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A Critical Evaluation of Molybdenum and

Its Alloys for Use in

Space Reactor Core Heat Pipes

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L. B. Lundberg

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A CRITICAL EVALUATION OF MOLYBDENUM AND ITS ALLOYS FOR USE IN
SPACE REACTOR CORE HEAT PIPES

by

L. B. Lundberg

ABSTRACT

The choice of pure molybdenum as the prime candi-
date material for space reactor core heat pipes is
examined, and the advantages and disadvantages of this
material are brought into focus. Even though pure
molybdenum heat pipes have been built and tested, this
metal's high ductile-brittle transition temperature and
modest creep strength place significant design restric-
tions on a core heat pipe made from it. Molybdenum
alloys are examined with regard to their promise as
potential replacements for pure molybdenum. The prop-
erties of TZM and molybdenum-rhenium alloys are exam-
ined, and it appears that Mo-Re alloys with 10-15 wt%
rhenium offer the most advantage as an alternative to
pure molybdenum in space reactor core heat pipes.

I. BACKGROUND

Pure molybdenum is presently the primary candidate material for both the
Space Reactor Electric Power Supply (SPAR) and Nuclear Electrical Propulsion
(NEP) reactor core heat pipes, and because it has been suggested that there
might be better material choices for this application, it is appropriate to
perform a critical evaluation of the use of pure molybdenum and to evaluate
other candidate materials for possible substitution.

Pure molybdenum was originally chosen as the prime candidate core heat
pipe material because of its well known chemical compatibility with alkali
metals and uranium dioxide. Another major factor in the selection was the
successful fabrication and high temperature operation of two 1.8 m long
molybdenum/lithium heat pipes[1] at LASL. The literature[2] indicated that
pure molybdenum also had sufficient high temperature strength to contain

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sodium at 1400 K, the SPAR operating temperature, and lithium at 1700 K, the NEP operating temperature. Finally, it is important to recall that when both the SPAR and NEP program began only pure low-carbon arc-cast (LCAC) molybdenum was being produced commercially into long tubing. Only pure, powder metallurgical (PM) molybdenum was being woven into fine mesh screen.

The major disadvantage to the use of pure molybdenum is the fact that the metal becomes brittle at about room temperature and below. This property impacts heavily on the fabrication of heat pipes, for example, by limiting the minimum molybdenum screen mesh to 150 by 150 and forcing most metalworking operations to be performed warm ($\geq$ 480 K). Because SPAR requires a much finer wick porosity than can be obtained from 150 by 150 mesh screen, we have had to develop special, complicated procedures for producing an annular wick,[3] and we have yet to develop procedures for producing fine pore molybdenum artery wicks.

The room temperature brittleness of molybdenum will require special design features in the reactor systems to insure against heat pipe breakage during handling, transportation to the launch site, and the launch sequences. A prototypical design of the core heat pipe is shown schematically in Fig. 1, and this heat pipe already incorporates a feature that is partly dictated by the room temperature brittleness of pure molybdenum, the pinch seal cover tube. This component serves to help protect the relatively fragile fill tube from breakage during normal handling and transportation. Breakage of molybdenum heat pipes during transportation has already occurred as shown in Fig. 2. These broken heat pipes had been packaged tightly in aluminum tubing with the heat pipe ends further protected by short pieces of the electrical mechanical tubing (EMT). The longest of these heat pipes was orginally 4 m long. As shown in Fig. 2(a), one of the container tubes was broken in two near the blind end cap, and the fill tube was broken off both tubes, Fig. 2(b). Both
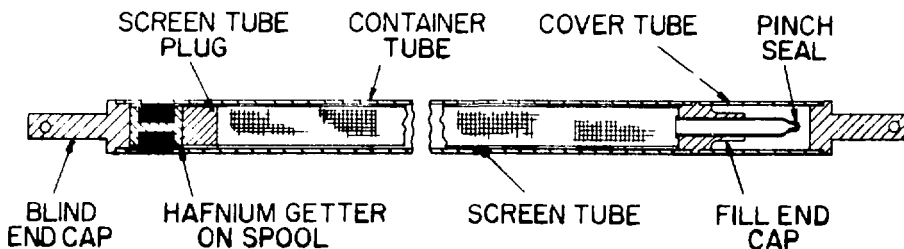

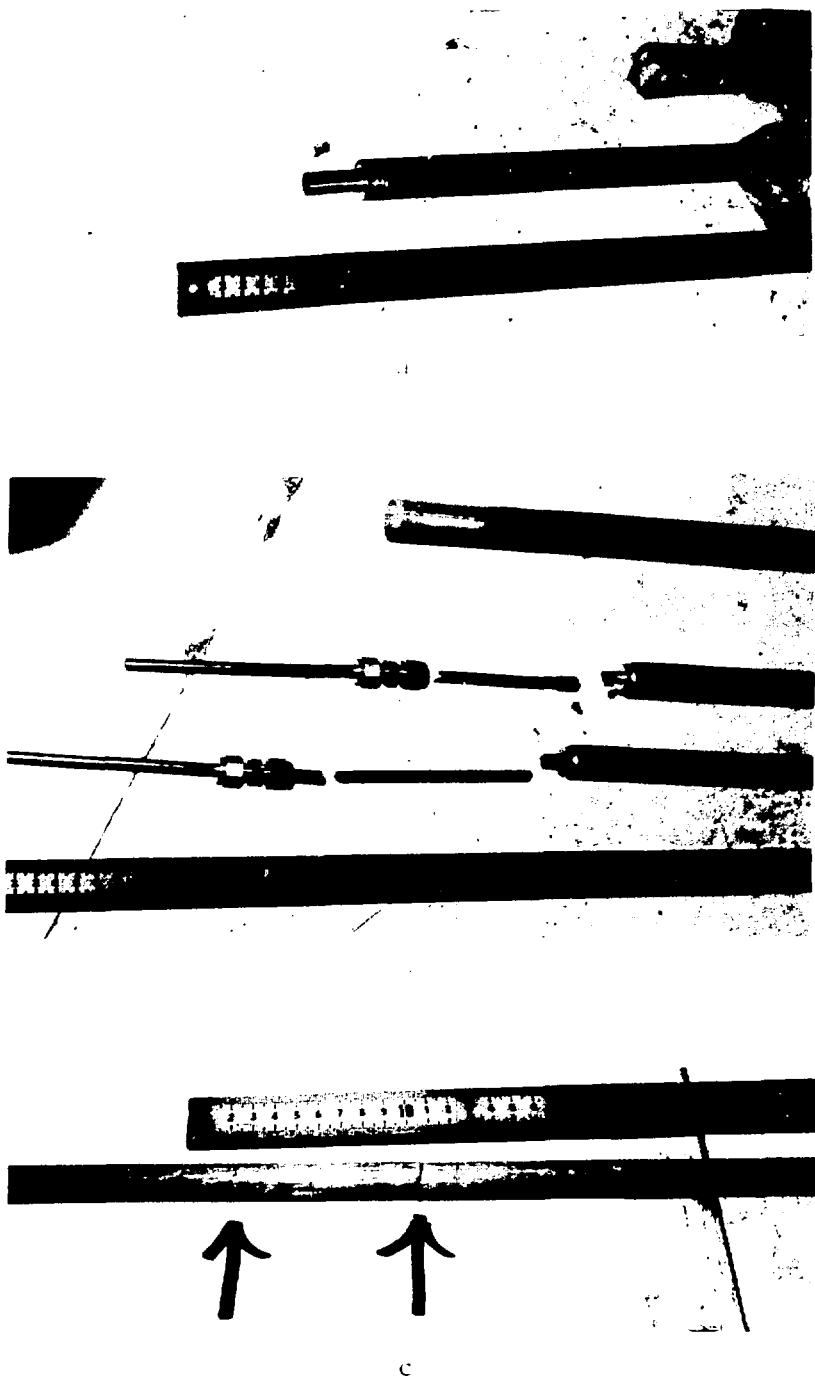Fig. 1. Prototypical space reactor core heat pipe.

Fig. 2. NEP heat pipe damaged in transit from ORNL.

of the screen tube wicks were broken in the manner shown in Fig. 2(c). All
of the molybdenum used to form the heat pipes shown in Fig. 2 had been
recrystallized. It should be emphasized that pure molybdenum heat pipes
would probably be launched with some of its parts, at least the weld
regions, in the recrystallized condition.

II. MATERIAL REQUIREMENTS FOR SPAR CORE HEAT PIPES

The SPAR core heat pipes are expected to operate at 1400 K, so that they
must be constructed from a material that has suitable physical, chemical,
and mechanical properties in this temperature regime. Furthermore, the
material must be formable, machineable and weldable so that heat pipes can
be fabricated from it.

High thermal conductivity, a high melting point, resistance to fast
neutron irradiation swelling and low thermal expansion are necessary physi-
cal properties for consideration as a core heat pipe material. Also, the
density of the material should be as low as possible to keep the power
system mass to a minimum. The material must be compatible with the sodium
working fluid, the uranium dioxide fuel and those materials in the thermo-
electric generator that can be transported to the heat pipe.

Short term mechanical properties of the core heat pipe material must be
sufficient to allow a minimum weight power system to be launched intact.
This means the material should have strength and ductility at room temper-
ature and below. Room temperature ductility would be most helpful in pre-
venting breakage during initial assembly and ground transportation.

The long term, high temperature mechanical properties should be suffi-
cient to allow minimum system weight without creep-rupture of the heat pipe
container tube and loss of the sodium working fluid prior to the desired end
of operating life. In other words, the core heat pipe material should have
the highest possible creep strength at 1400 K which is not significantly
degraded by fast neutron irradiation.

III. CANDIDATE MATERIALS

The SPAR core heat pipe container tubes are presently being fabricated
from pure, LCAC molybdenum, and the screen tubes are being produced from
wire mesh made with pure, PM grade molybdenum wire. Other candidate mate-
rials that we shall consider include TZM (Mo-0.5 Ti-0.08 Zr-0.03 C) and the

TABLE I

SELECTED PROPERTIES OF MOLYBDENUM, TZM AND Mo-Re ALLOYS

	LCAC Molybdenum	TZM Molybdenum	Molybdenum-Rhenium 14 wt% Re[f]	46 wt% Re
Physical Properties Density at 293 K, Mg/m^3	10.22	10.22	11.89	13.70
Thermal conductivity at 1400 K, w/m K	98	95	∿ 70	65
Thermal expansion at 1400 K starting at 300 K, %	0.66	0.66	No data (∿ 0.55)	0.74
Radiation swelling at 1400 K and 10^{26} neutrons/m^2 dose, %	1	1	No data	1
Melting point, K	2896	2896	2810[c]	2750[c]
Total normal emissivity at 1400 K	0.17			
Complete recrystallization in 1 h, K	1200	1700[b]	1645	1575[h]
Chemical Compatibility				
Sodium at 1400 K in heat pipe	No reaction expected	Leaching of carbon expected	No reaction expected	No reaction
UO$_{2.00}$ at 1400 K	No reaction	Reaction with Ti + Zr expected	No reaction expected	No reaction expected
Mechanical Properties				
Ductile-brittle transition temperature, K	340[d]	250[e]	140[d]	75
Creep deformation of 15.9 mm o.d. by 14.1 mm i.d. Na heat pipe after 7 y at 1400 K (σ = 7 Mpa)[a], %	1.0	0.05[e]	3 × 10^{-4}	∿0
Fabricability				
Formability	≥ 480 K excellent	≥ 370 K good	No low temperature formability data	Work warm or cold
Machinability	Good, like cast iron	Good, like cast iron	No difficulties expected	Good, use conventional procedures
Weldability	EB - borderline	EB - good	EB - expected to be good	EB - excellent
	GTA - poor, large grain HAZ	GTA - fair, HAZ grain growth	GTA - expected to be fair	GTA - good
Availability	Good	Fair	Not available	Not available

a) Assuming no effect from neutron irradiation
b) Starting material arc-cast
c) Approximate solidus temperature
d) Recrystallized condition
e) Stress relieved condition, Stephenson's data
f) Electron beam melted alloys
g) Calculated
h) Lowest reported value

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molybdenum-rhenium alloys containing up to 50 wt% rhenium. Niobium and
tantalum and their alloys are not viable candidates for SPAR heat pipe mate-
rials because they are chemically incompatible with uranium dioxide, and
tungsten and its alloys are not being considered because they are too heavy.

A. LCAC Molybdenum

Low carbon arc-cast molybdenum is 99.97% pure with less than 50 ppm
carbon and 15 ppm oxygen, and it is sufficiently fabricable to produce heat
pipes from it. Some selected properties of LCAC molybdenum are listed in
Table I. It has a high thermal conductivity and good creep strength, but
its recrystallization temperature is below the core heat pipe operating
temperature (1400 K). Also, in the recrystallized condition its ductile-
brittle transition temperature (DBTT) is above room temperature. The high
DBTT makes it necessary to always warm work LCAC molybdenum into the desired
shapes. The DBTT of molybdenum is also sensitive to factors such as impur-
ity content, microstructure, and strain rate. Interstitial impurities, i.e.
hydrogen, carbon, oxygen and nitrogen, tend to have the strongest influence
on the DBTT. Small additions of these impurities cause significant in-
creases in the DBTT. Hahn et al.[4] make reference to an ultra-high purity,
electron beam melted molybdenum with a DBTT below 4 K in a recrystallized
condition. Distribution of these impurities in the microstructure of molyb-
denum is important but ill-defined, and as pointed out by Thornley and
Wronski,[5] grain size appears to have only a small influence on DBTT which
can be overshadowed by more dominant factors.

As will be noted in Fig. 3, the DBTT increases with strain rate. These
data derived from the literature[6,7] can be interpolated reasonably well
with a simple power law relationship; $DBTT = 35\dot{x}^{0.062}$. It must be
mentioned that this relationship represents a best fit to the data rather
than any phenomenological relation suggested in the literature.[6,7] It is
not known whether or not these data are quantitatively relevant to the
behavior of the LCAC molybdenum. Nevertheless, it would not be unreasonable
to conclude that the DBTT of LCAC molybdenum in a Space Shuttle launch
environment could be in excess of 500 K.

The radiation swelling data for core heat pipe operating temperature are
sketchy and imprecise but are sufficient to show trends. Also, chemical
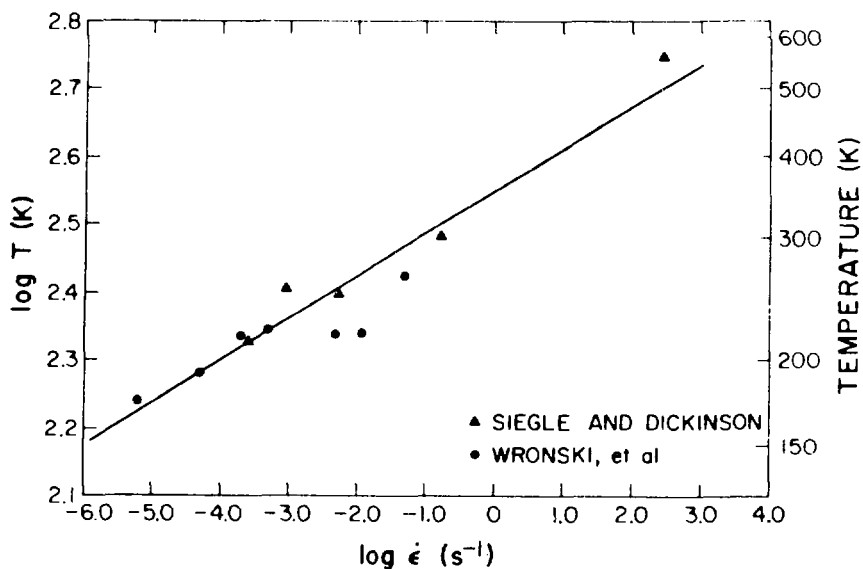compatibility with sodium is not well defined, but indications from our

Fig. 3. Effect of strain rate on tensile DBTT of molybdenum.

Mo/Li heat pipe life test give us encouragement. This heat pipe has operated over 19 000 h at 1700 K without failure.

Pure molybdenum is known to be chemically incompatible with hyper-stoichiometric uranium dioxide,[8] but it is compatible with stoichiometric uranium dioxide. The free energy plots in Fig. 4 clearly indicate that $UO_{2.05}$ will react with molybdenum to form MoO_2 but, as indicated in Table I, $UO_{2.00}$ will not. These curves also show that in a Mo/Na heat pipe that is surrounded by hyperstoichiometric uranium dioxide there is a stronger driving force to form sodium molybdate, Na_2MoO_4, inside the heat pipe.

The creep deformation listed for LCAC molybdenum in Table I is somewhat lower than the worst case predicted by Green and Weertman,[9] but my prediction is based upon an interpolation of medium temperature, low stress data[10,11,12] rather than a theoretical extrapolation.* Because the creep

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*Based on data in the stress and temperature regime of the operating SPAR heat pipe,[10,11,12] the best equation for predicting steady creep rate (s^{-1}) in pure molybdenum is $\epsilon = 9.5 \times 10^{-34} \sigma^{5.7} \exp(-53,000/T)$ where σ is in Pascals and T is in kelvins.
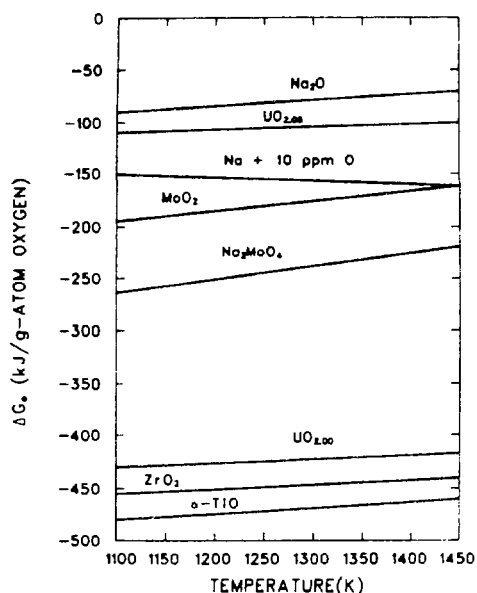
Fig. 4. Free energies of formation of SPAR core materials and
potential reaction products.

ductility of metals at low stresses tends to be rather low, it is felt that
the wall thickness of the present SPAR molybdenum heat pipe may be insuffi-
cient to prevent a creep failure during the lifetime of the reactor.

LCAC molybdenum is fabricable into such forms as tubing, wire and bar
which are the required starting shapes for constructing heat pipes. How-
ever, to be workable LCAC molybdenum must be heated to over 480 K. LCAC
molybdenum can be routinely machined much like cast iron. We have had some
difficulty machining the inside circumference of LCAC molybdenum tubing in
that longitudinal cracking of the tube occasionally develops in both
stress-relieved and recrystallized metal. Electron beam welding of LCAC
molybdenum is generally routine usually producing helium leak-tight joints
with medium grain size heat-affected zone (HAZ). Gas-tungsten-arc (GTA)
welding has produced helium leak tight joints, but these welds have very
large grains particularly in the fusion zone with smaller but still large
grains in the HAZ which generally reduces weld ductility.

The availability of LCAC molybdenum tubing and bar stock has never been
a major problem except that the sizes required for heat pipes have never
been shelf items. It has typically taken at least three months to obtain
the heat pipe container tubing. As previously indicated, LCAC molybdenum

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screen is not presently available primarily because the fine wire is not readily available. We have obtained some 25 μm diameter wire by having 0.76 mm wire redrawn.

B. TZM-Molybdenum

TZM is a commercially available molybdenum alloy that is characterized by high strength at elevated temperatures. It also has a somewhat lower DBTT than pure molybdenum. This alloy is produced commercially by either arc-melting or powder metallurgical procedures. TZM is a dispersion strengthened alloy deriving its high strength from finely dispersed titanium and zirconium carbide particles. A second benefit derived from these particles is the grain growth inhibiting effect which increases the recrystallization temperature of TZM to about 1700 K and reduces grain growth in weld HAZ's. As will be seen in Table I, the other physical properties of TZM are only slightly different from pure molybdenum. Total emissivity data were not found for TZM, but it is expected to be very close to the value for pure molybdenum. The irradiation swelling data are very meager, but they suggest that TZM swells slightly more than pure molybdenum under comparable conditions.[13]

Sodium corrosion data precisely comparable to SPAR conditions are not available for TZM. However, a TZM/Li heat pipe operating at 1833 K did not fail until it had logged 4600 h.[14] In this case and in potassium reflux experiments to 1573 K,[15] there was strong evidence of carbon leaching from the alloy. Carbon was also found to have been leached from TZM by lithium after 3000 h at 1475 K in a Nb-1Zr loop.[16] It is thus expected that carbon leaching will be observed with sodium in a TZM SPAR heat pipe.

Oxygen contamination in potassium has been found to enhance the corrosion of TZM in reflux capsules operated from 1090 to 1380 K.[17] Deposits were found mostly at the liquid-vapor interface in these capsules that appeared to be K_2MoO_4. Oxygen from hyper-stoichiometric uranium dioxide fuel in the reactor core might be expected to diffuse though a TZM heat pipe wall and cause a similar reaction with sodium and molybdenum. Because the oxides of both titanium and zirconium are more stable than $UO_{2.00}$ (see Fig. 4), these active elements are expected to be oxidized in an operating TZM SPAR heat pipe, thus an incubation period would be expected in any oxygen diffusion controlled process inside this heat pipe.

Liu, et al[18] have found that TZM also decarburizes when it is intern-
ally oxidized at 1425 K by exposure to an oxygen pressure of 1.3 mPa, and
this environment was found to eventually cause brittleness even at elevated
temperatures. Thus, an operating SPAR core heat pipe made of TZM might be
expected to embrittle with time, due to reaction with UO_2.

As will be noted in Table I, the DBTT of TZM is indicated to be below
room temperature, but the small quantity of TZM tubing we received recently
failed in a brittle manner at room temperature. This problem is presently
being studied in greater depth.

The creep strength of TZM is significantly higher than that of pure
molybdenum, but as reported by Stephenson,[19] the creep strength of TZM is
a strong function of processing variables. This feature of TZM may impose
severe limitations on heat pipe fabrication. If the creep strength could be
relied upon, it is possible that a significant weight saving could be
achieved with TZM because the container tube wall thickness could be
reduced. Using Stephenson[19] data, I calculate that a TZM container tube
with a wall thickness about half that of an LCAC molybdenum container tube
would creep less than 1% under SPAR core conditions.

TZM is presently available in both tubing and rod form but not fine
wire. It is not drawn routinely into wire less than about 0.2 mm diameter
because below this diameter the drawing becomes very difficult and expen-
sive. As noted in Table I, metal forming of TZM must be performed warm
above about 370 K,[20] about 100^0 lower than LCAC molybdenum. The higher
yield strength of TZM makes it more difficult to work than LCAC molybdenum.
The machinability of TZM is about the same as LCAC molybdenum, and the weld-
ability is better because of the reduced grain growth in both the fusion and
HAZ caused by the alloy additions. Consequently, TZM can be EB welded with
better success than LCAC molybdenum. Even though TZM can be GTA welded, EB
welding is preferred because it yields a much smaller and finer grained HAZ
and fusion zone.

C. Molybdenum-Rhenium Alloys

Alloying molybdenum with rhenium causes a significant increase in the
low temperature ductility of molybdenum.[21] This has been deduced to be a
fundamental, intrinsic effect which appears to become pronounced around
13 wt% rhenium.[22] As indicated in Fig. 5, more than 40 wt% rhenium is
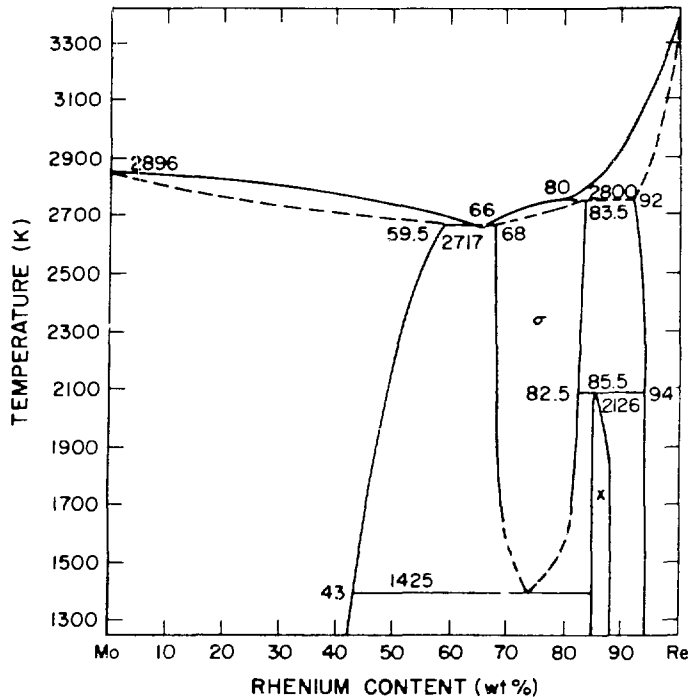soluble in molybdenum and alloys containing as much as 50 wt% rhenium have

Fig. 5. Molybdenum-rhenium equilibrium phase diagram.[23]

been commercially produced. In order to prevent tie formation of the brittle sigma phase during high temperature use, Metallwerk Plansee has recently chosen to produce a molybdenum alloy containing 41 wt% rhenium using powder. They also produce Mo-26 Re and Mo-5 Re alloys. Partly because of the very high cost and scarcity of rhenium, considerable attention has been given to the behavior of the lower rhenium content alloys.[11,22,24,26]

As can be noted in Table I, the density of the Mo-Re alloys increases with rhenium content as expected because of the high density of pure rhenium, 21.04 Mg/m^3. This fact gives added incentive to use a Mo-Re alloy with the lowest practical rhenium content in our weight-limited space application. The addition of rhenium to molybdenum reduces the thermal conductivity somewhat, expecially at lower temperatures. The thermal conductivities of several Mo-Re alloys are compared with pure molybdenum and TZM in Fig. 6. As will be noted, there is only a small difference between the thermal conductivities of pure molybdenum and TZM, especially at high
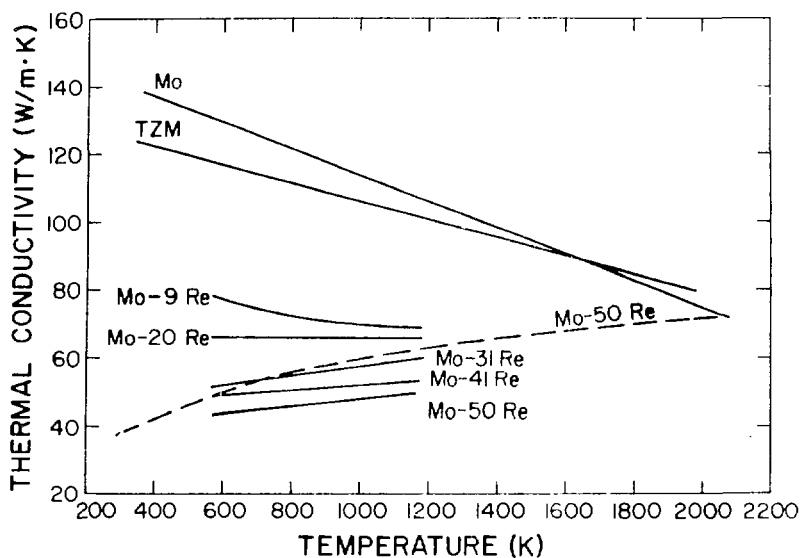
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Fig. 6. Thermal conductivity of molybdenum,[26] TZM[27] and Mo-Re[28,29] alloys.

temperatures, but the addition of rhenium to molybdenum causes a significant reduction in the thermal conductivity. However, the thermal conductivities for the Mo-Re alloys reported from the two cited references[28,29] are not very consistent. The dashed curve for Mo-50 Re in Fig. 6 represents the manu-facturers data[28] which indicates a significantly higher thermal conductivity than reported by Kotlyar, et al.[29] New measurements are clearly needed.

Thermal expansions of two Mo-Re alloys are compared with pure molybdenum and TZM in Fig. 7. The curves in this figure illustrate the fact that the addition of rhenium to molybdenum initially reduces thermal expansion, but as the rhenium content somewhat increases beyond 30 wt%, the thermal expansion exceeds that of both TZM and pure molybdenum. Here it will also be noted that TZM and pure molybdenum have identical expansion behavior. As with the ther-mal conductivity, there is significant variation between the reported value for Mo-Re alloy thermal expansion. For example, Kotlyar, et al.[29] report a mean coefficient of thermal expansion for Mo-10 Re of 4.7×10^{-6} K^{-1} over the temperature range of 293 to 873 K, while Savitskii, et al.,[30] report a value of 5.64×10^{-6} K^{-1} for the same alloy and temperature range.

There are no known irradiation damage data on the dilute Mo-Re alloys, but a small amount of data has been obtained for Mo-50 Re[31] which is
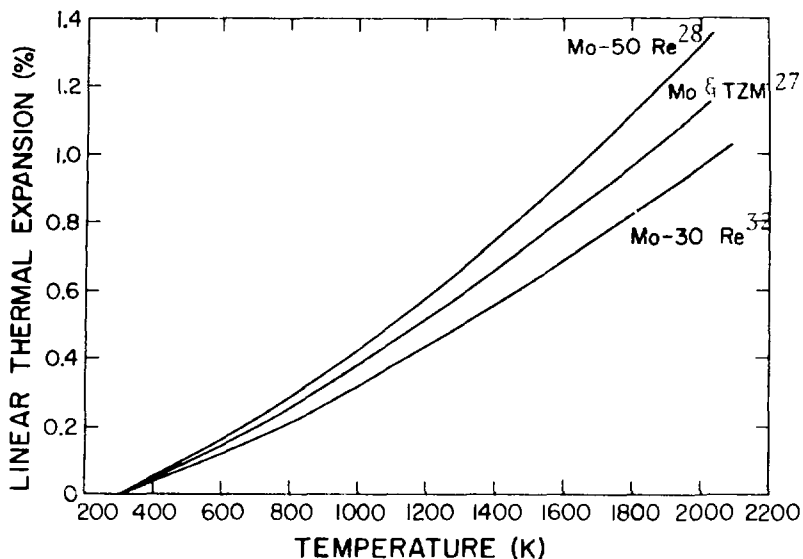
Fig. 7. Thermal expansion of molybdenum and selected molybdenum alloys.

considered to be applicable to Mo-46 Re. It is estimated that Mo-46 Re would swell about 1% in 7 years in an operating SPAR core.

The recrystallization temperatures of Mo-Re alloys are greater than for LCAC molybdenum but somewhat below that of TZM. The recrystallization temper⁺   ⁻ars to drop slightly with increasing rhenium content in the 14-5.   .. ⌐henium range.

    mpatibility of molybdenum-rhenium alloys with sodium is not established, but by inference from potassium corrosion experiments with tungsten-rhenium alloys[15] and lithium corrosion tests with Mo-50 Re[32] we should expect good compatibility between sodium and Mo-Re alloys. There is also no data on the compatibility of Mo-Re alloys with uranium dioxide, but because rhenium oxides are less stable than molybdenum oxides, Mo-Re alloys are expected to be as compatible with stoichiometric uranium dioxide as pure molybdenum.

    As previously mentioned, low temperature ductility is a desireable property for a SPAR core heat pipe material, and the Mo-Re alloys containing from 10-50 wt% rhenium definitely possess this characteristic. As will be noted in Fig. 8 and Table II, the DBTT for high purity electron beam melted alloys drops significantly within the first 15% addition of rhenium. As
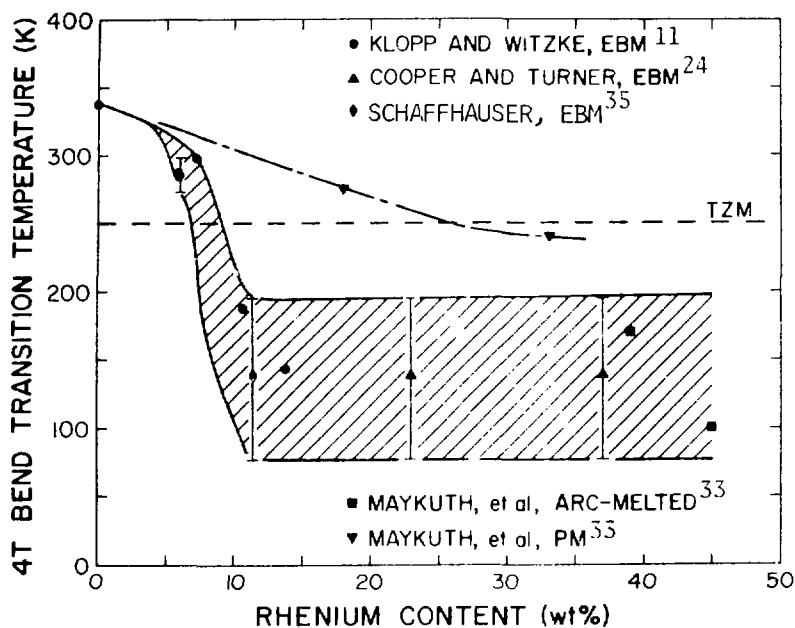
Fig. 8. Ductile-brittle transition for recrystallized Mo-Re alloys.

TABLE II

4T BEND TEST DATA FOR ELECTRON BEAM MELTED, RECRYSTALLIZED Mo-Re ALLOYS,
ACCORDING TO SCHAFFHAUSER[35]

Re Content wt%	Conditions	Bend Angle at Indicated Test Temp (K)			
		293	273	195	77
6	Bas. metal	90	20	0	0
	EB welded	40	0	0	0
11.5	Base metal	90	90	90	0
	EB welded	90	90	20	0
23	Base metal	90	90	90	0
	EB welded	90	90	80	0
	GTA filler	90	30	0	0
37	Base metal	90	90	90	0
	EB welded	90	90	90	0
	GTA filler	20	0	0	0

shown in Fig. 8, powder metallurgical alloys do not show significant reductions in the DBTT until more than about 35% rhenium is added. This probably is a reflection of alloy purity, especially interstitial content which is unfortunately not reported.[33] No references were found on the effects of either impurity content or strain rate on the DBTT of Mo-Re alloys.

The effects of adding rhenium to molybdenum on the room temperature mechanical properties of Mo-Re alloys are seen in Fig. 9 for high purity electron beam melted (EBM) alloys at the lower rhenium contents and arc-melted alloys[34] and EB melted alloys[36,37] at the higher ($\geq$ 15 wt%) rhenium contents. This plot also shows that significant room temperature strengthening does not result until the alloy contains more than 15 wt% rhenium. This plot also suggests a peak in ductility (elongation at failure) between 9 and 14 wt% rhenium. It is significant that this is precisely the rhenium content range for maximum softening observed experimentally[38] and explained on the basis of alloy electron concentration.[22]

As will be noted in Table I, the creep strength of the Mo-Re alloys is significantly higher than for LCAC molybdenum. A comparison of the predicted, creep behavior of Mo-Re alloys, TZM and pure molybdenum is given in Fig. 10. The curve for Mo-51 wt% Re is derived from the limited data found in Ref. 34, while the curve for Mo-14 wt% Re is derived from data found in Ref. 11. The curve for TZM is derived from an extrapolation of Stephenson's data,[19] while the curve for pure recrystallized molybdenum is derived from three consistent sets of data[10,11,12] for similar purity materials. It is clear from these curves that the wall thickness of SPAR core heat pipes could be reduced by at least 50% if Mo-14 wt% Re were used instead of LCAC molybdenum which would result in a weight reduction for the heat pipe of about 30%.

The formability of Mo-Re alloys near the rhenium solubility limit is well known to be very good. However, Schaffhauser[35] found that high purity, electron beam melted alloys containing more than 20 wt% rhenium could be cold rolled after an initial reduction of 50% at 1075 K. He also found that alloys containing less than 20 wt% rhenium down to 6 wt% could be rolled at 475 to 575 K without edge cracking. Mo-50 Re was once available in tubing form that was produced by either drawing or swaging.[39]

According to a supplier's technical data brochure,[28] Mo-50 Re can be machined by "standard procedures." Neither Klopp and Witzke[11] nor
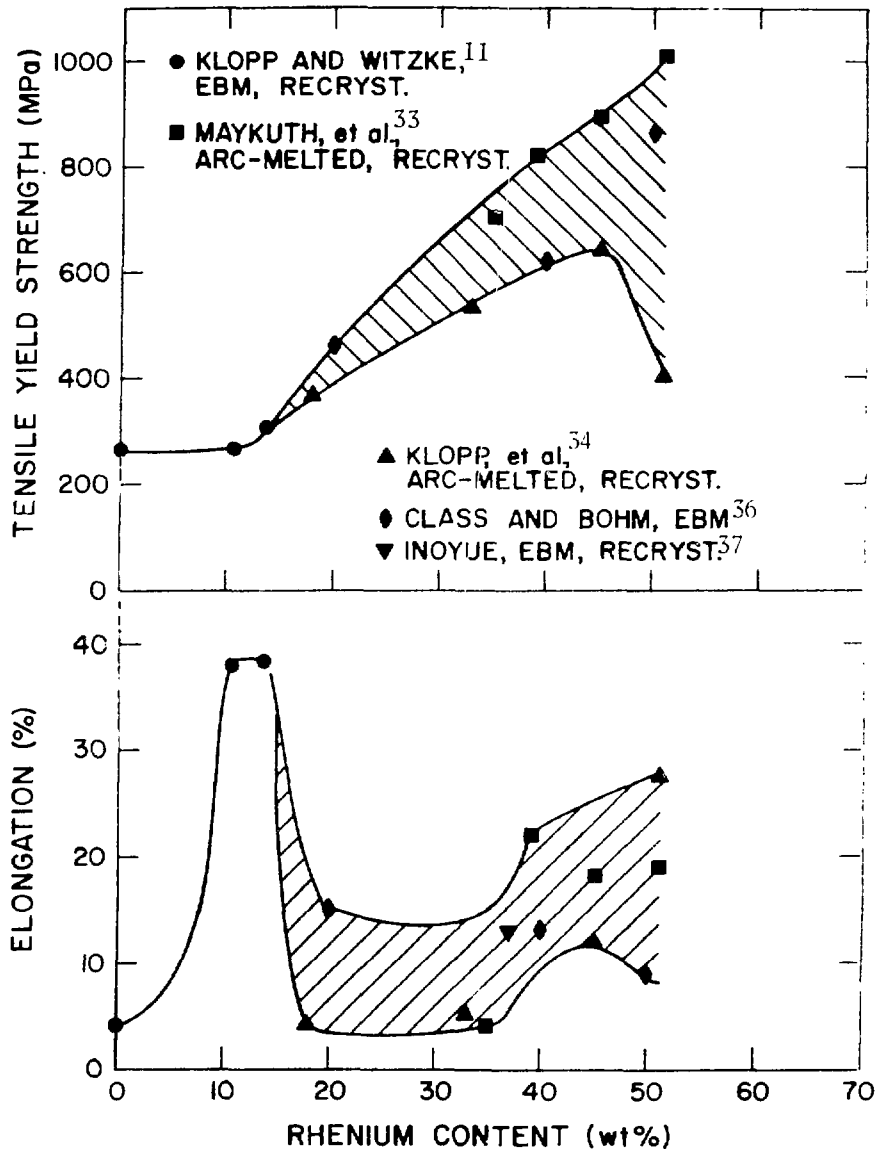
Fig. 9.   Room temperature mechanical properties of melted Mo-Re alloys.

Schaffhauser[35] indicate any difficulties machining tensile and bend test specimens from alloy bars or sheet containing as little as 6 wt% rhenium.

The outstanding weldability of Mo-50 Re by both electron beam and GTA methods is well known. Schaffhauser[35] has studied the weldability of
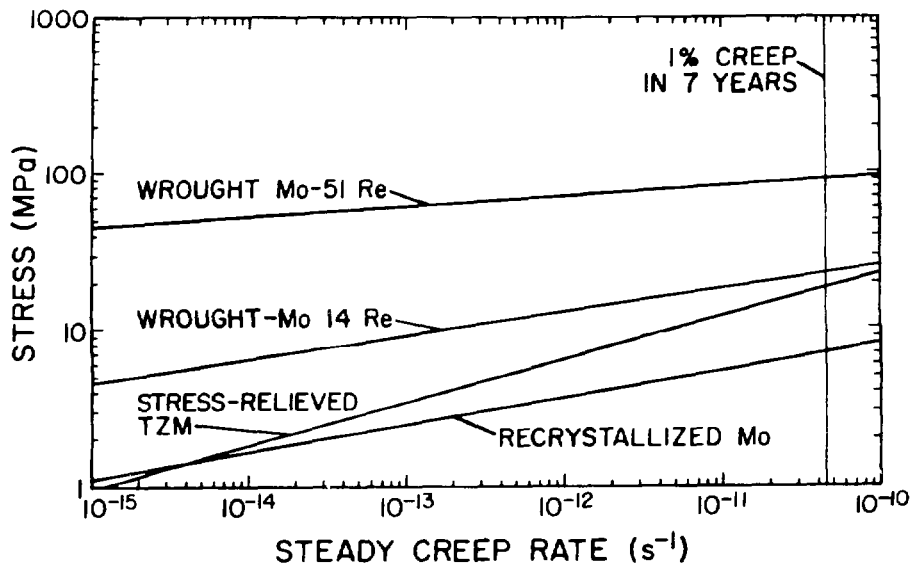
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Fig. 10. Predicted steady creep rate for molybdenum and selected molybdenum alloys at 1400 K.

electron beam melted lower rhenium content alloys using both electron beam fusion welding and GTA welding with Mo-46 Re filler metal. The results of standard 4T bend tests transverse to the butt-welded joints are included in Table II. It will be seen from these data that electron beam fusion welds have better bend ductility than the GTA filler welds. Class and Böhm[36] found that arc and electron beam melted alloys with from 30-50 wt% rhenium could be satisfactorily EB and GTA welded, but sintered alloys of similar compositions could only be EB welded.

IV. CONCLUSIONS AND RECOMMENDATIONS

It is clear from this study that some advantages could be derived from using either TZM or Mo-Re alloys instead of LCAC molybdenum for the SPAR core heat pipes. LCAC molybdenum is expected to be brittle under launch conditions, and because of newly correlated data, the present thickness of the heat pipe wall appears to be too small to insure against creep failure before the end of the lifetime of the reactor. TZM may offer enough improvement to the heat pipe container to make it the most practical alternative, but because fine TZM wire is not readily available, an easy transition to a TZM

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screen wick is not expected. A TZM container tube might be GTA welded so that we could consider making relatively simple weld closures on bent heat pipes. TZM should also offer a significant weight advantage over pure molybdenum because of its higher creep strength. Because arc-cast TZM tubing is presently avilable commercially, we have already ordered some TZM tubing for purposes of evaluation.

On paper, the Mo-Re alloys appear to offer the best alternative to LCAC molybdenum for the entire SPAR core heat pipe, but the availability of these alloys is at best limited. There is probably a weight advantage to the use of the low rhenium content alloys, but an optimization study must be performed to decide which alloy is best both from a performance viewpoint and a fabrication viewpoint. The literature contains a wealth of data on which to base an optimization study, and it is expected that hardware could be produced from the optimum alloy within as little as two years. It appears that electron beam melted alloys offer the best chance for success. It also appears that the optimum Mo-Re alloy contains from 10-15 wt% rhenium. It is therefore recommended that molybdenum-rhenium alloys in this composition range be produced and evaluated for use in SPAR core heat pipes.

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