which would make them more attractive. The alternative—converting hydrogen to electrical power via high temperature turbines—also is awaiting advances in technology. But minimizing the cost and maximizing the efficiency of the hydrogen production process may still pose problems, according to some observers.

The possibility of using solar energy (or some other intermittent energy source) brings with it its own energy storage problem. Here the question is one of matching the energy available only during sunny daylight hours to the demand that continues during cloudy days and at night. Solar energy has been proposed both for space heating or cooling individual homes, and for generating electricity in central power plants (*Science*, 22 September 1972, p. 1088). Except for those solar energy schemes that rely on photovoltaic cells, energy storage is most naturally accomplished via storage of thermal energy, since heat is the usual quantity that is collected. Facilities based on collection of solar energy via photovoltaic cells, which generate electricity directly, would require electrical storage systems, such as storage batteries or any of the several other alternatives.

Two Ways to Store Heat

Thermal storage can be accomplished in one of two ways. The sensible heat method works by simply heating up some object which can be thermally insulated from its surroundings. When the heat is required, a suitable working fluid is passed by the heated object, and the heat is carried away. Heat can be more easily stored if the temperature of the object in which the heat is stored is not too different from that of the surroundings; thus it is desirable to use objects with a large heat capacity as the storage medium. Among the many materials used for sensible heat storage are water, rocks, and metals, such as sodium (in liquid form). Disadvantages of this way of storing thermal energy are that the storage medium takes up a lot of space and that heat cannot be stored for long periods effectively. For example, Mason Watson of the Aerospace Corporation, El Segundo, California, noted that a study of the feasibility of a solar energy plant to generate power in the Southwest, with liquid sodium being both the storage medium and the heat transfer fluid, included estimates that about 1 million cubic meters of sodium would be required to accommodate 10 hours of storage. Because storage periods longer than 10 hours were found to be impractical, solar power plants using sensible heat storage might best serve as a supplemental daytime source of power (intermediate power) rather than as a primary or base load source.

A second method of thermal storage makes use of the latent heat associated with a phase change, such as the transition from a solid to a liquid (melting). Thus, collected solar heat can be stored by melting the solid storage medium, and can be recovered by allowing the liquid storage medium to solidify. The primary advantage of this method of thermal storage as compared to the sensible heat method is that a great deal more heat can be stored in the same volume of material. For example, Glauber's salt ($Na_2SO_4 \cdot 10H_2O$), a much-studied heat-of-fusion material, when storing the same amount of thermal energy as water, requires only one-eighth the volume. In addition, storage occurs within a narrow temperature range near the phase transformation, rather than over the wider range of temperatures required by the sensible heat method.

Despite the much greater ability of heat-of-fusion materials to store heat, a number of problems have yet to be overcome. Many heat-of-fusion materials are expensive. They are usually corrosive, thus presenting containerization problems similar to those of high temperature batteries. Some of them have short lifetimes because they tend to decompose in various ways as they are thermally cycled. Many materials exhibit a large degree of supercooling so that they do not freeze at the expected temperature. And the problem of efficient heat transfer (from the working fluid to the storage medium) limits the effectiveness of the storage. Thus, heat-of-fusion storage is often regarded as being farther off than sensible heat storage, especially when intended for use in large electrical power plants. Sensible heat storage systems are already in use in a number of solar-heated buildings.

Probably thousands of heat-of-fusion materials have been looked at for thermal storage. Maria Telkes of the University of Delaware's Institute of Energy Conversion has extensively studied salt hydrates, such as Glauber's salt, for thermal storage in home-sized units (*6*). Another salt hydrate, sodium thiosulfate pentahydrate ($Na_2S_2O_2 \cdot 5H_2O$), is being used in the University of Delaware's Solar I experimental solar house. At the University of Pennsylvania's National Center for Energy Management and Power, where there is also interest in solar energy for use in individual homes (*7*), researchers are studying, among other materials, organic materials, such as paraffin waxes, for storage where a long cycle life is required. For the higher temperatures needed in solar energy central power generating plants, several laboratories are studying eutectic salts, such as sodium nitrate–sodium chloride.

A number of other storage options are also emerging, and observers say there will likely be several more. For example, steam generated in central power plant boilers might be stored in tanks or caverns until it is needed to run turbines. Coal gasifiers, when operational, are expected to be most efficient when operated continuously. The gas produced might similarly be stored at high pressure in caverns. A rate structure for energy that reflected the cost of energy (base load electricity is cheaper to make than peak electricity) might reshuffle consumption patterns so that the demand for energy was more uniform. Or a new storage scheme may enter the scene with the potential of becoming dominant in its field. For example, recently, J. A. Van Vechten of the Bell Laboratories, Murray Hill, New Jersey, described a thermal storage scheme where molten semiconductors were used as a heat-of-fusion storage material (*8*). Van Vechten suggested that substantial improvements in storage efficiencies (because of larger heats-of-fusion and better heat transfer) and lower costs could result from the use of semiconductors.

Despite the importance of energy storage, the activity as indicated by funding can only be described as modest. The largest advanced storage research program in the federal government belongs to the Atomic Energy Commission, which is spending about \$1.8 million this year, the largest part going toward batteries. Overall, probably less than \$10 million is being spent throughout the United States on advanced energy storage (that is, excluding pumped hydroelectric and commercial batteries). A possible consequence is that some time will pass before any of the advanced energy storage systems become available.

—ARTHUR L. ROBINSON

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The Finite Element Method: A Mathematical Revival

The ideas that underlie a means to approximate solutions to differential equations, the finite element method, were first proposed by a mathematician, the late R. Courant of New York University, in 1943, but received little attention at that time. Even when other mathematicians again proposed similar ideas in 1953, mathematicians did not develop this method of approximation. Instead, the finite element method was developed by engineers who found other approximation schemes inadequate to enable them to solve problems in structural mechanics and elasticity. The method proved highly successful when applied to these engineering problems. As it came into extensive use, its defects as well as its advantages became clear and further analysis of the ideas on which it is based became necessary. Now, however, mathematicians are studying these ideas again and, together with engineers, are applying the finite element method to some extremely difficult practical problems.

A differential equation can be solved numerically by techniques, such as finite difference methods, that are based on approximations to the derivatives of a function. Alternatively, it can be solved by techniques based on approximations to the function that satisfies the differential equation. The finite element method is a technique that allows for an approximation to such a function.

When applying the finite element method to the solution of a differential equation, analysts consider a variational form of the equation. A variational form is an expression that can be derived from certain differential equations. It consists of a sum of integrals. A function that minimizes a variational form is also a function that satisfies the associated differential equation. By enabling investigators to approximate a function that will minimize a variational form of a differential equation, the finite element method allows for an approximation to a solution to that equation.

An approximation to a function that minimizes a variational form is constructed from combinations of certain trial functions. These trial functions are defined on the region in which a solution to the differential equation is sought. The region is divided into a grid, and the divisions of the region are called elements. In a two-dimensional problem (such as the problem of describing the forces on a vibrating membrane) the elements are usually triangles or rectangles.

Each trial function is zero on all parts of the region except for one element. The various trial functions—which are simple linear functions, polynomials of low degree, or the like—are joined together at the boundaries of the grid elements. Values of the trial functions are defined at certain points (nodes) of the elements, and for a given trial function, sufficiently many nodal values are stipulated so that only one function could satisfy all of those values.

In order to use a combination of these trial functions to approximate the solution to an equation, analysts must find the combination that will minimize a variational form of an equation. They thus formulate a sum of trial functions to be substituted into a variational form, each term of the sum consisting of a trial function multiplied by a constant. The constants are undetermined when the sum is formulated. The goal is to select a specific combination of constants that will result in a minimization of a variational form when the sum is substituted into that expression. Such a collection of constants can be determined when a matrix