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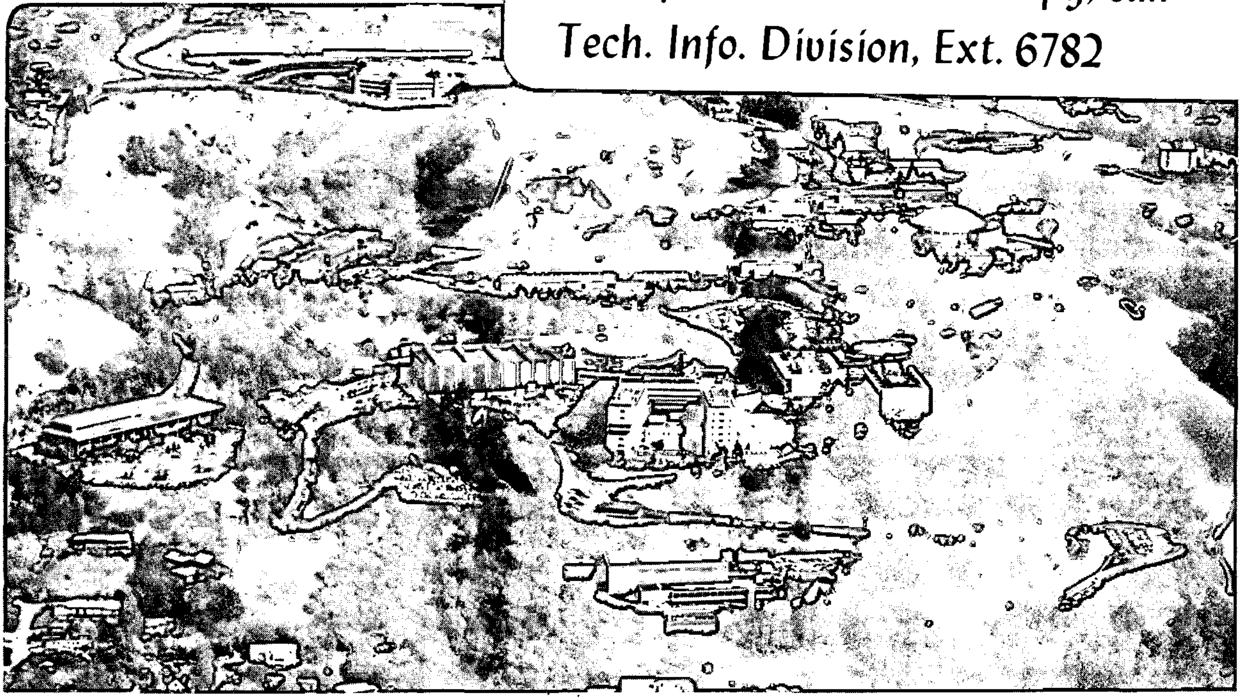

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ABSTRACT

This report describes a proposed solution to two outstanding problems in commercial-sized coal gasifiers, namely, detecting and locating any deterioration in the refractory thermal barrier and the construction of a safe pressure vessel utilizing advanced carbon fiber composite technology.

Design considerations are given for a typical gasifier some 30 feet in diameter by 150 feet tall with a maximum internal temperature and pressure of 2500°F and 1500 psi respectively.

A system of computer controlled cooling circuits is deployed between the refractory barrier and the external lightweight pressure vessel. Multiple levels of redundancy are built in to guard against any component failure. Through the sensing of coolant temperature and the modulation of coolant flow, a map of heat flux distribution over the gasifier wall may be generated with a spatial resolution of about 5 feet. It seems possible to maintain the coolant temperature rise by no more than 90°F with only a modest amount of coolant flow.

INTRODUCTION

In the coming decades, the U.S. is expected to rely increasingly on coal for a substantial fraction of its energy needs. Coal is one of nature's most important sources of energy and organic chemicals. The prudent and efficient use of this non-renewable resource is mandatory.

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Modern processes of coal conversion and combustion share a common (although to varying degrees) set of operating conditions, namely, high temperture, high pressure and a very corrosive and errosive environment. The combination of these conditions is particularly severe where very large commercial-sized coal gasifiers are to be contemplated. The question of how large these gasifiers may be scaled depends not only on process efficiency and total economy but also on the limits of material and fabrication technology. Moreover, since these giant pressure vessels are the critical components of a multi-billion-dollar operation, the questions of long term reliability and safety are of paramount importance.

Consider a coal gasifier some 30 ft. (9.1 m) in diameter by 150 ft. (46 m) tall with a maximum internal temperature and pressure of 2500°F (1371°C) and 1500 psi (10.2 MPa) respectively. These typical figures are taken as an example to illustrate the generic nature of the problems and solutions. A refractory thermal barrier is generally required to insulate the wall of the pressure vessel from the internal heat and to increase the thermal efficiency of the process by reducing heat loss. Under the full infuence of a very errosive and corrosive environment together with thermal stresses which may develop due to temperature excursions, fault conditions may eventually develop in the refractory barrier. There is, therefore, a need for continuous monitoring the heat flux over the entire refractory wall in order to detect any onset of wall deterioration. Accessibility and the capacity to withstand the hostile environment again pose difficult problems for traditional methods of areal temperature measurement using thermal couple or infrared techniques. Other methods such as temperature sensitive paints, amoung other drawbacks, lack the necessary time responsiveness[1].

A second outstanding problem relates to the difficulties faced by the conventional thick wall steel vessel technology. For a given vessel of diameter D and internal pressure P, the minimum required wall thickness X can be computed as[2]:

$$X = \frac{0.5PD}{(S/F) - 0.6P}$$

where S and F are the material tensile strength and the safety factor required respectively. With typical values of S = 80 ksi (544 MPa) and F = 4 (e.g. steel SAE-980), the 30 ft. diameter vessel under consideration will require a steel wall of 14 in. (36 cm) thick. Such a 150 ft. long cylinder would weigh 4278 tons (specific gravity 8.01 for steel) and obviously needs to be field assembled. The required plate fabrication, welding, and postweld heat treatment would clearly tax, if not exceed, the current limit of thick wall steel vessel technology. Moreover, an appropriate method for the safety inspection of such a vessel is yet to be found.

We shall attempt to take an integral approach to these two outstanding problems of continuous areal temperature monitoring and the fabrication of very large pressure vessels by considering the concept of an active thermal shield and the exploitation of high performance composite material technology[3].

"MEGACOON" DESIGN CONCEPTS

The "Megacoon" is a conceptual compound reactor construction designed as a substitute or extension of the conventional steel vessel technology. It consists of essentially two separate components which serve three functions: a lightweight fiber-wound outer cocoon which holds the pressure and a computer controlled active thermal shield which safeguards the cocoon from excess heat exposure as well as monitoring and localizing any development of hot spots from the possible degradation of the inner refractory wall.

Over the past decade, high performance carbon fiber composite materials are finding increasing applications in the military, aerospace and sporting goods industries[4]. The composite material consists of high strength carbon fibers of about 8 μm in diameter usually bonded in a matrix of thermal setting resin. The resulting composite possesses a unique combination of desirable properties which include very high tensile strength and stiffness, light weight, chemically inert, dimensionally stable, fatigue and creep resistant and ease of fabrication and shaping into required structural forms with a minimum of waste.

For example, the tensile strength and specific gravity of the Magnamite graphite AS/epoxy composite (Hercules Inc., Salt Lake City, Utah*) are

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*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

225 ksi (1.53 GPa) and 1.55 respectively. Compared with the 14 in. steel pressure vessel considered above, the equivalent wall thickness would only be 5.0 in. (12.7 cm). Combining the factor of 2.8 advantage in strength with the factor of 5.2 in density, a carbon fiber cocoon may realize a weight saving of up to a factor of 14.5 over its steel counterpart. It should be pointed out that the strength of carbon fiber is highest along the fiber axis. However, crossplied techniques may be used to achieve near isotropic properties with a tradeoff in strength by up to a factor of 2.7. Since the lines of force in a long cylindrical wall are along the circumference, maximum advantage of the fiber strength may be realized. A stress field analysis of an actual vessel of a given shape will help to optimize the manner in which fibers may be applied for maximum reinforcement with minimum additional material. The significant point is that filament winding is a cumulative and flexible process that can be readily performed in the field. Thus very large and very strong pressure vessels may be fabricated without the limitations and drawbacks of the conventional steel vessel technology.

The main disadvantage of the carbon fiber composite structure is its working temperature limit (e.g. $< 260^\circ$F or 127°C for graphite AS/epoxy). The question of adequate thermal shielding is therefore crucial.

One way of incorporating a system of active heat shields to assure the protection of the composite pressure vessel from the internal heat of a generic coal gasifier is depicted schematically in Fig. 1. As conceived, a primary and a secondary active heat shield are to be deployed between the refractory heat barrier and the composite pressure vessel. Each shield consists of an array of cooling pipes which are subjected to the same maximum pressure in the reactor but any convective contact with the hot gases is minimized. The water being circulated in the pipes will only be slightly above atmospheric pressure. There are, of course, many mixtures of optimum pipe sizes and configurations that may be chosen to suit a given set of reactor detail and temperature distribution. However, a simplistic example of uniformly spaced pipes will be given here to illustrate the principle.

Consider the cooling pipes to be, say, 6 in. (15.2 cm) in diameter. Each pipe constitutes a horizontal circle around the refractory barrier and is fed by pipes entering vertically from the end of the vessel. Each set of, for example, three pipes (labeled A1, A2 and A3 in Fig. 1) could be connected in parallel to form an individual circuit with temperature sensors and flow controllers. Thus a wall of 150 ft. high will have an array of 300 pipes forming 100 separate circuits. The neighboring sets of pipes (the A's, B's and C's) are interleaved or stacked in alternation such that if any of them fails, two thirds of cooling power will still remain at a given section of the wall. A complete system of secondary active heat shield is deployed outside of the primary system as an additional measure of redundancy and safety.

In operation, a servo system will adjust the flow velocity in each pipe such that the temperature increase $\Delta T = T_{out} - T_{in}$ between the outgoing and incoming water is no more than, say, 50°C. Therefore, if T_{in} is 20°C, the entire primary active heat shield will be maintained at under 70°C. Since convection in the heat shield area is restricted by design, the primary mode of heat transfer will be by radiation. When the refractory heat barrier is intact, the amount of heat transfer to the wall will be quite limited. For example, take the case of a maximum temperature drop of 1300°C across a 10 cm thick refractory wall that has a thermal conductivity of 120 w/cm°C, the heat loss towards the outside will be 1.56×10^4 w/m^2. The required flow velocity in the horizontal pipes to maintain a ΔT of 50°C is only 1.95 cm/sec. In the event of a failure in a certain section of the refractory barrier, the maximum radiative heat load at 2500°F (1644°K) on the primary active heat shield will be 4.14×10^5 w/m^2 and the flow velocity required to maintain the same ΔT will be 51.8 cm/sec. This corresponds to a maximum flow rate of 9.45 l/sec (150 gal/min or 20 cfm) in each of the horizontal pipes. Since the radiative heat transfer depends on the fourth power of the absolute temperature of the source, the temperature rise in a circuit of constant flow or alternatively, the increase in flow velocity in a circuit kept at constant ΔT can be a very sensitive measure of any abnormality that may develop in the refractory barrier. The location of a circuit of abnormal flow requirement will indicate the vertical height of the hot spot. The spatial resolution of course will depend on the circuit configuration. In the example considered, a resolution of about 5 ft. (1.5 m) can be achieved.

In order to locate the position of the hot spot along the circuit (its azimuthal coordinates), the computer may routinely scan each circuit by momentarily modulating the flow velocity V as idealized in Fig. 2. For example, V in circuit A is increased by a factor of two (or other appropriate factor) at time t_0 and returned to its normal flow at time t_3 as shown in Fig. 2a. For a normal circuit, ΔT will decrease linearly with time until it reaches a new equilibrium level "a" at time t_2. When the coolant is modulated from its normal flow rate, the rate of temperature change in approaching a new equilibrium is proportional to the rate of heat input per unit length along the conduit. Thus, a hot spot would give rise to an abrupt change in the ΔT vs. t plot as indicated by "c" at time t_1 in Fig. 2c. The time it takes the coolant to complete the flow circuit from the inlet temperature sensor to the outlet one is $t_2 - t_0$; therefore the determination of t_1 is the same as locating the hot spot along the flow circuit. If the hot spot is closer to the water inlet, t_1 will be proportionally closer to t_2. Similar arguments apply to the situation when the flow returns to normal level at t_3 and the location of t_4 with respect to t_3 and t_5 will be used as a check for the hot spot's circumferential position as determined during the high flow period.

It should be noted that the exact location of the hot spot can be even more readily identified by differentiating the change in temperature with time as is shown in Fig. 2d. The spikes "c'" and "d'" in Fig. 2d correspond to the signatures "c" and "d" in Fig. 2c. As a regular course of operation, the central location of these spikes may be pinpointed by additional mathematical techniques such as further differentiating Fig. 2d and locating the "zero crossing" points. With the aid of the on-line computer, a map of heat flux distribution over the entire reactor surface may be generated.

A noteworthy variation of the active heat shield described above is to devise an array of cooling pipes threaded by smaller pipes at appropriate intervals. The larger pipes are designed primarily for cooling, while the smaller ones are optimized for mapping heat flux distributions.

CONCLUSION

The preceding illustration of the generic Megacoon concept has shown that by exploiting the unique combination of desirable properties of carbon fiber composites, one may foresee a potential jump in the ultimate size at which large pressure vessels may be fabricated as compared with that achievable by conventional steel vessel technology.

We have also shown that computer controlled active heat shields may serve the dual purpose of protecting the pressure vessel and locating any onset of deterioration in the refractory barrier. The method is sensitive and provides adequately fast time response and spatial resolution. The flexibility in the mode of operation and circuit deployment strategy should provide any desired level of redundancy for safety considerations. It is noted that in the illustrating example, only a modest amount of coolant flow is required to cope with extremely high temperature exposures. This means that it is even possible to operate the gasifier with a defective refractory barrier until it is convenient to implement repair. The maintenance of the heat shields at low temperatures should make pipes and components able to better survive the corrosive service environment for long times. This is an important consideration for example, if a thin metallic barrier lines the inside of the composite pressure cocoon.

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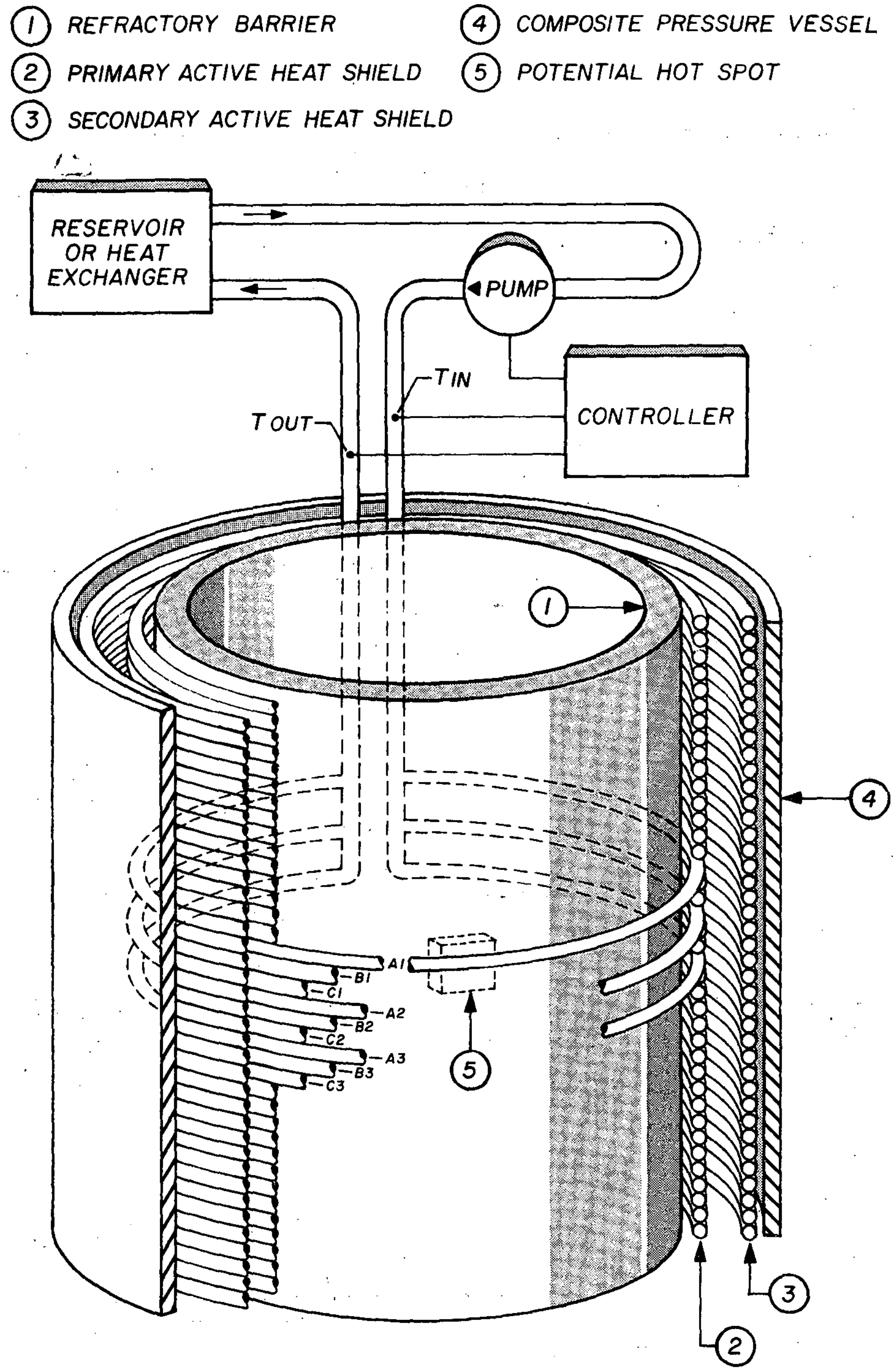

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Figure 1. A schematic illustration of a composite pressure vessel with computer controlled active heat shields.

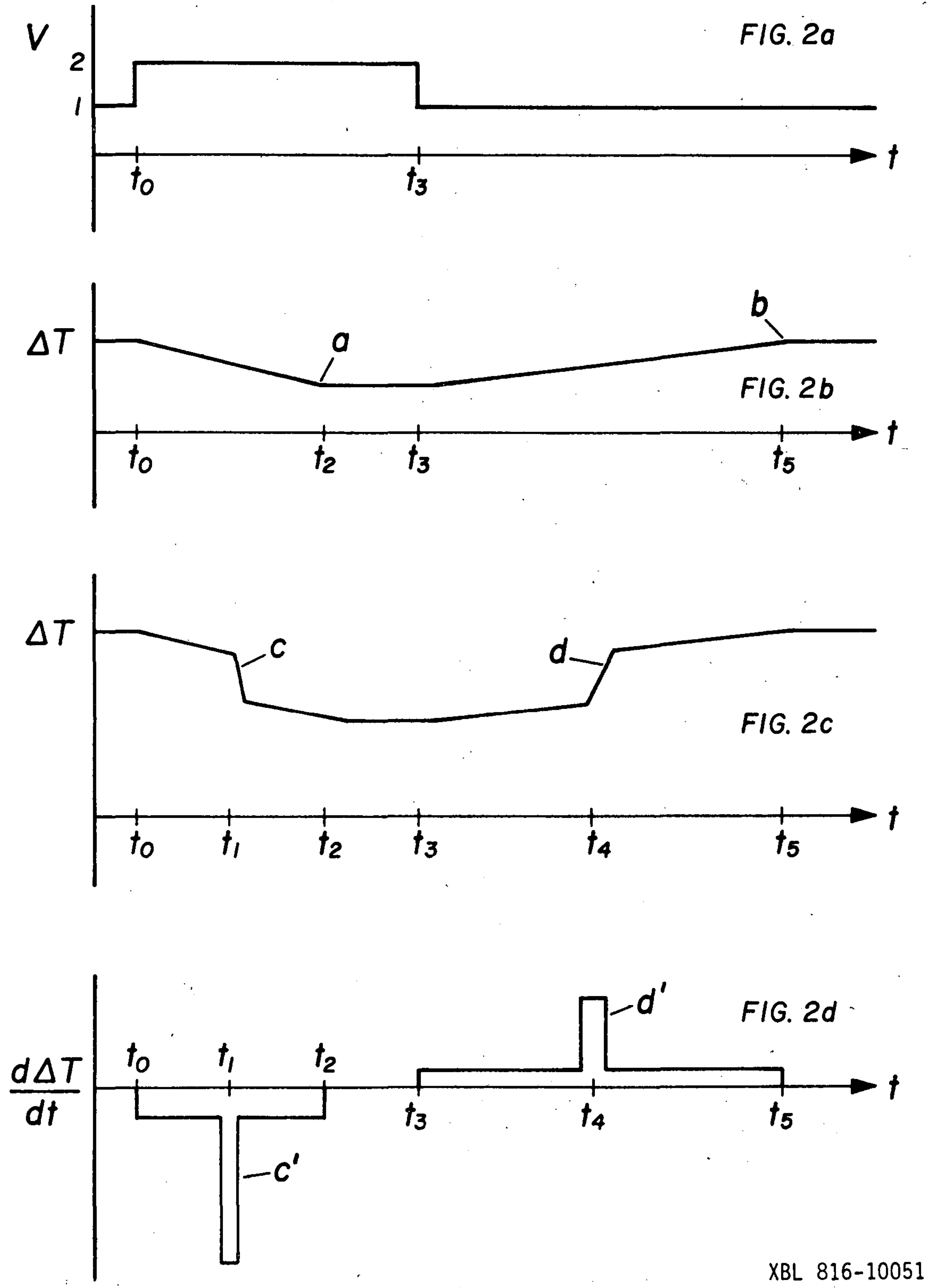

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Figure 2. Idealized time responses of coolant flow velocity and temperature differentials.

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