# MAGNESIUM AND RELATED LOW ALLOYS

by

## J. BERNARD, R. CAILLAT, R. DARRAS

Rapport C E A N° 1268

BERNARD, CAILLAT et DARRAS

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Magnesium and related low alloys.

Summary. - In the first part the authors examine the comparative
corrosion of commercial magnesium, of a magnesium-zirconium alloy
(0,4 per cent $\leq$ Zr $\leq$ 0,7 per cent) of a ternary magnesium-zinc-
zirconium alloy (0,8 per cent $\leq$ Zn $\leq$ 1,2 per cent) and of
english "Magnox type" alloys, in dry carbon dioxide-free air, in
damp carbon dioxide-free air, and in dry and damp carbon dioxide,
at temperatures from 300 to 600 °C.
        In the second part the structural stability of these
materials is studied after annealings, of 10 to 1000 hours at
300 to 450 °C. Variations in grain after these heat treatment and
mechanical stretching properties at room temperature are presented.
        Finally various creep rate and life time diagrams are
given for these materials, for temperatures ranging from 300 to
450 °C.

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Report CEA n° 1268

Magnésium et alliages faiblement alliés.

Sommaire. - Dans une première partie les auteurs étudient la
corrosion comparée du magnésium commercial, d'un alliage magnésium-
zirconium (0,4 pour cent $\leq$ Zr $\leq$ 0,7 pour cent), d'un alliage ter-
naire magnésium-zinc-zirconium (0,8 pour cent $\leq$ Zn $\leq$ 1,2 pour
cent), et d'alliages anglais "type Magnox", dans l'air sec
décarbonaté, l'air humide décarbonaté, le gaz carbonique sec et
humide à des températures de 300 à 600 °C.
        Dans une seconde partie, est étudiée la stabilité struc-
turale de ces matériaux après des recuits de 300 à 450 °C, et de
10 à 1000 heures. Sont présentées les variations, après ces
traitements thermiques, de la grosseur du grain, et des caracté-
ristiques mécaniques de traction à la température ambiante.
        Enfin, quelques diagrammes de vitesse de fluage et de
durées de vie sont présentés sur ces matériaux pour des températu-
res variant entre 300 et 450 °C.

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and Applied Chemistry,
C.E.A.   France

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– 1959 –

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# MAGNESIUM AND RELATED LOW ALLOYS

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Magnesium has a very small thermal neutrons cross-section. Moreover, it is easy to fabricate in the form of tubes or complex sections, is relatively cheap, can be welded with a minimum of precaution and forms no intermetallic compound with uranium. These features suggest it is a suitable material for uranium canning.

But from the corrosion point of view, its high chemical activity should militate against its use; in fact, in certain gaseous media and up to a certain temperature, a protective layer tends to form, which retards oxidation to a great extent. Thus the conditions of use of magnesium and its alloys in piles cooled by wet air, such as pile G.1. at Marcoule, or by carbon dioxide gas, such as pile EL.2 at Saclay, the Calder Hall and Marcoule G2–G3 twin reactors, have been specified. The large grain growth of unalloyed metal is also detrimental to its mechanical properties. However, the known ability of zirconium additions to refine magnesium grain suggested the use of alloys containing such additions, provided their corrosion resistance was satisfactory. These alloys have been subject to extensive study in France.

In what follows, three materials will frequently be mentioned and compared. These are:

(a) magnesium: except where indicated, it is commercial purity magnesium containing the following impurities, as an example:

Fe:     530 $\pm$ 50 p.p.m.
Al:     100 $\pm$ 30 p.p.m.
Cl:      35 $\pm$ 20 p.p.m.
Mn:     280 $\pm$ 20 p.p.m.
Cu:      27 $\pm$  5 p.p.m.

(b) a binary alloy Mg–Zr; this alloy made from high purity magnesium ($>99.95\%$), has a zirconium content defined as follows:

Zirconium soluble in cold dilute hydrochloric acid: $>0.5\%$
Zirconium insoluble in cold dilute hydrochloric acid: $<0.1\%$

(c) a ternary alloy Mg–Zn–Zr with the same purity, and the same zirconium content as the binary alloy, but containing in addition 0·8–1·2% Zn.

Some alloys of the British Magnox series are also reported upon. These alloys contain beryllium, and three examples of composition are given below:

|            | Be      | Ca    | Al    |
|------------|---------|-------|-------|
| Magnox 1   | 0·01%   | 0·2%  | 0·5%  |
| Magnox E   | 0·05%   | 0·1%  | 1%    |
| Magnox A12 | 0·01%   | —     | 0·8%  |

All these materials were studied in the extruded condition.

## 1. CORROSION

### 1. Methods for Corrosion Study

The study was both kinetic and morphological. The kinetic study was made by the continuous or discontinuous weighing of a metallic specimen heated in corroding gases. It was accompanied by a morphological study by microscopy and electron or X-ray diffraction, to identify the phases growing at the gas–metal interface.

The necessity for a rigorous definition, from the physico-chemical point of view, of the nature of the surfaces exposed to corrosion, is particularly important for magnesium and its alloys, and the composition of the corroding gases have to be followed very closely; thus droplets of water in the air change the type of corrosion completely, and a variable content of carbon dioxide gas in this air significantly affects the magnesium–air reaction kinetics.

### 2. Dry, Carbon-dioxide-free Air

Leontis and Rhines (1946) have shown that the oxidation of magnesium in dry air takes place in two stages: at low temperatures and at the beginning of oxidation at higher temperatures, the oxide layer is protective; when the oxide layer reaches a critical thickness, it breaks up spontaneously and the rate of oxidation then becomes linear.

Boussion et al. (1957) found that up to 400°C the oxidation of magnesium is small in dry air. The increase in weight is about 0·07 mg/cm$^2$ after approximately 300 hr of heating, but some tests lasting more than 1000 hr show the same weight increase.

According to Makolkin (1951) the oxidation rate becomes linear from 400°C. At 500°C, it is very fast, amounting 0·03 mg/cm$^2$ hr after 18 days.

The metal sublimation which takes place at 450°C (Grall, 1955) confirms that the oxide film is no longer protective at this temperature; on the contrary, the thick layers of magnesia formed insulate the reacting surface and cause acceleration of the reaction.

3. *Wet, Carbon-dioxide-free Air*

In wet air, saturated with water vapour at 25°C, the oxidation shows the same characteristics as in dry air, up to 350°C.

Above 350°C, however, the magnesia layer formed insulates the reacting surface as in the case of dry air; thus at 500°C, for example, the oxidation rate can increase from 0·1 to 0·4 mg/cm² hr in 12 hr. Moreover, from 350° to 380°C a new reaction appears, viz. the reduction of water vapour by magnesium. This agrees with the work of KUBASCHEWSKI (1947).

These results are not valid if condensation or spattering of water occur on the magnesium at low temperature; in such circumstances pitting corrosion takes place, damaging the metal much more rapidly.

As a conclusion, magnesium can be heated without danger of severe corrosion in dry air up to about 400°C, and in wet air up to 350°C.

These results are not affected by exposure to a fast neutron dose of $10^{18}$ n/cm² (DARRAS *et al.*, 1956).

4. *The Behaviour of Alloys by Heating in Air*

The alloys Mg–Zr and especially Mg–Zn–Zr do not behave better than commercial magnesium. Additions of Al, Zn and Mn have an unfavourable effect (MAKOLKIN, 1951).
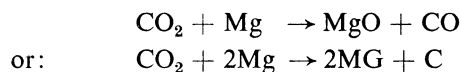
"Magnox" (HUDDLE and WYATT, 1957), however, containing at least 100 p.p.m. of beryllium, show very much better behaviour, even in wet air at 500°C. The increase in weight occurs very slowly and only reaches 0·10–0·25 mg/cm² after 3000 hr. No noticeable attack would be detected below 600°C (DARRAS *et al.*, 1955; MOORE and GOODLET, 1957).

5. *Corrosion by Oxygen and Nitrogen*

The alloys Mg–Zr and Mg–Zn–Zr show no detectable increase in weight after heating 100 hr at 400°C in nitrogen or in oxygen at atmospheric pressure. The rate of corrosion is perceptible and linear at 500°C in nitrogen (0·01 mg/cm² hr) (BOUSSION *et al.*, in press). These results are in agreement with those of MAKOLKIN (1951).

6. *Corrosion by Carbon Dioxide Gas*

According to thermodynamic data, magnesium should reduce $CO_2$, even at low temperatures, as follows:

$$CO_2 + Mg \rightarrow MgO + CO$$
$$\text{or:} \quad CO_2 + 2Mg \rightarrow 2MG + C$$
$$\text{and, secondarily:} \quad CO_2 + MgO \rightarrow CO_3\,Mg$$

In fact, a protective layer is formed and oxidation is very slow. $CO_2$ even seems to possess some inhibiting effect against corrosion by hot water vapour.

(a) *Dry carbon dioxide gas*—At atmospheric pressure, magnesium oxidation is very small, even after 1000 hr at 500°C ($\leqslant 0·02$ mg/cm²). It is the same for alloys Mg–Zr and Mg–Zn–Zr (BOUSSION *et al.*, in press). At 400°C the surface layer is essentially made of $MgCO_3$, whilst at 500°C MgO is dominant with some carbon.

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In $CO_2$ at a pressure of 15 kg/cm$^2$, the behaviours of alloys Mg–Zr and Mg–Zn–Zr are approximately identical, although the former is rather better: at 400°C the increase in weight reaches a limit near to 0·05 mg/cm$^2$, after about 3000 hr of heating; at 450°C this limit is only raised to about 0·07 mg/cm$^2$. But from 500°C, the alloy Mg–Zr is clearly better than Mg–Zr–Zn, probably owing to zinc sublimation. According to Makolkin (1951) the rate would become parabolic at 460°C, but his tests have been made over a limited period of time (100 hr maximum).

(b) *Impure carbon dioxide gas*—At atmospheric pressure the presence of a few per cent of nitrogen, oxygen or even 10% of air in the $CO_2$ has no considerable influence, even at 500°C. This suggests some inhibiting effect of carbon dioxide (Boussion *et al.*, in press).

(c) *Wet carbon dioxide gas*—The inhibiting effect is again met; for example, the alloy Mg–Zr stands up during heating at 450°C for several days in wet carbon dioxide gas, whereas under the same conditions in wet air, large pits appear (Caillat and Darras 1958).

Moore and Goodlet (1957) indicate that magnesium exhibits no notable reaction with dry $CO_2$ below 550°C, this temperature being lowered by approximately 50°C if the gas is wet. Huddle (1955) showed moreover that 10% of $CO_2$ in water vapour does away with any significant reaction, even above the melting point of magnesium. However, with some alloys, wet gas would produce pitting corrosion. Huddle (1955) also indicates that small beryllium or calcium additions to magnesium raise to more than 600°C the temperature where oxidation becomes appreciable. It should, however, be pointed out that some metallic contaminations should be avoided, such as mercury, tin, lead, bismuth, cadmium, aluminium and zinc (Anon., 1956) which can cause local perforation of magnesium sheaths.

(d) *The Magnox alloys*—For example, Magnox E could be heated at 615°C for 2500 hr in wet carbon dioxide gas, without failure. But the calcium addition, beneficial from the point of view of protective film stabilization, gives rise to difficulties in welding (Huddle and Wyatt, 1957).

Besides, Grainger and McIntosh (1957) showed that, with a $CO_2$ pressure of 8 atmospheres, the oxidation resistance of pure magnesium is better than that of Magnox.

(e) In conclusion, magnesium and its alloys, binary Mg–Zr, ternary Mg–Zn–Zr and Magnox can be used, from the corrosion point of view, in carbon dioxide gas cooled reactors, where the temperature of the can may reach at least 400°C.

## 7. Ignition Temperatures

Fassel *et al.* (1951) have determined ignition temperatures of magnesium and some of its alloys in oxygen. In air, their results are not very reproducible.

Some determinations have been made in various atmospheres by Darras *et al.* (to be published). Table 1 shows some results. The carbon dioxide pressure little affects the ignition temperature in this gas. But it is known that contaminating metals, such as copper, tin, silver, lead, antimony, aluminium and bismuth lower the ignition point.

*Table* 1

| Metal or alloy | Gaseous medium | Ignition temperature (°C) | Reference |
|---|---|---|---|
| Mg EMCO | Oxygen | 623 | |
| Mg + 1% Ca | Oxygen | 624 | FASSEL *et al.* |
| Mg + 3% Zn | Oxygen | 595 | (1951) |
| Mg − 5% Al | Oxygen | 558 | |
| Mg commercial French | Dry air | 630* | |
| Mg commercial French | Wet air | 610* | |
| Mg commercial French | Dry CO$_2$ | >800 | |
| Mg commercial French | Wet CO$_2$ | 650 | DARRAS *et al.* (to be published) |
| Magnox Be 115 p.p.m. Al 0·5% Ca 0·15% | Wet air | 620† | |
| Mg–Zr | Dry CO$_2$ | >800 | |
| Mg–Zr | Wet CO$_2$ | 660 | |

* "Self heating" could cause ignition above 550°C (MOORE and GOODLET, 1957) (DARRAS *et al.*, to be published).

† Some Magnox alloys could be melted in air without burning (MOORE and GOODLET, 1957).

## 2. GRAIN SIZE

The grain size of unalloyed magnesium grows considerably when maintained at pile operating temperatures of the order of 400°C.

ENGLANDER and LANIESSE (unpublished report) have shown that the fine homogeneous structure of the metal as drawn has polyhedral grains of 25–30 $\mu$, which grow rapidly from 350° to 450°C.

This increase in size is most rapid in the first 100 hr, and the structure becomes heterogeneous (grains of a few millimetres and of a few tens of microns).

After 1000 hr the structures are a little less heterogeneous but the maximum diameter changes little.

The purity of the metal does not seem to be an important factor since the same behaviour is shown by metals between 99·8 and 99·96% pure.

It has been known that zirconium can reduce the grain size of magnesium and reduce grain growth on heating. From this point of view, therefore, the alloys Mg–Zr are *a priori* attractive, although the increase of the grain size which may occur during heating under conditions of its use, should not be prejudicial as in the case of magnesium.

Figure 1 shows the increase of the number of grains per square millimetre, as a function of time, for these three materials heated at 350°, 400° and 450°C.

In the alloys Mg–Zr and Mg–Zn–Zr, defined at the beginning of this report (grain size in the initial state; 14–16 $\mu$), it is noted that the increase in grain

size is different but does not prevent the use of either alloy. In all the cases, between 350° and 450°C, grain growth takes place most significantly in the course of the first 100 hr but the polyhedral structure of these alloys develops homogeneously. After heating for 1000 hr at 450°C the grain size is increased by a factor:

$$150\text{--}200 \quad \text{for Mg}$$
$$4 \quad \text{for Mg--Zr}$$
$$1\cdot5\text{--}1\cdot6 \quad \text{for Mg--Zn--Zr}$$

## 3. MECHANICAL BEHAVIOUR

All the characteristics mentioned under the title are taken from various unpublished reports by BERNARD, BOUDOURESQUES and GAUTIER of the Commissariat à l'Energie Atomique.

### 1. Tensile Strength

(a) *As a function of the temperature*—The mechanical characteristics under load (ultimate tensile strength, conventional elongation to rupture and reduction in yield strength area) as a function of temperature on unalloyed magnesium, Mg–Zr and Mg–Zn–Zr, in the extruded condition, are similar for these three materials. As an example, Fig. 2 shows the variation of their ultimate tensile strengths as a function of temperature.

For the binary alloy Mg–Zr the variation with the temperature of the three principal tensile characteristics is shown in Fig. 3.

(b) *Influence of long period annealing on the room temperature tensile characteristics*—The three materials of these tests are affected by annealing for a long time at an elevated temperature (350°–450°C). Their ultimate tensile strength and their elastic limit at room temperature decrease substantially. This reduction which, for heating periods of short duration (10 hr), is most perceptible in the unalloyed metal, becomes fairly marked after 100 hr in all three materials (Fig. 4).

For any annealing the reduction in elongation to rupture is always relatively greater than the reduction in the ultimate tensile strength. Figure 5 illustrates this in the case of Mg–Zr annealed at 400°C. For this same material, the elongation to rupture is lowered after an annealing of 100 hr: by half (from 24 to 12%) if annealing takes place at 400°C, and by two thirds (from 24 to 8%) if annealing is at 450°C.

If the relative reduction is in the same ratio for magnesium, the disadvantage is more serious since unalloyed metal, annealed under the same conditions (100 hr at 450°C) only retains at room temperature a very small elongation to rupture (about 2%), which can constitute a serious risk in utilization.

The variation in the mechanical properties after prolonged annealing at high temperature is a corollary of the variation of grain size. Accordingly, if the mechanical characteristics—for example, ultimate tensile strength and elongation to rupture are related to the corresponding grain sizes, results are obtained such as those of Fig. 6 for the Mg–Zr and Mg–Zn–Zr alloys.
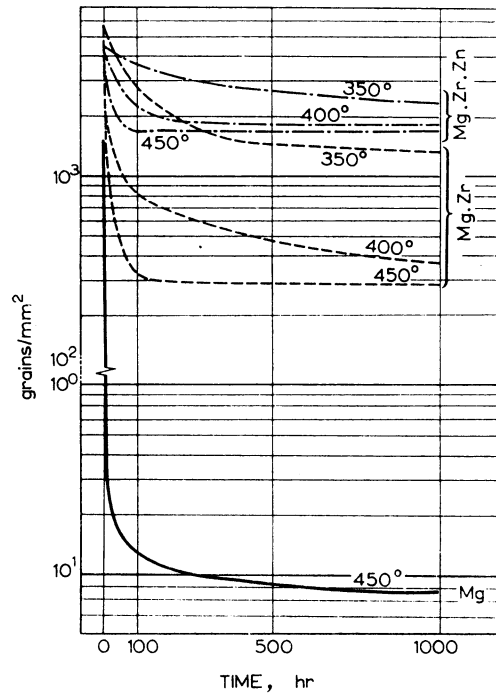
Fig. 1. Mg, Mg–Zr and Mg–Zn–Zr: change in the number of grains per square millimetre as a function of heating time at temperatures of 350°, 400° and 450°C.
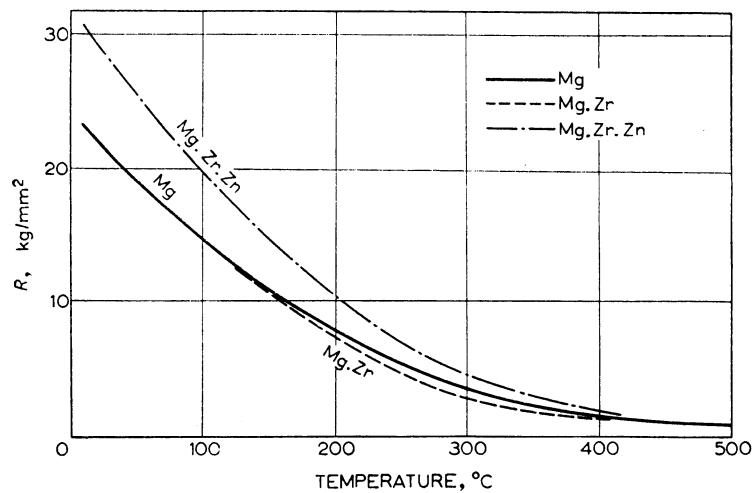


Fig. 2. Mg, Mg–Zr and Mg–Zn–Zr; variation of ultimate tensile strength as a function of temperature.
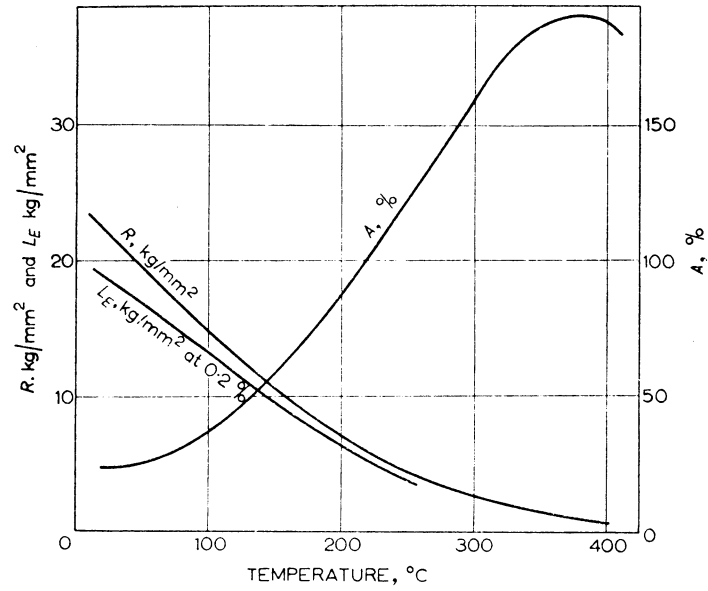
Fig. 3. Mg–Zr: variation as a function of temperature of the ultimate tensile strength ($R$) of the conventional elastic limit at $0.2\%$ $L_{E0.2}$ and the elongation ($A$) to rupture.
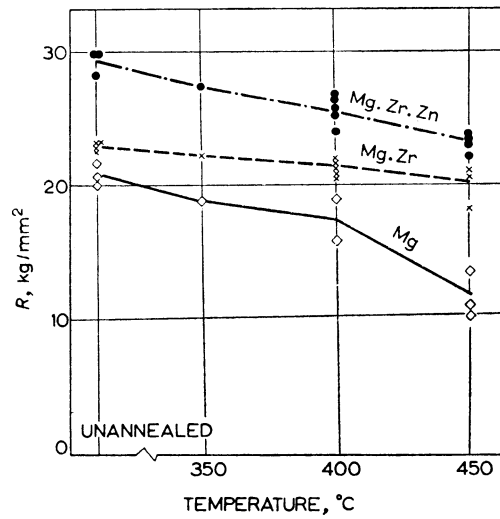


Fig. 4. Mg, Mg–Zr and Mg–Zn–Zr: influence on the ultimate tensile strength at room temperature of annealing for 100 hr at 350°, 400° and 450°C.

Fig. 5. Mg–Zr: influence on the tensile characteristics at room temperature of annealing for various times (9, 100 and 1000 hr) at 400°C.



Fig. 6. Mg–Zr and Mg–Zn–Zr: stresses and elongations to rupture as a function of the number of grains per square millimetre.

## 2. Capacity for Localized Deformation

When considering the application of an alloy as a sheathing material, it is an advantage for two reasons to know the capacity of this material for supporting a localized deformation.

(a) the technique itself of sheathing presupposes in general a certain formability of the sheathing metal.

(b) the sheath in use must be able to support, without serious risk, deformations due to localized pressures, exerted by the underlying uranium (radiation effect).

To fulfill these two requirements, two series of tests have been made:

(a) *Cupping test at room temperature*—We have noted the values of the punch force ($P$, kg) at the time of fracture for sheets (of 1 mm thickness) of each of the three materials considered, as well as the corresponding depth of cup ($I$, mm). (PERSOZ and ERICKSEN tests.)* The punch had a radius of 10 mm in its hemispherical part. The results in Table 2 show the alloys to have a better punch force at room temperature than the unalloyed metal.

*Table* 2

|          | Persoz test | | Ericksen test | |
|----------|-------------|--------------|----------------|--------------|
|          | $I_p$ mm | $P_p$ Kg | $I_E$ mm | $P_E$ Kg |
| Mg       | 4   | 130 | 2·8 | 150 |
| Mg–Zr    | 7·5 | 380 | 5·6 | 420 |
| Mg–Zn–Zr | 5   | 240 | 3·8 | 240 |

(b) *Capacity for localized deformation as a function of the temperature*—To simulate the kind of action which local pressures of the fuel might exert, a piercing test has been made a follows: the hemisphere at the end of the punch for the stamping test had a radius of 1 mm, which pressed on an unfixed sheet of thickness 1 mm. The opening of the lower bed had a diameter of 10 mm.

Under these conditions, the deformation force was exerted locally and avoided a yielding of the whole of the specimen. These tests were of short duration.

Figure 7 shows the variation as a function of temperature of the loads causing the break under these conditions and Fig. 8 the yields at the instant of fracture.

Bearing in mind the very small diameter of the punch used, one concludes that the capacity for deformation before breaking is good enough for the proposed application of these materials. With these materials the risk of fracture of the sheath by the effect of local growth of the fuel is small since in practice such deformations develop progressively and make it possible for the material to adapt itself by creeping under the action to which it is subjected.

* In the Persoz test the sheet is secured on its periphery on a diameter of 30 mm, whereas in the Ericksen test it is free.
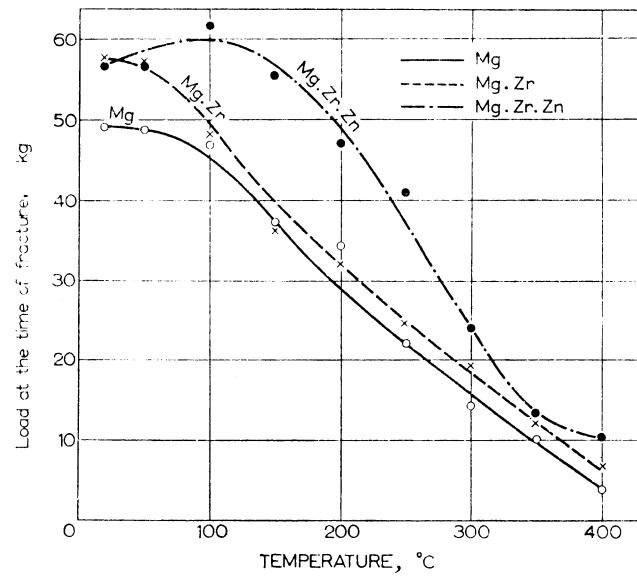
Fig. 7. Mg, Mg–Zr and Mg–Zn–Zr: variation, as a function of temperature of loads to fracture by penetration of a punch (end hemisphere: dia. 1 mm) in an unfixed sheet (thickness 1 mm) resting on a hollowed out support (opening dia. 10 mm).
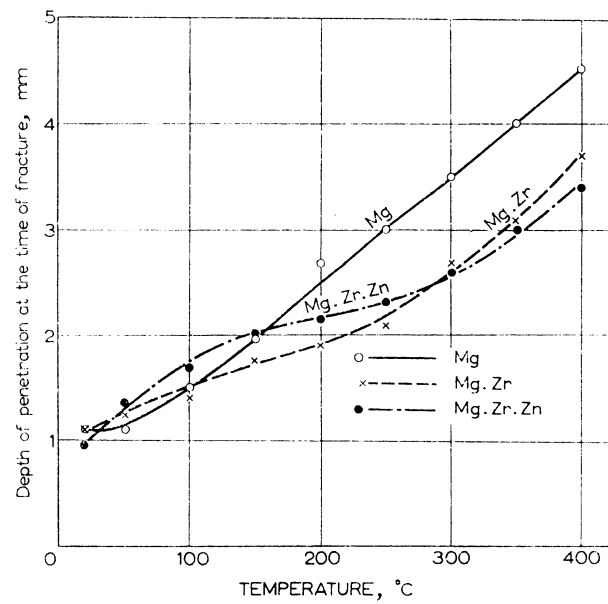


Fig. 8. Mg, Mg–Zr and Mg–Zn–Zr: variation as a function of temperature of the yield at the instant of fracture (see Fig. 7).
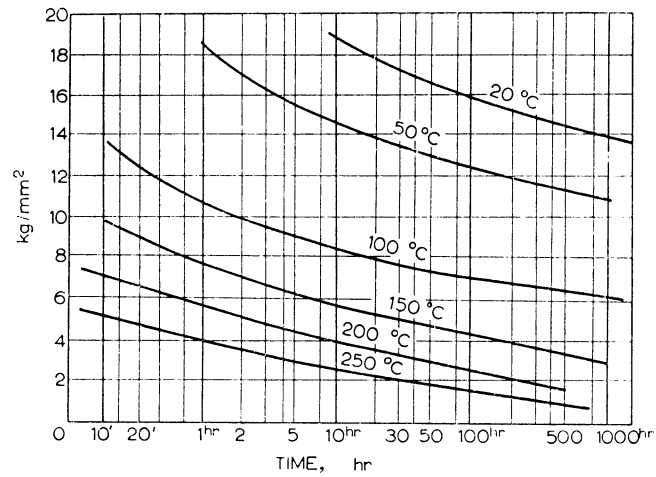
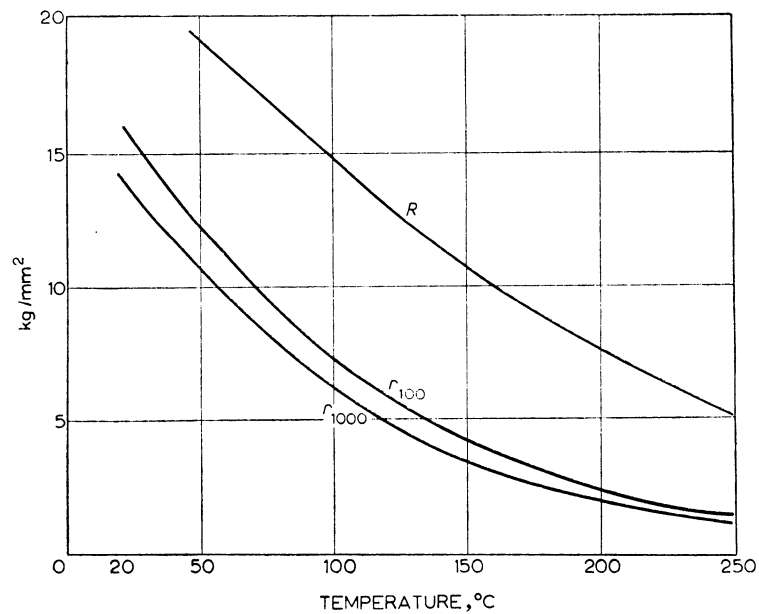Fig. 9. Mg: time to rupture as a function of stress, at temperatures of 20°–250°C.



Fig. 10. Mg: stress, as a function of temperature which causes rupture:
instantaneous $(R)$; after 100 hr $(r_{100})$; after 1000 hr $(r_{1000})$.

## 3A. Creep Behaviour Magnesium

(a) *Time to rupture*—The time to rupture of the unalloyed metal, under variable stresses is shown in Fig. 9 for temperatures ranging from 20° to 250°C.

If stresses causing rupture in a given time—100 and 1000 hr for example—are compared with stresses causing instantaneous rupture, the important influence of the duration of application of the load on the conditions of rupture is realized. This is illustrated by Fig. 10 and Table 3, at temperatures from 20° to 250°C.
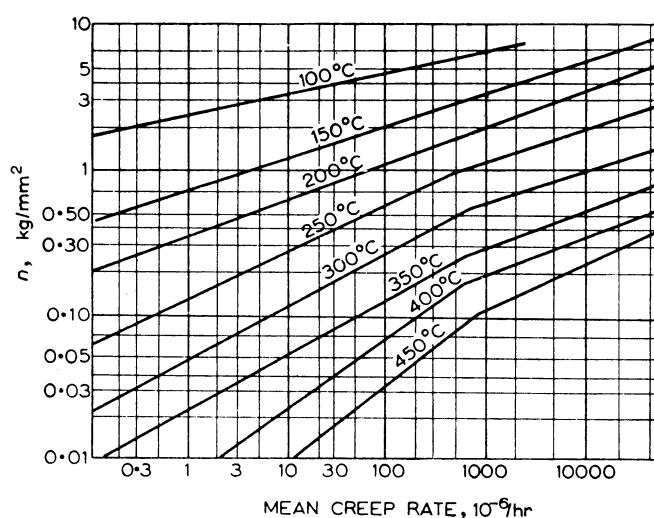


MEAN CREEP RATE, $10^{-6}$/hr

Fig. 11. Mg: diagram of mean creep rates as a function of stress at temperatures of 100°–450°C.

The effect of the time of application of the load is the more marked the higher the test temperature.

*Table* 3

| Temperature °C | Stress in kg/mm² at rupture | | |
|---|---|---|---|
| | Instantaneous $R$ | In 100 hr $r_{100}$ | In 1000 hr $r_{1000}$ |
| 20 | 21·9 | 16 | 14 |
| 50 | 19·1 | 12·2 | 10·7 |
| 100 | 14·7 | 7·1 | 6 |
| 150 | 10·6 | 4·1 | 3 |
| 200 | 7·6 | 2·3 | 1·6 |
| 250 | 5·1 | 1·5 | 0·9 |

(b) *Creep rate*—Figure 11 shows the curve of the mean creep rate for temperatures ranging from 100° to 450°C. It can be seen that an elongation of 1%

in 1000 hr (mean creep rate $= 10^{-5}$/hr) is obtained at high temperatures under very low stress as shown below:

| Temperature (°C) | Order of magnitude of the stress (g/mm²) |
|---|---|
| 300 | 120 |
| 350 | 53 |
| 400 | 23 |
| 450 | 10 |

A peculiarity is to be pointed out in the creep behaviour of unalloyed magnesium in the course of a creep test of long duration, two successive distinct regimes of linear flow as a function of time were noted. (We would remark that this is neither a slow transient creep nor a premature reacceleration.) The mean rates corresponding to these two linear laws of viscous flow differ by about a factor two in the course of the same test, at a given temperature, under weak stress the regime with smallest creep rate appears first, but the opposite is true under large stress. This is illustrated in Fig. 12 where the variations of creep rates (instantaneous) are shown as a function of stress after 100 and 1000 hr for different temperatures.

(c) *Creep elongations*—If one notes the total elongation due to creep under the same stress at various temperatures, it can be shown that, even at moderate temperatures, a rise of temperature brings with it a large increase of the elongation due to creep (Fig. 13); for example, with an increase in temperature of 100°C, the elongation due to creep grows on average: by a factor 30, from 200° to 300°C, under 0·5 kg/mm², and by a factor 100, from 150° to 250°C, under 1 kg/mm².

### 3B.  *Creep Behaviour: Alloys* Mg–Zr *and* Mg–Zn–Zr

The binary and ternary alloys have a creep behaviour (time to rupture, creep rate and elongation) very similar to that of unalloyed magnesium.

As an example, the curve of mean creep rate of the alloy Mg–Zn–Zr in Fig. 14 can be compared with Fig. 11 for magnesium.

In a general way, one can say that, from the point of view of creep resistance, these alloys show an advantage of approximately 50°C when compared with the unalloyed metal, for moderate temperatures; for example, Mg–Zr and Mg–Zn–Zr at 350°C are similar to magnesium at 300°C. Above these temperatures, the behaviour of these three materials tends to merge. Their behaviour is practically identical at 450°C.

However, at temperatures above 400°C none of these materials can claim to be creep resistant. When they are used in this temperature region their subjection to an appreciable stress must be avoided. In Fig. 15 the curves of creep from four tests of each of the three materials subjected to the same stress of 16 g/mm² at 400°C, in an atmosphere of $CO_2$ are shown. Bearing in mind the very small value of the applied stress one can say that creep is important at this temperature.
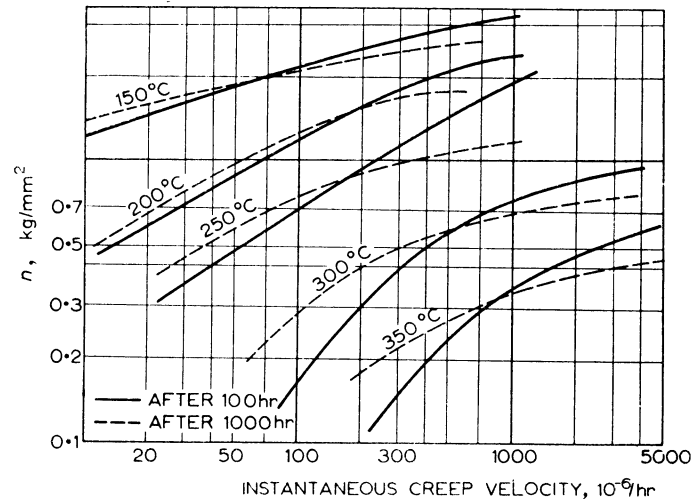
Fig. 12. Mg: instantaneous creep rate at the 100th and the 1000th hour, as a function of stress, at temperatures of 150°-350°C.
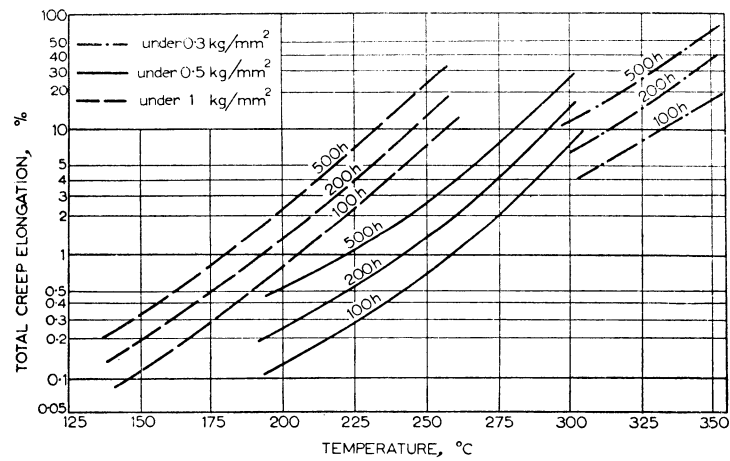


Fig. 13. Mg: total elongation after 100, 200 and 500 hr due to creep, as a function of the temperature, under stresses of 0·3, 0·5 and 1 kg/mm².
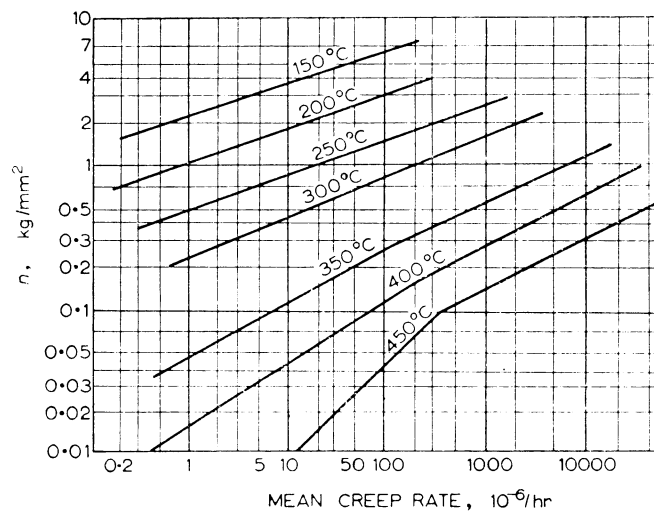
Fig. 14. Mg–Zn–Zr: graph of minimum creep rate as a function of stress, at temperatures of 150°–450°C.



Fig. 15. Mg, Mg–Zr and Mg–Zn–Zr: total elongation (including expansion) due to long period creep of specimens (four per material) subjected to a stress of 16 g/mm² at 400°C in carbon dioxide gas.

Although perceptible differences between the mean behaviour of each of the three materials is observed, the order of magnitude of their deformation due to creep is the same; i.e. elongation reached in 3000 hr is 0·6–3 % for all twelve tests.
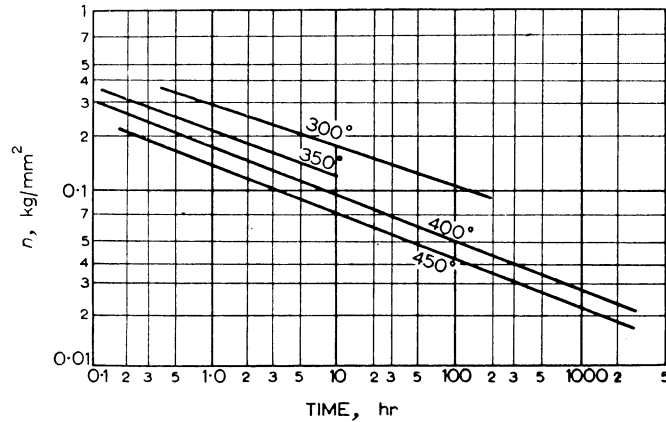


Fig. 16. Mg–Zr: graph of stresses which, at temperatures of 300°–450°C, cause as a function of time, a total creep elongation of 1 %.
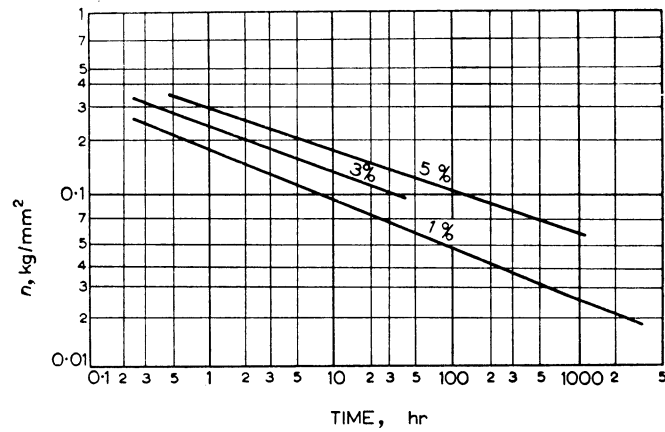


Fig. 17. Mg–Zr: graph of stresses which, at 400°C, cause as a function of time, total creep elongations of 1, 3 and 5 %.

Thus with regard to the laws of creep for the binary alloy Mg–Zr as represented above, Fig. 16 shows curves of stress which, at temperatures of 300°–450°C cause a total creep elongation of 1 % as a function of time and Fig. 17 shows curves of stress which at 400°C cause creep elongations of 1, 3 and 5 % as a function of time.

### 3C. Creep Behaviour: "Magnox" alloys

Without wishing to go into detail on the mechanical behaviour of the alloys of the British series "Magnox", we feel it useful, as a comparison with the materials
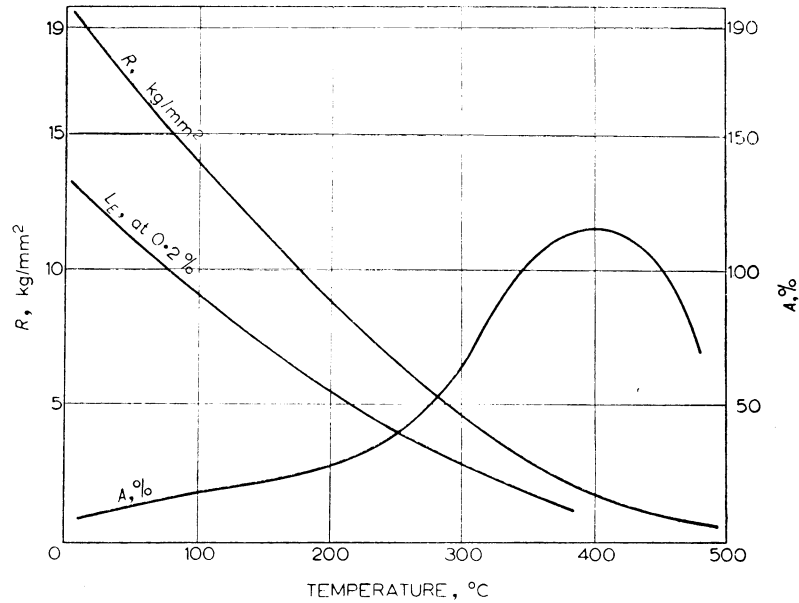


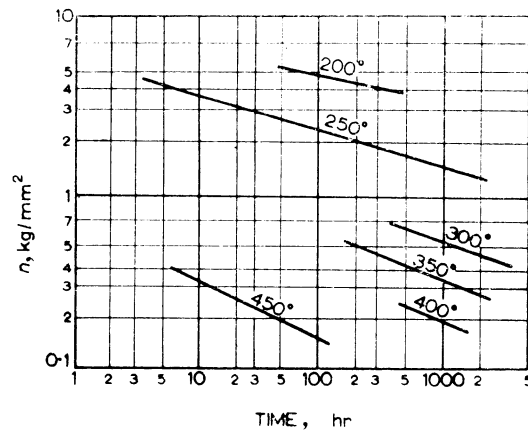Fig. 18. Magnox: tensile characteristics, as a function of the temperature.



Fig. 19. Magnox: duration of time to rupture as a function of stress, at temperatures of 200°–450°C.

mentioned up to now, to show a few high temperature characteristics of one of the alloys of this family. The Magnox in question has a composition: calcium $1 \pm 0.1\%$ aluminium: $0.82 \pm 0.1\%$ beryllium $0.02 \pm 0.003\%$.

The tensile characteristics as a function of temperature (Fig. 18) of this alloy in the drawn state are very similar to those of the three materials considered above and are found in practice to be between those of magnesium and its two Zirconium alloys. With regard to creep behaviour at high temperature (from
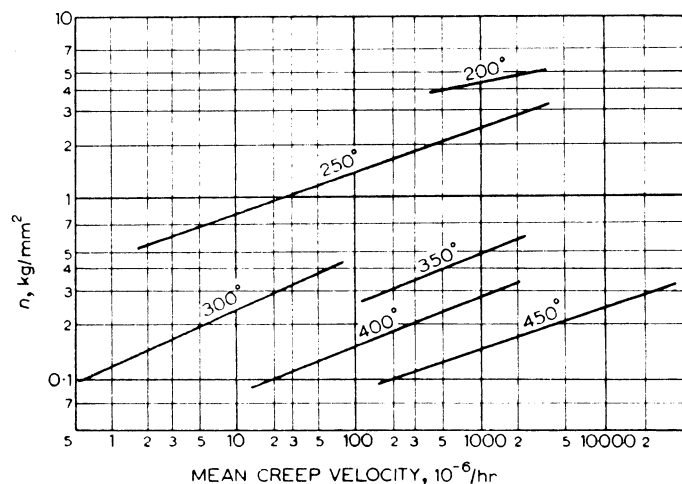


Fig. 20. Magnox: graph of minimum creep rate as a function of stress, at temperatures of 200°–450°C.

200°–450°C) this is illustrated by Fig. 19 which shows the time to rupture, and Fig. 20 the mean creep rate.

The creep behaviour of this magnox alloy agrees with that for the alloys Mg–Zr and Mg–Zn–Zr.

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