The Role of Light Metals in Nuclear Engineering

M. K. Asundi

ALUMINIUM, magnesium and beryllium have been used extensively in research and power reactors chiefly because of their low neutron absorption properties. In this respect, beryllium is superior to magnesium and aluminium. While aluminium and magnesium are used as canning and structural materials, beryllium has been used mainly as reflector and moderator, although attempts are being made to employ it for canning also.

The primary functions of fuel element cans in a reactorare : (*a*) to protect the fuel from corrosion and (*b*) to prevent the fission products from contaminating the coolant. Simultaneously the cans should also act as extensible envelopes to accommodate dimensional changes occurring in the fuel due to irradiation and thermal fluctuations. In the case of finned fuel elements, the material should also possess sufficient creep resistance at operating temperatures to withstand the coolant pressure on the heat transfer fins. Other equally important requisites of the cans are good compatibility with fissile material and coolant media and adequate corrosion resistance.

For structural components, such as end supports, spacer units and bracing sections, the specifications are that they should have low absorption cross-section, low geometric cross-section (to avoid disturbance to the coolant flow) and good mechanical strength. Creep behaviour and thermal cycling characteristics have to be taken into consideration in the final selection.

Nuclear properties essential for moderator and reflector are a high scattering cross-section and low absorption cross-section. Beryllium is the only metal which can be employed with advantage for such purposes.

The considerations for canning and structural components have led to a vast development of aluminium and magnesium alloys. The difficulties in the fabrication of beryllium, added to its high cost, have restricted its extensive utilisation in reactors in spite of its excellent nuclear properties. An account of the merits of these metals and their alloys, developed specifically for such purposes, is given in the sequel.

Aluminium and its alloys

The choice of aluminium as a canning and structural material in the initial nuclear reactors was not surprising considering its very well developed technology and cheap availability in pure form. It has good thermal conductivity, adequate corrosion resistance in water and tolerable neutron absorption properties. At present aluminium is mostly used in experimental and plutonium producing reactors. It may be mentioned here that the fuel element for the Canada-India Reactor, now in operation at Trombay, consists of natural uranium canned in 1S aluminium. This "can" material is the purest commercially available aluminium containing at least 99·5% aluminium.

The structural components in a reactor have to withstand the mechanical load imposed by the fuel. Pure aluminium, though preferable from nuclear considerations, cannot be used as it has low creep strength. For this purpose various alloy systems have been investigated.

Aluminium-magnesium alloys

Binary alloys of magnesium and aluminium have much greater strength than pure aluminium and have improved nuclear properties. Commonly, alloys contain 1·3% and 5% magnesium. They possess good structural stability, ductility and mechanical strength. Higher percentage magnesium alloys are unsuitable as they have low ductility and have difficulty in homogenising.

Complex alloys

The creep behaviour of aluminium-magnesium alloys above 350°C is not satisfactory. Complex alloys containing copper, magnesium, iron, nickel, maganese and chromium have been developed. The high temperature creep properties of these alloys are much superior to either pure aluminium or binary aluminium-magnesium alloys. However, it is to be noted that alloying additions affect the neutron economy and therefore the choice is based on both these considerations.

Apart from the binary complex alloys, sintered and wrought products known as sintered aluminium products (SAP) have evoked considerable interest due to their remarkable creep properties. These are essentially sintered and wrought aluminium-alumina mixtures. One such product *SAP 865* containing 13·5% of oxide, has a creep rate 4,000 times less than that of aluminium

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at 300°C and stresses above 1 kilogram per square millimetre. Fig. 1 shows the creep behaviour of the various systems. The possibility of using SAP for canning purposes depends on the improvement of the ductility of these products.

Aluminium has been used as a matrix material in the fabrication of dispersion type fuel elements. The composition of core of the fuel element is a near eutectic of aluminium-uranium having about 14% by weight of uranium. The core is clad in aluminium by the picture frame technique. The structure of the core is modified by suitable hot rolling and heat treatment to give a dispersion of the UAl_4 intermetallic phase in a form suitable from nuclear considerations.

The close contact of the can with the fuel is necessary for heat transfer purposes. At the operating temperature of about 250°C, diffusion between uranium and aluminium takes place resulting in the formation of intermetallic compounds. Since these compounds have higher specific volumes and low adhesion, rupture of the can takes place. The low thermal conductivity of the compounds give rise to hot spots as well. Anodising the surface of the can prevents this reaction up to 550°C. Aluminium shows good chemical compatibility with carbon dioxide coolant up to 500°C.

The problem of aluminium corrosion is a serious limitation to its wider applications. Below 200°C aluminium and its alloys show a normal behaviour towards corrosion in distilled water. The surface reaction is rapid at the beginning but later the reaction is very low and follows a linear law (Fig. 2). Above 200°C blisters appear on the surface of the metal which increase in size as the time progresses. At 315°C, aluminium completely disintegrates in 4 hours. The formation of blisters and subsequent rapid attack on aluminium at elevated temperatures is believed to be due to the producution of hydrogen atoms in the corrosion reaction and their subsequent formation of molecules at structural defects. The molecules from pressure pockets giving rise to blistering. When the blisters rupture, fresh water will attack the metal and the process is accelerated. Aluminium-nickel alloys have been found to possess excellent resistance to blistering attack presumably because of a nickel rich second phase appearing at the grain boundaries. The corrosion behaviour of aluminium nickel alloys containing 2% and 0·5% nickel is shown in Fig. 3. It has been observed that addition of 0·5% nickel is sufficient to give good corrosion resistance. High percentage nickel alloys do not show significant improvement. Other alloys containing iron, silicon, beryllium, zirconium and titanium developed for high temperature work show good corrosion resistance. Another aspect of aluminium corrosion is the prevention of pitting. It has been observed that the corrosion resistance is seriously impaired by the presence of ions in solutions as well as by the contact with other metals. The presence of even 1 part in 10 million of copper ion in solution gives rise to pitting. This sets restrictions on the use of copper bearing alloys in the reactor components.

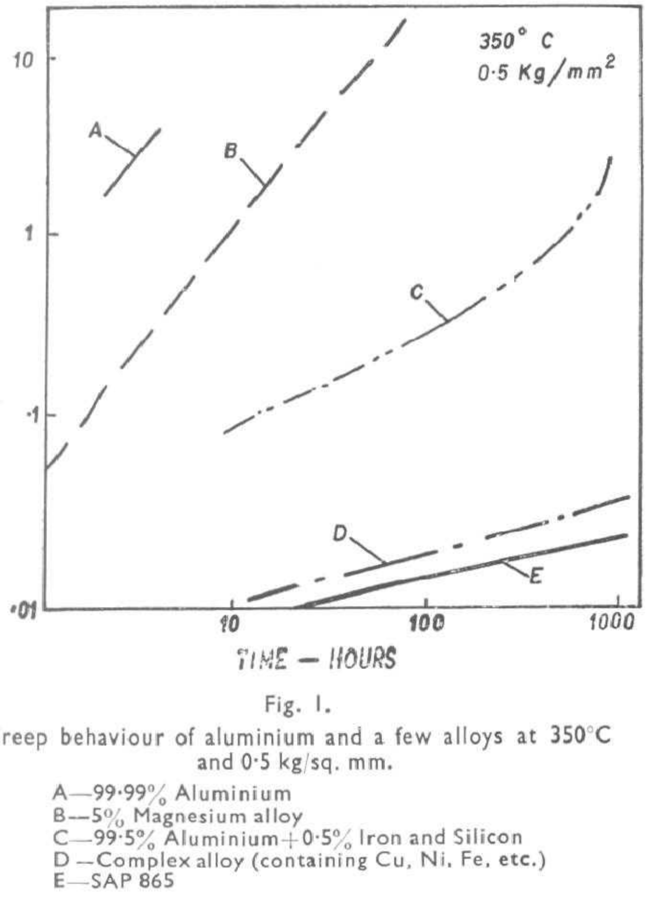

Fig. 1.

Creep behaviour of aluminium and a few alloys at 350°C and 0·5 kg/sq. mm.

A—99·99% Aluminium
B—5% Magnesium alloy
C—99·5% Aluminium+0·5% Iron and Silicon
D —Complex alloy (containing Cu, Ni, Fe, etc.)
E—SAP 865

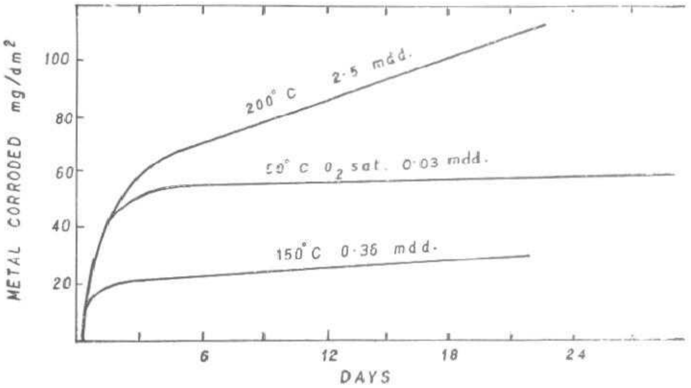

Fig. 2.

Corrosion of commercially pure aluminium in distilled water.

Irradiation effects on aluminium have to be considered in its applications in reactor components. It has been observed that the yield strengths and the ultimate tensile strengths of aluminium alloys are considerably increased on irradiation. This effect is particularly noticeable in annealed material. On the other hand the ductility is reduced but this is not much compared to the reduction obtained by equivalent strain hardening.

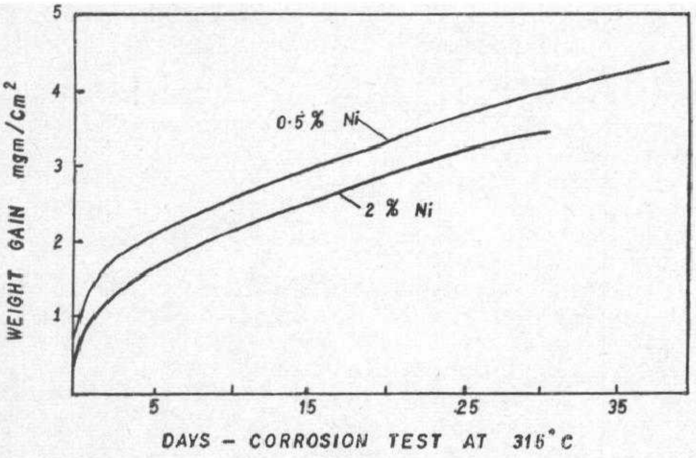

Fig. 3.

Effect of nickel concentration on the corrosion of nickel-2S aluminium alloys in distilled water at 315°C

Beryllium

Beryllium has been favoured as moderator and reflector in a reactor because of its high scattering cross section for neutrons. The high flux Material Testing Reactor in U.S.A. employs beryllium as a reflector while the Belgium Reactor (under construction) utilises it as a moderator. Beryllium moderated reactors have a slow "shutdown" which is a serious drawback in the event of a reactor accident. Attempts have been made to use beryllium as a canning material. There are certain difficulties which have prevented a wider adoption. It is brittle below 500°C and swells due to the precipitation of helium during the reactor operation. Both these factors contribute to the ultimate failure of the cans. It can however be used for canning purposes if UO_2 is used as a fuel (as has been envisaged in Advanced Gas Cooled Reactor at Windscale). The dimensional changes in UO_2 on irradiation are relatively small and if the can temperature is also not allowed to exceed 600°C serious swelling in beryllium can be avoided.

Fabrication of beryllium presents certain difficulties because of its inherent coarse grains and brittleness. Attempts to refine grain size by alloying additions have not been successful so far. These difficulties have been overcome to a considerable extent by powder metallurgical techniques. Metal refining by vacuum melting is necessary prior to the preparation of powder in order to eliminate undesirable impurities such as chlorides and fluorides which adversely affect the nuclear and corrosion properties. Melting is done in beryllia crucibles with high frequency heating. Casting is usually made in a graphite mould. The cast ingots are then machined to get turnings which are ball-milled to fine powder under a protective atmosphere of nitrogen. The powder obtained has a thin film of oxide on the surface which resists grain growth during sintering operations. Oxide content of the powder increases with the decrease in particle size. Yet the compacts from fine powder exhibit superior mechanical properties at room temperatures.

Beryllium powder can be compacted to its full density by : (*a*) hot pressing, (*b*) cold pressing, sintering and mechanical deformation, (*c*) warm or hot pressing under atmospheric pressure, (*d*) hot working the powder using protective sheaths.

The effect of compacting pressure on the density and sintering atmosphere is shown in Fig. 4, which indicates that vaccum sintering yields better results. High temperature sintering is necessary to obtain high density although loss of metal occurs due to evaporation especially in vacuum. The variation of density with sintering temperature is shown in Fig. 5. It is to be noted that sintering is most effective above 1,000°C. Hot pressing of beryllium up to 600°C at pressures of 20–100 tons per square inch yields compacts of theoretical density. At high temperatures the pressure required is less and only the time of application of pressure becomes important. Vacuum hot pressing techniques have been developed in the fabrication of various components. A recent development in this field is the pressureless sintering technique. High density compacts are made in a variety of shapes by a consolidation of loose powder and sintering in vacuum with high frequency heating.

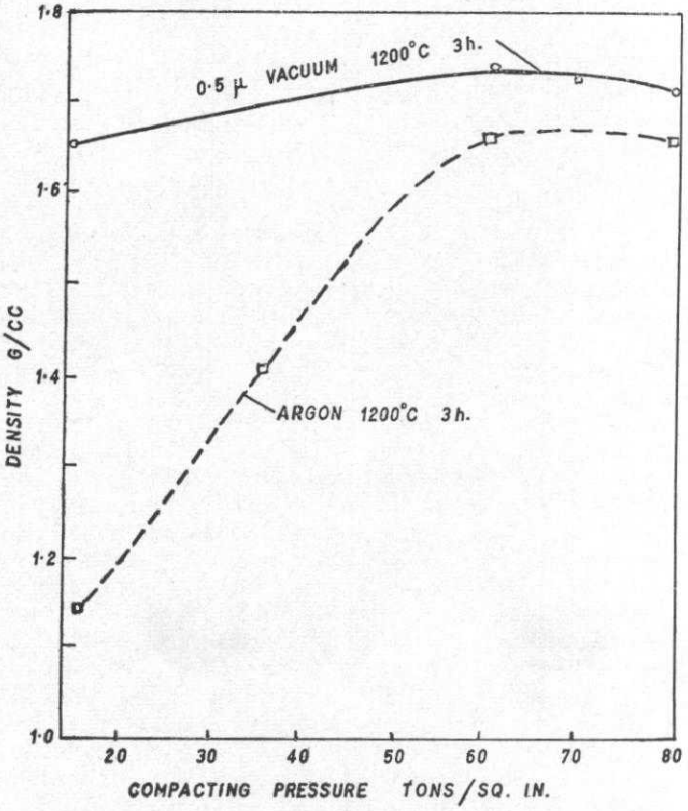

Fig. 4.

Effect of varying compacting pressure and sintering atmosphere on the sintered density.

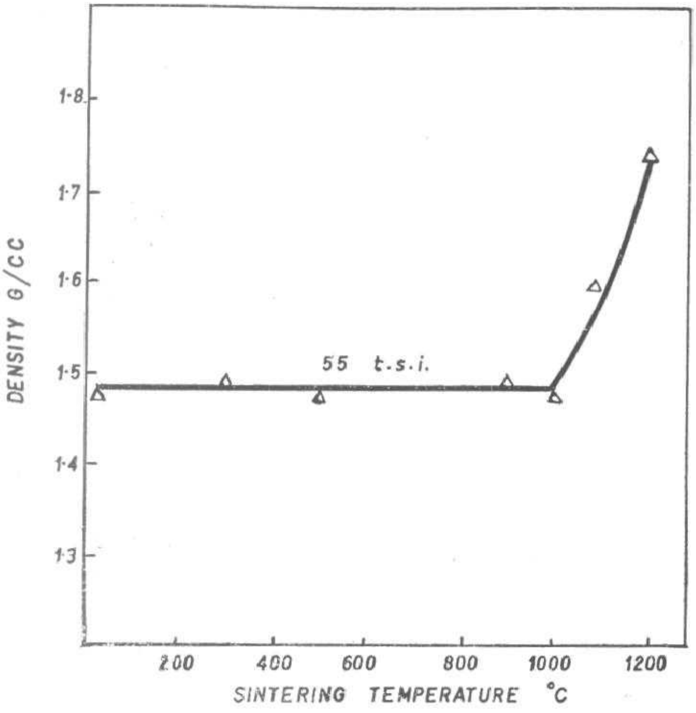

Fig. 5.

Effect of sintering temperature on density. Specimens sintered 3 hours in vacuum.

Beryllium can be worked in a number of ways. The choice of the process is determined by the available techniques and the shape and size of the product. Hot extrusion has been carried out at about 1,000°C using mild steel as a protective sheath. Bare metal can be extruded at low temperatures only. Hot rolling at 800 to 1,100°C is also possible if beryllium is adequately protected by cladding with mild steel, stainless steel, copper or molybdenum. Finishing passes are usually carried out at 350–400°C to improve surface finish and to prevent mild steel sticking to beryllium. Reduction of about 95% is possible by this process. Solid blocks can be prepared by forging the metal powder sealed in can. The can is usually made of mild steel. An interesting application of this method is the sheath forging to can uranium in berylli[illegible]. Beryllium powder is sheath forged round the [illegible]nium bar in a steel sheath which is then dissolved [illegible]way. This method has been found to be very reliable.

The mechanical properties of beryllium very much depend upon the mode of fabrication as well as the specimen axis direction in which tests are made and the temperature of tests. Extruded metal tested at room temperature has maximum elongation in the longitudinal direction. The effect of tensile testing temperature on the ductility of beryllium is shown in Fig. 6. The increase in ductility up to about 400°C is associated with the ease of slip on (1010) planes. Par[illegible] weakening of the grain boundaries between 400 [illegible]°C is thought to be the cause of loss of ductility within this range. The change in the mode of fracture from transgranular to intergranular above 600°C gives rise to the second peak.

The problem of welding beryllium has been satisfactorily solved by argon arc process and by electron beam technique.

Beryllium possesses very good compatibility with carbon dioxide, uranium and liquid metals up to a temperature of 500°C. It is unaffected by distilled water up to about 300°C.

Irradiation of beryllium causes a series of nuclear transformations resulting in the production of helium and tritium atoms. These may, depending upon the temperature, coagulate to form bubbles and cause swelling. It has been reported that beryllium shows excellent irradiation resistance even after extensive bombardment ; the changes in dimensions, crystal structure, density and hardness being negligible. However, no data on the irradiation dosage and temperature has been given along with. Mechanical strength is little affected by irradiation while ductility is severely affected.

Magnesium and magnesium alloys

The extensive utilisation of magnesium as canning material in graphite moderated gas cooled power reactors is due to its favourable properties such as low neutron absorption cross section and excellent compatibility with uranium. The large scale application of magnesium is in the Calder Hall Reactors and the French Reactors EL2, G2 and G3 where it is serving as canning material.

Pure magnesium has low creep and rupture strength and exhibits grain coarsening at high temperatures. It gets oxidised easily and may even get ignited at these temperatures. As such, consideration was given to development of magnesium alloys which could safely be used as canning and structural material.

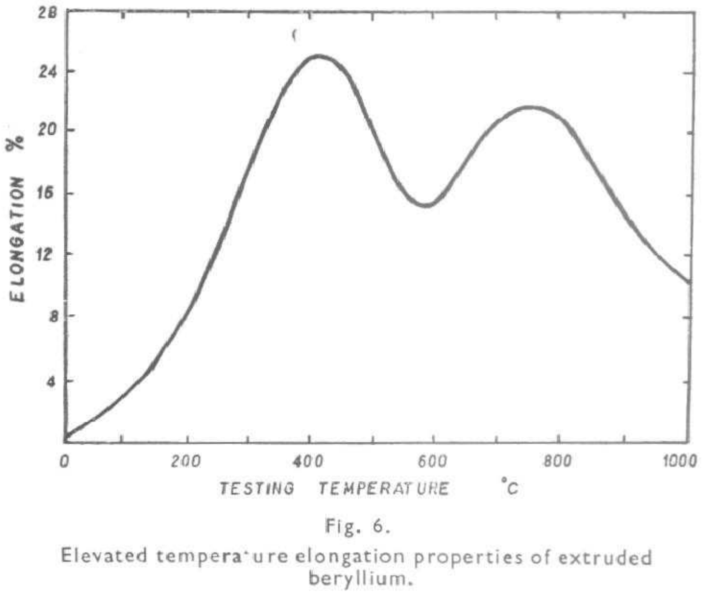

Fig. 6.

Elevated tempera·ure elongation properties of extruded beryllium.

A series of magnesium alloys known as Magnox alloys have been developed to obtain good oxidation resistance, and high creep strength. Beryllium and calcium were tried as alloying additions in the early stages, but the alloys showed poor weldability which was attributed to the presence of calcium. Elimination of calcium by substitution of aluminium overcame this difficulty. Beryllium imparts oxidation resistance while aluminium strengthens the alloy. The best of the Magnox series is Magnox A1-2 and has a chemical composition as indicated below :

Beryllium	...	0·002–0·03%
Aluminium	...	0·7 –0·9%
Calcium	...	0·008 max.
Iron	...	0·006 max.
Silicon	...	0·01 max.
Zinc	...	0·01 max.

The composition of Magnox alloy is of vital importance as it affects the chemical and physical properties significantly. For this reason, rigid control in the preparation of the alloy has to be exercised. However, this alloy develops coarse grains at high temperatures and has poor creep ductility around 200°C. In Fig. 7 the ductility of Magnox Al-2 is shown as a function of temperature at various strain rates. At slower creep rates there is a loss in ductility between 200–300°C. These drawbacks are considered serious as they prevent "shuffling" of fuel elements in a reactor. For a uniform burn up of fuel it is essential that the central fuel elements are shifted in due course to outer positions of the core. The coarse grains developed during high temperature in the centre cannot creep at low temperature and give rise to intergranular cavitation. This may lead either to a rupture of the can or develop porosity allowing the coolant to oxidize the fuel and finally rupturing the can. Cavitation in magnesium alloys has been found to be a function of strain rate and total strain. The number of cavities formed increases with decreasing strain rate and increasing total strain. Cavitation is little dependant upon temperature between 200—400°C and completely absent at 500°C.

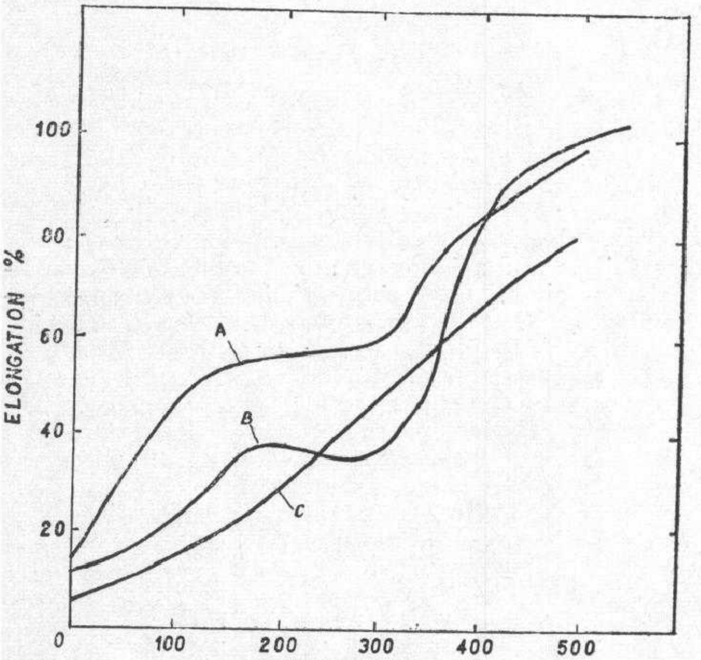

Fig. 7.

Ductility of Magnex A12

A—Strain rate 18% per hour as extruded condition

B—Strain rate 18% per hour heat treated condition

C—Strain rate 1075% per hour heat treated condition

Grain refinement and stabilisation in magnesium has been achieved by the addition of zirconium. A binary alloy ZA containing about 0·6% zirconium is one of the several such alloys developed for canning and structural purposes. Table I, given below, shows the composition of various alloys.

TABLE I

Compositions of magnesium canning alloys

Alloy		Weight per cent		
		Zr	Mn	Zn
ZA	...	0·57	—	—
ZW1	...	0·7	—	1·03
M15	...	0·50	0·11	—
M15Z	...	0·50	0·10	0·53
M25	...	0·37	0·24	—
M25Z	...	0·35	0·22	0·39

These alloys are superior to Magnox Al2 in their low temperature creep ductility and grain size stability. The grain coarsening in magnesium alloys has been studied thoroughly. It is found that after annealing for 1000 hours at 450°C the grain size increases by a factor of 150–200 in the case of Magnox, by 4 in the case of ZA and by 1·5 to 1·6 in the case of ZW1.

The creep ductility of the alloys has been studied at constant strain rates of 1% per hour and 0·1% per hour at various temperatures. The results are shown in Table II.

TABLE II

Ductility of magnesium alloys at slow strain rates

Alloy	Strain rate% per hr.	% elongation at fracture at temps. (°C) indicated					
		20	100	200	300	400	[illegible]0
ZA	1·0	20	74	77	106	132	55
	0·1	—	—	76	—	218	—
ZW1	1·0	50	53	62	88	140	132
	0·1	—	—	50	—	150	—
Magnox Al2	1·0	9	20	37	45	124	96
	0·1	—	—	31	—	98	—

It is seen that the zirconium alloys are superior to Magnox alloys in their creep ductility throughout the temperature range.

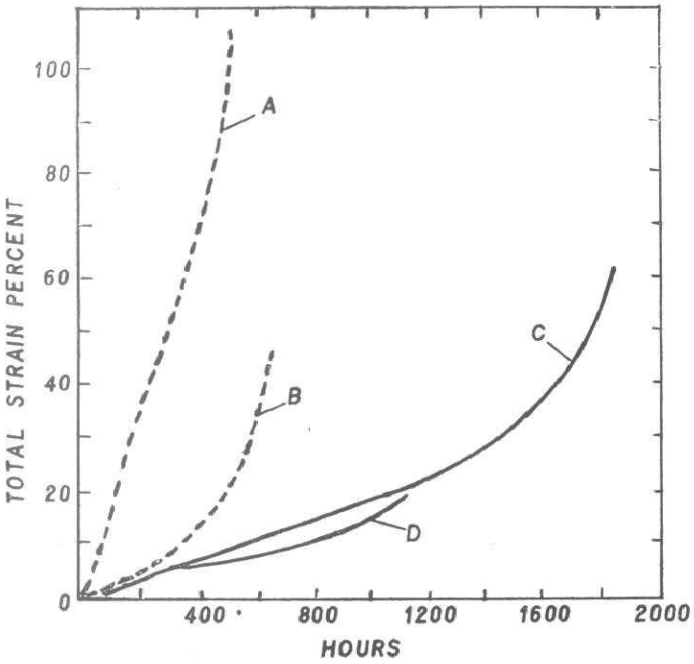

Fig. 8.

Creep curves for extruded bar specimens tested at 200°C and 400°C in ZA and A12 alloys.

A—ZA temp. 400°C ; stress 0·1 tsi
B—ZA temp. 200°C ; stress 1·5 tsi
C—A12 temp. 400°C ; stress 0·1 tsi
D—A12 temp. 200°C ; stress 1·5 tsi

The drawback of ZA alloy is its inferior creep strength compared to Magnox alloys. Fig. 8 shows the creep strength of the ZA and Magnox alloys at 200°C and 400°C at stresses 0·1 tsi and 1·5 tsi from which the difference in life and ductility of the two materials can be compared. High temperature creep strength is necessary to resist creep deformation so that heat transfer fins of the cans do not deform under small pressure of the coolant at the highest operating temperature. Development work in improving this property has indicated that addition of manganese to the extent of 0·1 to 0·2 per cent imparts the necessary high temperature creep strength. The alloys M15 and M25 have been found to be as good as Magnox in this respect.

Fabrication of magnesium alloys has been fully developed. Magnesium is melted in steel pots under a flux cover and after suitable refining and alloying the metal is chill cast into round billets or rectangular slabs. Magnesium used for nuclear applications has to be of highest quality and calls for a very rigid inspection and control over the quality of the cast ingot. Particular care has to be taken about the entrapped flux particles which later give rise to serious corrosion problems.

Horizontal extrusion of the billets in temperature range 300–350°C at 50-100 ft per minute speed gives good surface finish. The alloys, particularly Magnox Al2, have very good rolling characteristics. The cans having radial fins are fabricated by machining solid extruded bars taking advantage of the excellent machinability of magnesium. The cans having helical fins are fabricated in two steps. Hot impact extrusion produces the longitudinal fins on the can which are later twisted on a lathe at a suitable temperature. Ancillary components are made by machining extruded bars. Argonarc welding is found to be quite satisfactory for magnesium alloys.

Magnesium has excellent compatibility with uranium. It does not react or diffuse into uranium even when the temperature is near about the melting point of magnesium. It forms low temperature eutectics with most of the common metals and their contamination is to be avoided. The tolerable temperature of contamination for various metals is given in Table III below :

TABLE III

Tolerable temperatures of contamination by various metals.

Contaminant		Temperature °C
Mercury	...	Suspected at all temps.
Tin	...	above 200
Lead, Bismuth	...	above 250
Cadmium, zinc	...	above 300
Aluminium, calcium	...	above 400
Silver, copper	...	above 450
Nickel	...	above 500

In some cases anodising has been adopted to prevent such failures.

Compatibility of magnesium alloys with carbon dioxide is quite satisfactory up to about 500°C and at a pressure of 8 atmospheres. Magnesium gets attacked easily by aqueous media due to galvanic action. It is therefore necessary to adjust the pH very carefully while storing irradiated fuel elements in water to avoid can failure and subsequent attack on the highly radioactive uranium. Corrosion resisting magnesium-beryllium alloys have been developed in USSR. A high content of beryllium up to 10% or more in magnesium is obtained by simultaneous condensation of magnesium and beryllium vapours under high vacuum. The condensed powder is pressed and sintered into any desired shape. This alloy is claimed to withstand corrosion up to the melting point of the alloy.

The effect of irradiation on magnesium alloys does not give rise to any serious difficulty.

Conclusions

The impetus given by nuclear engineering has been responsible for the significant progress in the fabrication techniques and alloy development of light metals. This is particularly evident in the case of beryllium and magnesium. The present trend is towards the utilisation of improved aluminium alloys for high temperature applications in reactors as these alloys are much cheaper and easier to fabricate. Magnesium alloys have already proved their utility in power production programmes. Being unique in nuclear properties, beryllium holds the key to the development of mobile reactors.

Acknowledgement

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DISCUSSIONS

Dr. B. C. Kar, NML: May I know from the author as to what should be the purity of Be, Mg and Al to be used as a canning or moderating material in nuclear reactors and how these very minute traces of impurities are determined ?

Mr. M. K. Asundi, (Author) The amount of impurities that can be tolerated in reactor applications is based on two factors. The impurities should be such that they should neither have a large neutron absorption cross-section nor should adversely affect the mechanical strength. So each impurity is evaluated in this light. The usual impurity tolerance is about 0·5 ppm Boron equivalent for fuel elements and 1 ppm Boron equivalent for canning materials. The minute traces are usually determined spectroscopically.

Mr. H. P. S. Murthy, NML: The Atomic Energy Commission, Trombay, has been running reactors and we would be interested to know their experience and how their materials have behaved during service.

Mr. Asundi (Author): We have not collected sufficient amount of data on the behaviour of light metals in reactor environments. So it will not be possible for me to answer this question.

Mr. U. P. Mullick, Institution of Consulting Engineers, Calcutta: The author may please indicate the requirements of aluminium, magnesium and beryllium alloys by the Atomic Energy Establishment for their use during the next 5 years.

Mr. Asundi (Author): In such an expanding organisation as ours, it will be difficult to forecast our requirements.

Dr. B. R. Nijhawan, NML: I would like to refer to the Canada-Indian reactor of the Atomic Energy Establishment at Trombay wherein the canning of fuel elements and their canning had been done by the A.E.E.T. staff. The canning by aluminium of the uranium fuel element rods is a specialised job because complete adhesion between the fuel rod and the canning material is necessary. Perhaps Mr. Asundi can explain to us the exact technique they followed in canning the fuel rods with super-purity aluminium and the precautions that were taken to see that the bond between the fuel element and aluminium can was up to the requisite specifications.

I would further like to know if the National Metallurgical Laboratory can in any way collaborate with the A.E.E.T. in developing binary and ternary alloys suitable for canning purposes. I am making these enquiries in an exploratory way which, of course, would be pursued by personal discussions and contacts.

Mr. Asundi (Author): The uranium rod is first beta-quenched and then straightened on a roller straightener before rough grinding on a centreless grinder. Both the ends are then threaded on a lathe and the rod finish-ground to its final diameter. The machining of uranium is carried out with special carbide-tipped tools. The finished rod then undergoes a series of cleaning operations such as degreasing, pickling, spray-washing and drying. After final inspection, the aluminium end-plugs are screwed on their two threaded ends. The rod is then vertically lowered into a finned 1S aluminium tube and the assembly drawn through a special die on a 5-ton draw-bench whereby the aluminium tube collapses on the uranium rod, thus ensuring good heat transfer. After drawing, the sheaths are cut to approximately 3/16″ longer at each end than the aluminium end-plugs; each end is then rolled over the end-plugs and finally the two outer aluminium plugs are screwed, one at each end. The end-closure is carried out by argon-arc welding. In order to eliminate the human factor in welding and obtain uniformity in welds, a special welding machine provided with automation is employed.

For quality control, the central uranium section is tested by radiography for welding defects and in a special glycol testing unit for any pinholes, or hairline cracks in the sheath, and porosity in the welds.

With reference to the second question raised by Dr. Nijhawan, I am sure that some common ground could be found for collaboration between our Metallurgy Division and the NML in the development of light metals and alloys used as canning materials.

Prof. G. Reginald Bashforth, Banaras Hindu University, Varanasi: This morning we had papers on the development of light metals and their alloys and their application in railways and nuclear engineering. Perhaps one of the most important uses of light metals is in the aircraft industry. It has been suggested and agreed that we would like to hear something about light metals in the aircraft industry and I request Mr. Shankar of Hindustan Aircraft Ltd. to give us a few details of the requirements of aircraft industry with regard to light metals.

Mr. M. B. Shankar, Hindustan Aircraft Limited, Bangalore: I am very grateful to Prof. Bashforth this morning for inviting me to deal with the uses of light alloys in the aircraft industry. I shall attempt to briefly cover the field in the limited time available.

As I survey the development of metallurgical industries generally, I comprehend the entry of "steel" and "light-metal alloys" into aircraft usages from totally different backgrounds and stages of growth. *Steel* through general consumer industries gradually made its way into the engineering industry and then into the very elaborated and comprehensive automobile field, where it received its greatest impetus and underwent vast and rapid development to find its way into the aircraft field. The aircraft industry constitutes the highest quality metallurgical industry where no compromises are considered or sought. Into this highly precision industry, steels of super-quality made their advent. While, on the other hand, *light alloys*, the subject of our Symposium, by virtue of their lightness, were the first to be directly drawn into the aircraft industry. All developments were urgently concentrated on meeting the special demands of the industry. Today with its growth in catering to the aircraft industry, the light alloys are trying to extend their usage downwards to railways, automobile, general engineering and consumer industries.

With this brief introduction, let me attempt to trace some of the salient features and trends of development and usage of several types of light alloys for aircraft applications.

Sheet metal

Aluminium alloy sheets, widely used for aircraft, constitute an important field. They may be classed as (1) Non-Heat Treatable, (2) Heat Treatable. The initial strength of the non-heat treatable alloys is derived from the alloying elements. They are work-hardened. Their varying strengths are as a result of different degrees of cold work. Some of the alloys containing Mg are only stabilised by a thermal treatment. In contrast, the strength of the heat treatable alloys is derived from the unique property of the alloying elements (Cu, Mg, Zn, Si) singly or in combination showing very rapid fall in solid solubilities at room temperatures. I shall deal with the techniques of heat treatment presently.

The principal heat treatable Al alloys used for aircraft are the clad Duralumin type (Al-Cu-Mg-Si) and high strength Al-Zn-Mg (with small additions of Cu and Cr). The latter are the highest strength Al alloys so far commercially developed. The other lightest group of alloys, not so abundantly used as aluminium, are the Mg alloys containing Al/Zn and Zr with good formability. These alloys have less spring back than Al alloys and are, therefore, more easily worked.

Aluminium alloy castings

Many castings are used in aero-engines and aircraft. Some castings, as in wrought alloy series, do not require heat treatment. Others are heat treated for obtaining optimum properties. There is a wide choice of aluminium alloys for casting purposes ; but castability and quality are basic considerations. A good castable alloy may yield higher mechanical properties than alloys with high test bar values but difficult to cast. These considerations, including design features, weigh in the choice of alloys for particular end-uses.

Of the elements generally used for alloying, copper provides strength and hardness, while silicon improves casting characteristics and corrosion resistance. Mg, while improving corrosion resistance, adds only a little to castability. Al-Si alloys have excellent casting qualities and are used for fine design details involving large differences in section thickness ; but this involves some machining difficulties. Al-Cu-Si alloys have better casting qualities than Al-Cu alloys. Al-Si-Mg alloys also, having good castability and corrosion resistance, are comparable in strength to Al-Cu alloys.

Magnesium alloy castings

The lightest alloys commonly used of Mg are those containing : (1) Al and Zn (yielding strength, toughness and good casting characteristics) and (2) Zn and Zr (yielding highest strength of the series and ductility). They are cast both in sand and permanent moulds.

I have previously, under discussion on paper No. 2, dealt with the use of Ti alloys—intermediate between aluminium and steels—for aero-engines and skins of supersonic aircraft.

Heat treatment

Light alloys are heat treated to obtain most beneficial properties. The treatment consists heating the alloy to just below melting range for a specified time followed by rapid cooling or quenching. By heating, the amount of alloying elements in the solid solution is increased bringing about a more uniform or homogeneous distribution. Quenching or rapid cooling renders the elements in solid solution to be retained on, in a super-saturated condition. Ageing consists in precipitating the elements from solid solution leading to increase in strength and hardness. No doubt, prolonged ageing brings about dimensional stability but mechanical properties pass through the maximum to lower values with a slight increase in elongation. Light alloys responsive to such heat treatment, resulting in improvement of their mechanical properties, are abundantly used in aircraft applications. You are no doubt aware that some steels and non-ferrous alloys undergo ageing effects either by cold working or by quenching, but not so appreciably as the light alloys.

Finishing

Cleaning and finishing operations consist in degreasing, vapour blasting, chemical polishing, etching, painting, stove-enamelling, anodising, hard-anodising, chromating, hard chrome, silver, nickel, lead-indium plating and numerous other operations, entailing strict metallurgcial control throughout.

Machining and chemical milling

Another important aspect, preliminary to fabrication in production, is costly but precise (correct to fifth or sixth decimal place of the dimensions) and flawless machining. Very costly precision machines using optical devices are abundantly used. Elaborate and very time-consuming contour milling has been rendered possible by the latest types of machine tools evolved. But such milling of airframe and wing structures are, to a certain extent, accomplished by chemical milling. Chemical milling techniques for each type of alloys have to be developed with proper ageing and sequestering agents as responses are different. Great caution is imperative as chemical milling in certain of the alloys depreciates fatigue strength, by end grain pitting, etc. Some important work is being undertaken in HAL both in chemical milling and research.

Surface defects

A good surface finish plays a vital part in minimising failures under operating conditions by fatigue. Mechanical testing, metallurgical examination and non-destructive testing, together with standard dimensional checks of every component and certifications as imperative, are undertaken in the aircraft industry.

Indigenous production of light alloys

As we have a very long way to go in establishing the production of light alloys of quality (super alloys, special steels and non-ferrous alloys, Nimonics—not mentioned as not falling within the purview of the subject of this Symposium) a great deal of research work with proper orientation needs to be undertaken in the country. HAL have undertaken to produce all the castings and forgings for aircraft and aero-engines for which provision is being created. Dr. Nijhawan has very rightly mentioned that our researches should be confined to some of the common basic alloys as a fundamental step. In the interest of building up a quality raw-materials industry for aircraft uses the existing research facilities in the country should be harnessed and mobilised, and problems allocated to different interested research institutions with proper co-ordination and close liaison. National Metallurgical Laboratory under the wise guidance of Dr. Nijhawan, is to play a very important role in close collaboration with HAL in our new and difficult but vital endeavours.

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